Using in-stream biotopes to assess the effectiveness of stream rehabilitation projects

A thesis submitted for the degree of

Doctor of Philosophy

at the

University of Leicester, UK

By

Ahmed Faraj Ali Al-Zankana

College of Life Sciences

October, 2018

Declaration

I hereby declare that no part of this thesis has been previously submitted to this or any other university as part of the requirements for a higher degree. The content of this thesis is the result of my own work unless otherwise acknowledged in the text or by reference.

The work was conducted in the field at Leicestershire, East Midlands of England and College of Life Sciences, University of Leicester, UK during the period September 2013 to September 2016.

Ahmed Al-Zankana

Dedication

*I dedicate this work to my **father** and **mothe**r, their prayers in the middle of nights were the bridge I needed to complete this journey.*

*To my **kids**, the source of positive energy in my life.*

*To my **amazing wife**, whose sacrificial care for me and our children made it possible for me to complete this.*

Using in-stream biotopes to assess the effectiveness of stream rehabilitation projects

Ahmed Faraj Ali Al-Zankana

Abstract

Hydromorphological rehabilitation is increasingly being used to reverse degradation and destruction of stream and river ecosystems. There have been many criticisms of river rehabilitation projects, because many have not met their goals, while many others have not been monitored sufficiently well to assess whether their goals were met. With increasing investment in rehabilitation, there is an urgent need to develop effective approaches to assessing treatment efficacy and effect. The lack of appropriate monitoring has meant that the effectiveness of stream rehabilitation has generally not been rigorously demonstrated. This research proposes a novel, structure- and function-based methodology for evaluating linkages between river and stream "hydromorphological rehabilitation", "in-stream biotope heterogeneity", and "macroinvertebrate community structure and function" in support of reach-scale river and stream hydromorphological rehabilitation ecology.

In Before-After-Control-Impact (BACI) study designs, in-stream biotopes and their macroinvertebrate assemblages as structural and functional units were used to assess the ecological effectiveness of two different river rehabilitation projects – one using large woody material installation and the second one using entire channel hydromorphological rehabilitation.

Both rehabilitation projects were successful in enhancing the rehabilitated reaches' in-stream biotope number and diversity. Macroinvertebrate density, biomass, richness, diversity, and secondary production values were increased significantly. Macroinvertebrate community taxonomic composition and functional composition were enhanced to become more similar to those of the natural reaches. Changes in in-stream biotope number and their percentages of cover were significantly related to changes in the rehabilitated reaches' macroinvertebrate community metrics. The results of both projects indicate that comparing in-stream biotopes between reaches can provide a rapid method for monitoring rehabilitation outcomes. Macroinvertebrate structural and functional metrics can provide a quantitative basis for assessing reach-level rehabilitation outcomes if samples are collected in a random sampling protocol stratified at the in-stream biotope-level using a BACI design.

Summary

I conducted a global review of all published stream and river rehabilitation studies in the literature from 1984 to 2016 to identify the factors limiting effective rehabilitation. The apparent lack of effect on macroinvertebrate communities of many previous hydromorphological rehabilitation projects is thought to be due to: (a) a failure of the rehabilitation measure applied to enhance hydromorphology; (b) to swamping of small changes by large-scale external drivers; or (c) to a combination of the two. It seems, however, that methods used to evaluate the outcomes of rehabilitation projects may have failed to properly assess the outcomes, which has led to a poor diagnosis of both the "problem" and the effectiveness of any "solution". In this literature review I identified four methodological limitations that have meant that the effectiveness of stream rehabilitation has generally not been rigorously demonstrated: 1) a full multi-habitat sampling protocol - as outlined in the official European Union Water Framework Directive (EU WFD) - would reflect the proportion of in-stream biotopes present with ≥5% cover; but such protocols were rarely applied; 2) the most comprehensive study design - Before-After-Control-Impact (BACI) was not common practice; 3) most studies sampled rivers for only one season, and therefore could not account for seasonal variations that could affect macroinvertebrate community composition; 4) the most commonly employed indicators of success were macroinvertebrate taxa richness and diversity, even though these measures may fail to identify other consequential changes in ecosystem structure and function. Ecosystem functional indicators such as macroinvertebrate density, biomass and secondary production were rarely assessed.

I have used in-stream biotopes and their macroinvertebrate assemblages as structural and functional units to assess the effectiveness of two different river rehabilitation projects – one using large woody material (LWM) installation at the Rolleston Brook, a headwater tributary of the River Welland; and the second one using entire channel hydromorphological rehabilitation of a reach of the Upper Welland in Market Harborough, both in Leicestershire, UK. Furthermore, I have analysed the taxonomic assemblages, densities, and biomass to provide information on feeding traits and the productivity of the macroinvertebrate communities in order to provide a comprehensive assessment of rehabilitation effectiveness for the first time. BACI study designs were

applied to assess inherent differences between the control and rehabilitated reaches and to partition the effects of the applied rehabilitation measures from natural sources of variation. Seasonal changes in channel morphology, in-stream biotope number and diversity were recorded before the rehabilitation processes, and after the processes for two years. Macroinvertebrate samples were collected in random sampling protocols stratified at in-stream biotope-level. Three replicate samples were taken from all existing biotopes that covered at least 1% area of the riverbed. A Surber sampler (500 µm mesh size and area of 0.09 m^2) was used to collect quantitative samples.

To study the ecological effects of LWD installation, logs (larger than 10 cm diameter and 1 m in length) were installed in a 350 m reach of the Rolleston Brook: a) parallel to the channel to enhance the water flow; b) perpendicular (70-90°) to the channel to create meander patterns and promote riffle-pool sequences, and increase hydraulic roughness; c) angled (30°) as deflectors to kick flow over to one side to promote bank scour for outer meander bend development; d) as wing deflectors from both sides spanning the stream channel to create steps along the channel profile, regulate sediment movements through the channel system, and enhance leaf litter retention. A 220 m reach of the rehabiltated site was compared with a 220 m reach of a nearby natural tributary as a reference.

Installed LWM was successful in reducing downstream transport of leaf-litter, dissipating flow energy, enhancing the stability of the stream-bed through controlling the distribution of silt, generating coarse biotopes and increasing in-stream biotope diversity. In the first post rehabilitation year, the rehabilitated reach's macroinvertebrate total density, total biomass, taxa richness, Ephemeroptera, Plecoptera, Trichoptera (EPT) count, and EPT biomass all increased significantly. Shredders became the dominant feeding group in terms of density and biomass. The rehabilitated reach became similar to the natural reach in winter and spring seasons according to the total density of their macroinvertebrate communities; and in winter and autumn seasons according to their EPT biomass percentage. However, in the second post-rehabilitation year, the installed LWM had been washed away during a preceding flood event. Trapped silty materials were dispersed so that they covered the cobble and gravel patches, and retained leaf-litter was either washed out to the channel banks or downstream. As a consequence, channel morphological metrics, in-stream biotope%, and macroinvertebrate metrics all declined.

To study the ecological effects of an entire-channel rehabilitation project, a 1.8 km reach of the Welland River which had been extensively straightened, widened and deepened by past flood defence works was actively restructured and rehabilitated. Rehabilitation included removing weirs and re-opening a meander where it had previously been bypassed by a flood channel. Within the study reach the channel was meandered and narrowed, and a low-flow channel created by building berms constructed from the spoil derived from the excavation of pools. A series of riffle-pool sequences were constructed by digging pools in meander bends and depositing the material between the bends; silt was carried away by water flow. Creating a shallower bank profile provided more marginal space for plants. Native macrophytes were planted to provide allochthonous organic matter and shade. 250 m reaches of the rehabilitated, physically degraded, and natural sites were compared.

Rehabilitation of the Welland River increased the variability of channel depth and width. It increased in-stream biotope number and diversity. Macroinvertebrate taxa richness, taxa diversity, total density, total biomass, EPT richness, EPT diversity, EPT count%, and EPT biomass increased significantly. Shredder and Scraper feeding group density and biomass also increased significantly. Macroinvertebrate community production increased significantly during the second post-rehabilitation year compared to the first post-rehabilitation year. The rehabilitated reach attained conditions of the natural reach by the second post-rehabilitation spring and summer according to total biomass, taxa richness, EPT richness, EPT diversity, EPT biomass%, and Chironomidae count%.

In both rehabilitation projects, macroinvertebrate community taxonomic composition and Functional Feeding Groups (FFGs) composition were enhanced after the rehabilitation process to become more similar to those of the natural reaches. Changes in in-stream biotope number and percentages were significantly related to changes in the rehabilitated reaches' macroinvertebrate community metrics.

These positive outcomes would not have been detected using the less comprehensive sampling strategies or study designs most frequently employed in the literature (see Table 2.5). These findings relate to gaps in stream rehabilitation ecology; they can serve as a guide for more effective rehabilitation strategies and monitoring protocols. The methodology developed in this dissertation is broadly applicable and extensible to other river systems and ecosystem functions. The findings can be used to understand complex control of in-stream biotope deterioration, assess stream rehabilitation outcomes, and inform river rehabilitation strategies. Overall, this research improves scientific understanding of the linkage between hydromorphology rehabilitation and river ecosystems, which may permit more efficient allocation of scarce water resources for human and environmental objectives.

Acknowledgements

I would like to thank all those who gave me the possibility of completing my thesis. Especially, I am deeply indebted to my supervisors Dr. Tom Matheson and Professor David Harper for their steadfast commitment to mentorship. This work would not have been possible without assistance in the field from Ramesh Patel, Tom Richards and Dr. Natalie E. Simmonds who helped in collecting samples. Thanks are also due to Dr. Sam Gandy for showing me tiny mouthparts of water creatures, and how to identify them. I acknowledge the contribution of people from Welland Rivers Trust especially Lisa Smallwood for teaching me how to map in-stream biotope compositions and record morphological variables. A big thanks also to the people in my laboratory 322 for their help.

Thanks to Freshwater Biological Association (FBA) at Windermere, Cumbria for the high-class training courses about sampling and identification of freshwater macroinvertebrates, especially Professor Ian Wallace for his Caddis fly identification training, and Steve Brooks' Chironomid identification training.

I am also indebted to Professor Bob Clark from Marine Biological Association, Plymouth, UK for inspiring me to analyse multivariate ecological data using PRIMER v7 and PERMANOVA, and for his continuous support during my data analysis.

I am most grateful to the Iraqi government Higher Committee for Education Development (HCED) for their generous sponsorship of my PhD studies, and the Kurdistan government – Ministry of Education for granting me leave of absence to carry out this PhD.

Finally, I would like to thank Shilan, my wife, for her unwavering support, love and willingness to run our small family, while I was looking after my tiny water creatures. I do apologise to you my lively little friends Shna and Ari that I have not had enough time to play with you for four years, whilst I was trying to save our planet's environment. A big hug and welcome to our new family member, Awin. She is not talking yet, but she shows her love by hugging and kissing me.

Ahmed Faraj Ali Al-Zankana

Publication arising to date from this thesis

Harper, D., Barham, P., Smallwood, L., Coombs, N., Al-Zankana, A. & Chase, R. (2015). Holistic river restoration – The Welland at Market Harborough. *River Restoration Centre 16th Annual Conference*, Northamptonshire, U.K. http://www.therrc.co.uk/sites/default/files/files/Conference/2015/Outputs/presentations/2.1.3_david_harper.pdf

Al-Zankana A, Matheson T, Harper DM (2016) Using biotopes for monitoring success of stream restoration; short-term effects of woody debris dam in a small rural stream on macroinvertebrate community structure and function. A case study from England. *Annual Meeting of the British Ecological Society. Liverpool, U.K.* http://www.britishecologicalsociety.org/wp-content/uploads/2016/11/BES-Programme-2016-web.pdf *p.44.*

Al-Zankana A, Matheson T, Harper D (2016) Biotopes as design for restoration and units for monitoring success. *River Restoration Centre 17th Annual Conference*, Blackpool, U.K. http://www.therrc.co.uk/sites/default/files/files/Conference/2016/presentations/2.3.2._ahmed_al_zankana.pdf

Al-Zankana A, Matheson T, Harper DM (2016) Using biotopes as units for monitoring success of stream restoration; effects of woody debris dam in a small rural stream on macroinvertebrate community. *10th European Conference on Ecological Restoration, Freising, Germany*. http://www.ser2016.org/download/SER2016_Freising_Abstract_Book.pdf p.32.

List of Contents

Chapter 1. General Introduction 1
1.1. Introduction 1
1.2. Aim and objectives 4
1.3. Thesis structure 5

Chapter 2. Study background and literature review 6
2.1. Introduction: Structure & Processes in Natural River Ecosystems 8
2.1.1. The Scale of Physical Structure in River Channels 9
2.2. Physical degradation and its negative ecological consequences 16
2.2.1. Driving forces of river degradation and their negative ecological effects 18
2.3. River rehabilitation ecology, techniques and their practical value 25
2.3.1. Approaches to river rehabilitation and evidence of success 30
2.3.2. Does river rehabilitation work? 38
2.4. Evaluating stream rehabilitation projects: A new global literature review 42
2.4.1. Introduction 42
2.4.2. Methods 43
2.4.3. Results 44
2.4.4. Discussion 54
Chapter 3. Rehabilitation of Rolleston Brook using Large Woody Material 68
3.1. Introduction 68
3.2. Aim and objectives 75
3.3. Materials and methods 77
3.3.1. Study reaches and LWM installation 77
3.3.2. Surveying channel morphological features and mapping in-stream biotopes 83
3.3.3. Sampling and preservation of macroinvertebrates 84
3.3.4. Identification and counting of macroinvertebrate specimens 86
3.3.5. Assessing biomass 86
3.3.6. Feeding strategy assignment 88
3.3.7. Calculating reach-level macroinvertebrate community composition 89
3.3.8. Calculating reach-level macroinvertebrate univariate metrics 92
3.3.9. Data analysis 92
3.4. Results 95
3.4.1. Channel morphological metrics and in-stream biotope structure 95
3.4.2. Macroinvertebrate community structure and diversity metrics 101
3.4.3. Macroinvertebrate community taxonomic composition 107
3.4.5. Macroinvertebrate FFGs abandance and biomass 114
3.4.6. Macroinvertebrate FFGs community composition 121
3.4.7. Relationships between morphological variables and macroinvertebrate community structure, diversities and composition 125

Chapter 4. Short-term ecological effects of rehabilitation of the Welland River at Welland Park, Market Harborough 136
4.1. Introduction 136
4.2. Aim and objectives 141
4.3. Materials and methods 143
4.3.1. Study sites 143
4.3.2. Rehabilitation activities 145
4.3.3. Surveying channel morphological features and mapping in-stream biotopes 147
4.3.4. Sampling and preservation of macroinvertebrates 148
4.3.5. Identification and counting of macroinvertebrate specimens 149
4.3.6. Assessing biomass 149
4.3.7. Feeding strategy assignment 149
4.3.8. Calculating reach-level macroinvertebrate community composition 150
4.3.9. Calculating reach-level macroinvertebrate univariate metrics 150
4.3.10. Data analysis 150
4.4. Results 154
4.4.1. Channel morphological metrics and in-stream biotope structure 154
4.4.2. Macroinvertebrate community structural and functional metrics 159
4.4.3. Macroinvertebrate community taxonomic composition 165
4.4.4. Macroinvertebrate FFGs community composition 175
4.4.5. Macroinvertebrate FFGs abundance and biomass 179
3.4.6. Relationships between morphological variables and macroinvertebrate community structure, diversities and composition 184
4.5. Discussion 187

Chapter 5. Secondary production of macroinvertebrates as a tool to assess the success of a stream rehabilitation process 192
5.1. Introduction 192
5.2. Aim and Objectives 194
5.3. Methods 195
5.3.1. Study sites 195
5.3.2. Macroinvertebrate sampling and data processing 195
5.3.3. Estimation of macroinvertebrates secondary production 196
5.3.4. Data analysis 197
5.4. Results 198
5.5. Discussion 205

Chapter 6. General Discussion 209
Appendices 224
References 371

List of Tables

Table 2.1. The full list of biotopes. 13
Table 2.2. In-stream flow biotopes. 13
Table 2.3. Meta-analyses reviewed on the effects of hydromorphological rehabilitation processes on macroinvertebrate communities. 41
Table 2.4. The outcomes of stream or river rehabilitation projects as assessed by macroinvertebrate community parameters. 53
Table 2.5. Summary of published studies on the effects of rehabilitation projects on habitat heterogeneity and macroinvertebrate community structure and function. 55
Table 2.6. Reference used to calculate rehabilitation success in each of four categories of rehabilitation measures (A, entire channel hydromorphological rehabilitation projects; B, in-stream hydromorphological rehabilitation projects; C, lateral and longitudinal connectivity projects; D, riparian rehabilitation projects). 64
Table 3.1. Summary of published studies addressing the effects of LWM rehabilitation projects on habitat heterogeneity and macroinvertebrate community structure and function. 73
Table 3.2. Macroinvertebrate sampling dates according to the study reaches. 84
Table 3.3. Macroinvertebrate functional feeding group (FFG) types, adopted from Chevene, Doleadec and Chessel (1994). 89
Table 3.4. Univariate macroinvertebrate community metrics transformations. 94
Table 3.5. Mean and standard deviation (±SD) of macroinvertebrate community structural and functional metrics. 106
Table 3.6. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Count m^{-2}) data (at family-level), identifying those families most affected by morphological changes and contributing at least 70% of the temporal dissimilarity in community composition of the impact reach. 112
Table 3.7. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Biomass m^{-2}) data (at family-level), identifying most affected families by morphological changes and contributing at least 70% of the temporal dissimilarity in community composition of the impact reach. 113
Table 3.8. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate FFGs composition (Count m^{-2}), identifying feeding groups were most affected by the addition of LWM and contributing at least 70% of the temporal dissimilarity in community composition of the rehabilitated reach. 115
Table 3.9. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate FFG composition (Biomass m^{-2}) data, identifying feeding groups most affected by the morphological change and contributing at least70% of the temporal dissimilarity in community composition of the impact reach. 117
Table 3.10. Average abundance of functional feeding groups based on the number of individual m^{-2}. 119

Table 3.11. Average biomass of functional feeding groups (FFGs) based on mgDM m^{-2}. 120
Table 3.12. Summary of sequential tests, obtained from distance-based linear models (DISTLM), seeking relationships between temporal variations in macroinvertebrate univariate metrics and channel morphological variables. .. 126
Table 3.13. Summary of sequential tests, obtained from distance-based linear models (DISTLM), seeking relationships between macroinvertebrate FFGs density and channel morphological variables. 127
Table 3.14. Summary of sequential tests, obtained from distance-based linear models (DISTLM), seeking relationships between macroinvertebrate FFGs biomass and channel morphological variables. 128
Table 3.15. Optimal BIOENV selected morphological variables with total Spearman's rank correlation coefficient (ρ) for temporal variations in macroinvertebrate community taxonomic and feeding groups composition. 128
Table 4.1. Macroinvertebrate sampling visit dates for each study reach........ 148
Table 4.2. Macroinvertebrate feeding strategies, adopted from Chevene, Doleadec and Chessel (1994). 149
Table 4.3. Transformations applied to Univariate macroinvertebrate community metrics. 153
Table4.4. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Count m^{-2}) data, identifying families contributing 70% of the temporal dissimilarity in community composition of the rehabilitated reach. 172
Table4.5. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Biomass m^{-2}) data, identifying families contributing 70% of the temporal dissimilarity in community composition of the rehabilitated reach. 174
Table4.6. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate FFGs composition (Count m^{-2}) data, identifying the most affected feeding groups that contributed 70% of the temporal dissimilarity in community composition of the rehabilitated reach. 181
Table4.7. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate FFGs composition (Biomass m^{-2}) data, identifying the most affected feeding groups that contributed in 70% of the temporal dissimilarity in community composition of the rehabilitated reach. 183
Table 4.8. Optimal BIOENV selected morphological variables with total Spearman's rank correlation coefficient (ρ) for temporal variations in macroinvertebrate community taxonomic and feeding groups composition. 186
Table 5.1. Macroinvertebrate sampling visit dates used for calculation of secondary production for each study reach........ 196
Table 5.2. Mean (SD) secondary production (mgDM m^{-2}) for each macroinvertebrate taxonomic group in each study reach for the 1st and 2nd post-rehabilitation years. 202

Table 5.3. Mean (SD) secondary production (mgDM m^{-2}) for each macroinvertebrate feeding group in each study reach for the 1st and 2nd post-rehabilitation years. 203
Table 5.4. Percentage secondary production contributed by each macroinvertebrate taxonomic group to the study reaches total production. 204
Table 5.5. Percentage secondary production contributed by each macroinvertebrate feeding group to the study reaches total production for the 1st and 2nd post-rehabilitation years. 204

List of Figures

Figure 1.1. Schematic diagram of the thesis structure. 7
Figure 2.1. In-stream biotopes with examples of positively associated macroinvertebrate trait categories (Demars et al. 2012)... 12
Figure 2.2. The dependence of in-stream biotopes upon stream power (Smith, Harper & Barham 1991). 15
Figure 2.3. The important of in-stream biotopes at the interface between the geomorphological processes and human land uses in a river, and its in-stream biodiversity (Harper & Everard 1998). 15
Figure 2.4. Conceptual overview of the relationship between drivers, hydromorphological pressures, and associated habitat and flow alterations....................................... 17
Figure 2.5. The process-focused aims of river rehabilitation projects and associated techniques to restore characteristic habitat, biodiversity and connectivity, adopted from (Addy et al. 2016). 29
Figure 2.6. Summary of geographic distribution of rehabilitation projects, most common rehabilitation methods, study designs and most common macroinvertebrate metrics used to quantify the outcomes of rehabilitation for 359 independent rehabilitation projects. 50
Figure 3.1. Influence of large woody materials on geomorphological processes in streams, adopted from Baillie (2011). 69
Figure 3.2. Concrete obstructions are affecting the channel longitudinal connectivity.. 79
Figure 3.3. Map of the impacted reach shows positions and ways of LWM installation. 79
Figure 3.4. LWM installed to enhance the reach hydromorphological features. 80
Figure 3.5. The natural woody material in the rehabilitated reach. 80
Figure 3.6. Map of study reaches. 81
Figure 3.7. Natural tributary of Rolleston Brook. 82
Figure 3.8. Surber sampler. 85
Figure 3.9. Diagram shows calculation of the reach-level T_{count} data list from the biotope-specific T_{count} data lists. 91
Figure 3.10. Two sections of the rehabilitated reach, before (2014) and after the LWM installation (2015 and 2016). 96
Figure 3.11. Seasonal variations in morphological metrics. 97
Figure 3.12. Installed LWM washed down in spring 2016 by a flood. 98
Figure 3.13. The second concrete obstruction affected the rehabilitated reach longitudinal connectivity. 99
Figure 3.14. PCA ordination plots showing seasonal trends of a) channel morphological metrics, and b) in-stream biotope composition, depending on reach-level data measured over five successive seasons during the first and second years after LWM installation in both natural and rehabilitated reaches. 100
Figure 3.15. Seasonal variations in macroinvertebrate community structure according to the study reaches. 102
Figure 3.16. Seasonal variations in macroinvertebrate community structure according to the study reaches. 103

Figure 3.17. Seasonal variations in macroinvertebrate community structure according to the study reaches. 104
Figure 3.18. Seasonal variations in macroinvertebrate community structure according to the study reaches 105
Figure 3.19. nMDS ordination plots, based on the 4th root transformed Bray-Curtis similarities of macroinvertebrate taxonomic composition. 108
Figure 3.20. nMDS ordination plot of macroinvertebrate taxonomic composition (Count m-2) showing that dissimilarity between the natural and rehabilitated reach decreased after LWM installation in spring 2015... 109
Figure 3.21. Shade plot of macroinvertebrate community taxonomic composition data matrix, showing families contribution to seasonal dissimilarities between the natural and rehabilitated reach. 110
Figure 3.22. Macroinvertebrate functional feeding groups' structure based on a) average abundance (individual m^{-2}), b) average biomass (mgDM m^{-2})........................... 118
Figure 3.23. nMDS plot, based on the 4th root transformed Bray-Curtis similarities of FFGs composition showing separation of both reaches. 122
Figure 3.24. nMDS ordination plot of macroinvertebrate FFG composition (Count m-2) showing that dissimilarity between both reaches has decreased after LWM installation process.. 123
Figure 3.25. Shade plot of macroinvertebrate community Functional Feeding Groups (FFGs) composition data matrix, showing feeding groups contribution to seasonal dissimilarities between the natural and rehabilitated reach. 124
Figure 4.1. A section of the study reaches. 140
Figure 4.2. Map of study reaches of Welland River and Jordan River at Market Harborough, Leicestershire, UK.. 144
Figure 4.3. A section of the rehabilitated reach (entire study reach) shows low flow channel design and rehabilitation measures applied... 146
Figure 4.4. Hydroscope with clear plastic bottom. 147
Figure 4.5. Changes in the rehabilitated reach channel morphology and appearance of new in-stream biotopes after the rehabilitation process. 154
Figure 4.6. Seasonal variations in morphological metrics. 156
Figure 4.7. Seasonal variations in morphological metrics. 157
Figure 4.8. PCA ordination plots showing seasonal trends of a) channel morphological metrics, and b) in-stream biotope composition, depending on reach-level data measured over seven successive seasons during the first and second years after rehabilitation in degraded, natural and rehabilitated reaches. 158
Figure 4.9. Seasonal variations in macroinvertebrate community structure according to the study reaches. 161
Figure 4.10. Seasonal variations in macroinvertebrate community structure according to the study reaches. 162
Figure 4.11. Seasonal variations in macroinvertebrate community structure according to the study reaches. 163
Figure 4.12. Seasonal variations in macroinvertebrate community structure according to the study reaches. 164

Figure 4.13. nMDS ordination plots, based on the 4th root transformed Bray-Curtis similarities of macroinvertebrate taxonomic composition. 166
Figure 4.14. nMDS ordination plot of macroinvertebrate taxonomic composition (Count m^{-2}) showing that dissimilarity between the rehabilitated and natural reaches was decreased after rehabilitation. 167
Figure 4.15. Shade plot of macroinvertebrate community taxonomic composition data matrix, showing taxa contribution to seasonal dissimilarities between the study reaches. 168
Figure 4.16. nMDS plot, based on the 4th root transformed Bray-Curtis similarities of FFGs composition. 176
Figure 4.17. nMDS ordination plot of macroinvertebrate FFG composition (Count m^{-2}) showing that dissimilarity between the rehabilitated and natural reach compositions was decreased after the rehabilitation process. 177
Figure 4.18. Shade plot of macroinvertebrate community Functional Feeding Groups (FFGs) composition data matrix, showing feeding groups' contribution to seasonal dissimilarities between the study reaches. 178
Figure 4.19. Macroinvertebrate feeding groups average abundance (individual m^{-2}). .179
Figure 4.20. Functional feeding groups based on average biomass (mgDM m^{-2}).......... 182
Figure 5.1. Total production of macroinvertebrate community in each study reach for the 1st and 2nd post-rehabilitation years. 199
Figure 5.2. Secondary production contributed by each macroinvertebrate taxonomic group to the study reaches total production for the 1st and 2nd post-rehabilitation years. 200
Figure 5.3. Secondary production contributed by each macroinvertebrate feeding group to the study reaches total production for the 1st and 2nd post-rehabilitation years..201
Figure 6.1. A diagram illustrating the aims and methods of LWM installation, and the positively affected ecological metrics. 213
Figure 6.2. A diagram illustrating the aims and the rehabilitation techniques applied in the Welland River rehabilitation project, and the positively affected ecological metrics. 218

List of Appendices

Appendix 1. Species names for macroinvertebrates, dry mass conversions and linear measures used to assess individuals dry mass. 224
Appendix 2. Assigning of macroinvertebrate taxa count and biomass into functional feeding groups according to Tachet *et al.* (2010) fuzzy codding. 229
Appendix 3. Data analysis of Chapter 3. 235
Appendix 4. Data analysis of Chapter 4. 269
Appendix 5. Data analysis of Chapter 5. 368

List of Abbreviations

BR	Boulders/rock surface
CO	Cobbles
G	Gravel
SA	Sand
SI	Silt
R	Tree Root
TV	Tree branches/Vegetation
MP	Marginal Plants
LL	Leaf Litter
WM	Woody Materials
ME	Macrophytes Emergent
MF	Macrophytes Floating-leaved
MSF	Macrophytes Submerged, fine-leaved
MSB	Macrophytes Submerged, broad-leaved
M	Moss
MA	Macroalgae
EPT	Ephemeroptera-Plecoptera-Tricoptera
BA	Before-After
CI	Control-Impact
BACI	Before-After-Control-Impact
GES	Good Ecological Status
GEP	Good Ecological Potential
PCA	Principal Components Analysis
db-RDA	distance-based Redundancy Analysis
DISTLM	Distance-based linear modelling
SD	Standard Deviation
RHS	River Habitat Survey - UK
LWM	Large Woody Material
LWD	Large Woody Debris
FFGs	Functional Feeding Groups
EEA	European Environment Agency
WHO	World Health Organisation
WFD	Water Framework Directive
PSI	Proportion of Sediment-sensitive Invertebrates
QMCI	Quantitative Macroinvertebrate Community Index
B-C Similarity	Bray-Curtis Similarity
BI	Invertebrate Biological Index
CV_depth	Coefficient of variation of channel water depth
CV_width	Coefficient of Variation of channel water width
nMDS	non-metric Multidimensional Scaling
SIMPER	Similarity percentage

AIC	Akaike Information Criterion
ρ	Spearman's rank correlation
SWI_biotope	Shannon-Winner Index of Biotope Diversity
ANOSIM	Analysis of Similarities
RRP	River Restoration Project
mgDM	Milligram Dry-Mass
SS	Sum of Squares
TP	Total production

Chapter 1. General Introduction

1.1. Introduction

Freshwaters provide a wide range of ecosystem services, especially, provisional services like drinking water and food, and regulating services like self-purification, nutrient spiralling and water regulation (WHO 2005). The benefit of natural river corridors for human physical and mental wellbeing have been recognised in a statement of the UK Faculty of Public Health (2010), that encourages integration of the environment and human wellbeing as inspiring natural areas can benefit human health and aid recovery from illness.

In Europe, more than 50% of freshwaters are not meeting their environmental quality objectives of Good Ecological Status (GES) or Good Ecological Potential (GEP)[1] under the EU Water Framework Directive (WFD) (Solheim *et al.* 2012). According to the first river basin management plans (RBMPs), hydromorphological pressures and altered habitats are the most extensive impacts affecting around 40% of river ecosystems today (European Environment Agency 2012). The aim of the WFD is that all water bodies should fulfil a requirement of GES by 2027 at the latest. As a consequence, there is increasing emphasis in Europe on river rehabilitation driven by demands of the WFD (Friberg *et al.* 2016).

Rehabilitation of lost hydromorphological features seems to be the best way to minimise the ecological effects of rivers hydrological and morphological degradations (Mitsch & Jørgensen 2003; Ormerod 2003; Pedersen, Baattrup-Pedersen & Madsen 2006), which is an important component in achieving GES (Friberg *et al.* 2016).

Understanding the effectiveness of river rehabilitation techniques is critical for directing future rehabilitation projects, planning and design (Roni & Quimby 2005). The need for monitoring to achieve this has been acknowledged in recent years (Roni & Beechie 2013), but evaluation and monitoring the outcome of river rehabilitation projects are still rare (Bernhardt *et al.* 2005; Palmer, Menninger & Bernhardt 2010; Wolter *et al.* 2013; Kail *et*

[1] In the case of irreversible human impacts (e.g. heavily modified water bodies, HMWB).

al. 2015). The majority of river rehabilitation schemes fail to assess outcomes and effectiveness (Cowx *et al.* 2013), or use inadequate statistical designs, or inappropriate biological methods, which hamper rehabilitation ecologists' ability to detect changes (Friberg *et al.* 2016). Despite the increasing number of rehabilitation interventions and an increased social drive to identify effective solutions that have economic benefits (Everard 2012; Smith, Clifford & Mant 2014; Reichert *et al.* 2015), evidence for strong and long-term positive ecological effects of hydromorphological rehabilitation – particularly on macroinvertebrates - are generally limited (Palmer, Menninger & Bernhardt 2010; Feld *et al.* 2011; Friberg *et al.* 2014), with few notable exceptions (Miller, Budy & Schmidt 2010; Kail *et al.* 2015). These findings partly reflect the lack of robust scientific assessments of rehabilitation measures (Verdonschot *et al.* 2015). The conflicting results together with the relative infancy of stream rehabilitation science (Palmer, Hondula & Koch 2014) indicate the urgent need for more and better studies to address the links between hydromorphology rehabilitation and stream biota (Louhi *et al.* 2011; Wolter *et al.* 2013). Ideally, monitoring success of a rehabilitation project should be carried out both pre- and post- project condition and over a sufficient length of time to allow the recovery to be adequately assessed (Addy *et al.* 2016). Scientifically sound sampling design is required to separate the changes which result from rehabilitation processes, from the noise caused by natural variability like seasonal and annual differences (Friberg *et al.* 2011). Degraded (control) and natural or semi-natural (reference) sites would allow these natural changes need to be taken into account and to track the direction of changes after the rehabilitation.

In-stream 'biotopes' with distinct macroinvertebrate assemblages have been shown to be a useful way of linking macroinvertebrate ecology and stream hydromorphological rehabilitation, and can be used as a tool to assess the hydro-morphological status of rivers (Harper, Smith & Barham 1992; Demars *et al.* 2012). The consideration of stream ecology at this scale is important as it has also proved to be useful in the UK river habitat survey RHS (Environment Agency 2003), and river management (Harper & Everard 1998) because in-stream biotopes can be used in a simple building-block approach to rehabilitation (Harper, Smith & Barham 1992; Petersen, Petersen & Lacoursiere 1992; Kemp, Harper & Crosa 1999) as the interface between organisms and the physical processes of a stream. The in-stream biotope approach treats stream as being composed of distinct habitat units, recognisable and classifiable both on the basis of their physical and biological attributes (Buffagni *et al.* 2000). They are a useful unit of study in river channels, a rapid and effective way to assess river condition (Kemp 1999; Kemp, Harper & Crosa 2000). Working at this level "makes [the system] easier to study, understand or manage" (Rabeni, Doisy & Galat 2002). It also "can be a cost-effective tool, and can increase reproductively and comparability of field results, and indices application" (Buffagni *et al.* 2000). The quantification of in-stream biotope diversity gives a surrogate measure of macroinvertebrate diversity and an indication of overall ecosystem health (Harper & Everard 1998). It can be used as a rapid and effective way of providing information of sufficient detail to assess the ecosystem without the need for painstaking identification of macroinvertebrates or complex hydraulic modelling (Kemp, Harper & Crosa 2000). Macroinvertebrates have been regarded as the best indicators of environmental condition in lotic systems for many years (e.g. Chandler 1970). Any study should include both the structure and function of macroinvertebrate communities, as a way of assessing ecosystem health, because assemblages consist of many species with different trophic levels and different sensitivity to environmental factors (Cook 1976). The inclusion of functional traits such as feeding traits as well could additionally provide a cornerstone in the development of new metrics sensitive to subtle changes, within hydromorphological modification (Friberg, Sandin & Pedersen 2009) and thus an alternative method to evaluate the effects of stream rehabilitation (Friberg *et al.* 2016). Accurate assessment of invertebrate production would include measures of both their structure and function (Dolbeth *et al.* 2012), and is additionally a fundamental requirement for understanding and quantifying energy flow in lotic system (Benke 1993). In addition, most invertebrates are sedentary and represent specific ecological conditions (Cook 1976).

In this study, I am using in-stream biotopes and their macroinvertebrate assemblages as a structural and functional unit to assess effectiveness of two different river rehabilitation projects – one on the Rolleston Brook, a headwater tributary of the River Welland, and the second a reach of the Upper Welland in Market Harborough, both in Leicestershire, UK. Furthermore, I am analysing the taxonomic assemblages, densities, and biomass to provide information on feeding traits and the productivity of the most abundant taxa in order to provide a comprehensive assessment of rehabilitation effectiveness for the first time.

1.2. Aim and objectives

The overall aim of this thesis is to quantify the ecological effects of hydromorphological stream rehabilitation projects, with one focus on large woody debris installation "hitherto referred to in its currently-accepted name, 'woody material'," and one on entire channel hydromorphological rehabilitation. It will combine BACI study design with semi-natural 'reference' reach, using in-stream biotopes for sampling and evaluation and use macroinvertebrate structural and functional metrics, especially secondary productivity. This is a novel approach to address a current knowledge gap in the field of river rehabilitation.

The specific objectives were to:

1) Explore available literature on the ecological effects of stream hydromorphological rehabilitation processes, and defined the factors limiting effective rehabilitation (Chapter 2).
2) Understand the role of installed LWM in a small rural stream in enhancing stream hydromorphology, in-stream biotope number and diversity, and macroinvertebrate assemblage composition, structure and function (Chapter 3).
3) Understanding the scientific basis of an entire-channel hydromorphological rehabilitation process and its role in an urbanised river to enhance stream morphology, in-stream biotope number and diversity, and macroinvertebrate assemblage composition, structure and function (Chapter 4).
4) Explore the effects of rehabilitation techniques on aquatic macroinvertebrate productivity, and suitability of this functional metric for monitoring rehabilitation projects success (Chapter 5).
5) Discover which macroinvertebrate metrics (taxonomic or functional metrics) provide the most understanding of ecological effects of stream rehabilitation (Chapter 6)?

6) Highlight the suitability sampling at in-stream biotope level and BACI study design as an approach to assess the ecological success of hydromorphological rehabilitation projects (Chapter 6).

The hypotheses tested in this thesis and the rationale for predicting these hypotheses can be found in the core chapters of the thesis, Chapters 3-5.

1.3. Thesis structure

The structure of this thesis and the content of each chapter is summarised in Figure 1.1. Chapter 2 begins with a general introduction on natural river ecosystem structure and processes. It explores the pattern of macroinvertebrate community composition, structure and function in natural channel hydromorphology and in-stream biotope heterogeneity. The most common types of stream degradation, rehabilitation techniques and needs for rehabilitating degraded streams were also considered. It moves on to explore the findings of previously published case-studies on the influence of physical rehabilitation and rehabilitation techniques on channel hydromorphology and in-stream macroinvertebrate community composition, structure and function. It explores geographical distribution of stream rehabilitation projects, common rehabilitation measures applied, common monitoring study designs used and common macroinvertebrate metrics used for accessing biological influences. It concludes by discussing the factors limited positive biological outcomes.

The main aims and objectives of this thesis are explored within the three result chapters (Chapter 3, 4, 5). These three chapters have been produced as a series of manuscripts for publication. As a result, there is some overlap between them. Chapter 3 presents the results of using large woody material LWM (a common type of physical rehabilitation measure) to restore a formerly straightened reach of the Rolleston Brook (a headwater stream tributary of the Welland River, Leicestershire - England). In this case-study, short-term influences of the rehabilitation process on the rehabilitated reach morphology and macroinvertebrate community composition, structure and function were explored using a Before-After-Control-Impact study design (BACI). The rehabilitated reach was compared with a nearby natural reach of the same stream which has been used as the goal state of the rehabilitation. Chapter 4 presents the results of an entire-channel rehabilitation process (another common type of stream physical rehabilitation technique) of the Welland River at The Welland Park (Market Harborough - Leicestershire – England) on the rehabilitated reach channel morphology, in-stream biotope heterogeneity and macroinvertebrate community structure, composition and function. Study reaches were mapped, and macroinvertebrate samples were collected in a BACI study design. The rehabilitated reach was compared with a control and reference reach; a physically degraded reach of the Jordan River just before the confluence with the Welland River downstream of the rehabilitated reach was used as a control of degraded and a natural reach of the Welland River at the upstream of the rehabilitated reach was used as a reference. Specific aims and objectives of both case-studies, study sites, rehabilitation activities, in-stream biotope mapping, and macroinvertebrates sampling protocol are described in details in each relevant chapter. Chapter 5 extends the biotic evaluation of both kinds of stream rehabilitation measures, by calculating macroinvertebrates secondary production as a variable metric.

Chapter 6 discusses the results in relation to the aims and objectives of the thesis. It also addresses the applications of the research especially using in-stream biotopes as physical units to assess both morphological and biological outcomes of these kinds of physical rehabilitation techniques. The chapter concludes with the suitability of macroinvertebrate (taxonomy, FFGs or secondary production) metrics for assessing the short-term biological effect of stream rehabilitation process, and provides recommendations for future stream rehabilitation projects and monitoring studies.

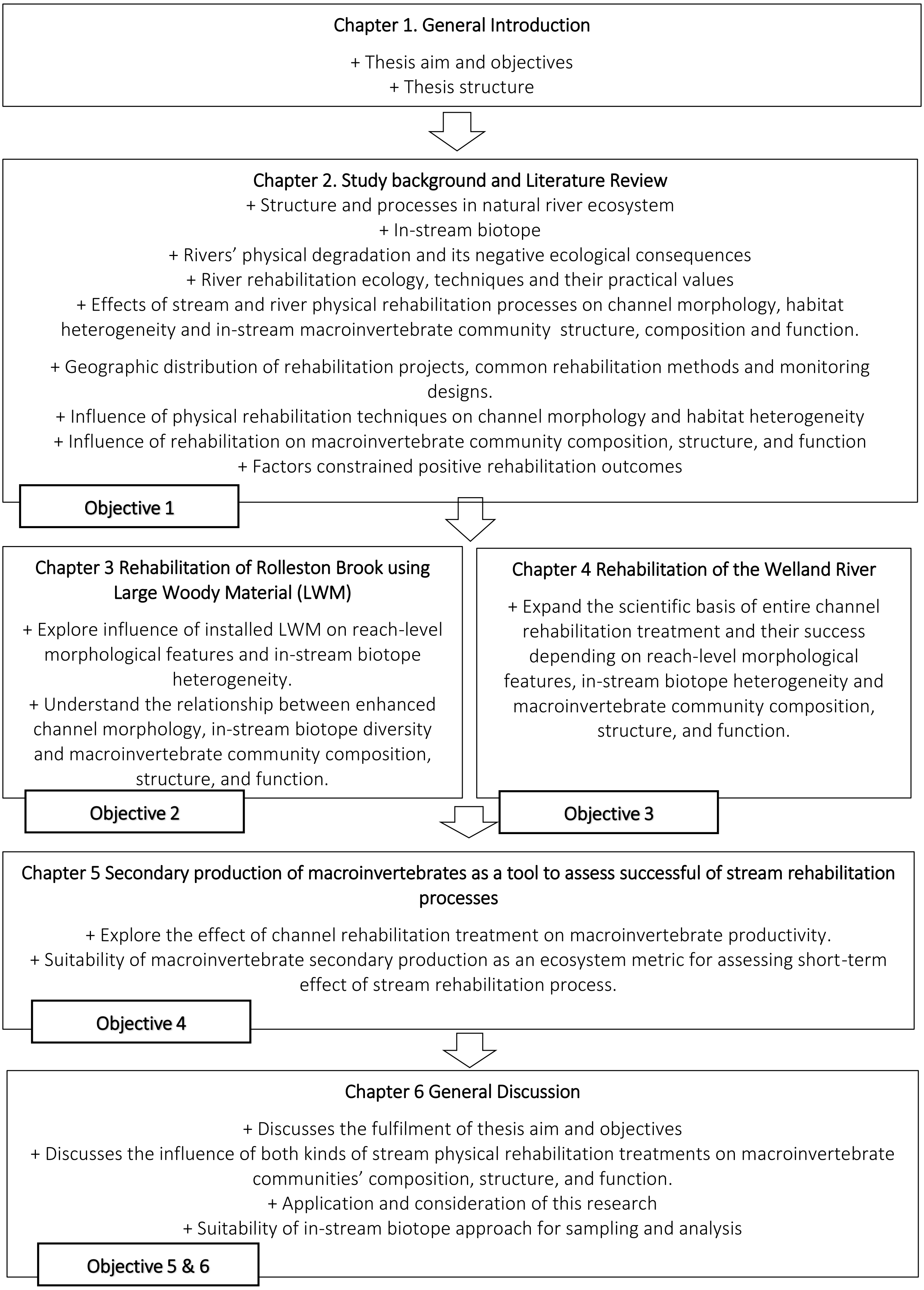


Figure 1.1. Schematic diagram of the thesis structure.

Chapter 2. Study background and literature review

2.1. Introduction: Structure & Processes in Natural River Ecosystems

Lotic ecosystems range in size from springs a few centimetres wide to great rivers kilometres wide (Allan 1995). They are complex hydrological, geomorphological and ecological continua (Naiman 1992). Their ecosystems structurally are a combination of the physical structure of a place, a group of organisms selected by natural selection plus a set of processes by which the biotic factors manipulate energy and materials in interaction with each other and with abiotic factors (Moss 2010).

The natural morphology of a river is determined by its catchment-scale structural controls, its reach-scale channel patterns differences, and small-scale differences in the river's form and composition, with continuing change over time (Frissell *et al.* 1986; Friberg 2014). A river's physical structure is centred upon the channel that has been cut by water. Its exact discharge characteristics will change due to gravity, the nature of the bedrock and the quantity, duration and speed of flow. The energy of the discharge – weight of water and downhill movement due to gravity – moves materials of different size –silt, sand, gravel and boulders – during bank full high discharges. These features are variable with passage downstream, and may also be affected by organic material that washed from the riparian zone or floodplain (Moss 2010). These natural physical properties of a river, all of which respond in different ways to degradation (Downs 1995), are classified geomorphologically as features like the 'dominant bed type', 'entrenchment ratio', 'sinuosity', 'width:depth ratio' and 'water surface slope' (Rosgen 1994).

Photosynthetic biota, known as phytobenthos, together with bacteria and fungi in a biofilm over surfaces underwater, are the essential sources of energy to stream ecosystems (Vannote *et al.* 1980), either directly (phytobenthos, known as autochthonous producers), or indirectly (microbial decomposition of sources from outside the ecosystem, known as allochthonous producers). Several hundred species of invertebrates, of many phyla, are then the fundamental link in the stream food web between organic matter and fishes (Hynes 1970). Lotic macroinvertebrates include arthropods, molluscs, annelids, nematodes, and platyhelminthes. Most of them are benthic or macrozoobenthic, living on or between stable surfaces rather than being routinely free-swimming. They are associated with surfaces such as bedrock, cobbles, finer sediments, fallen trees, snags, roots, and aquatic vegetation (submerged or emerged) (Hauer & Resh 1996).

Natural processes include primary production by photosynthesis via absorption of solar energy, transferring this energy in food webs through herbivores and predators and, after death, through detritivores and microbial consumers. There are thus two kinds of production in stream ecosystems – allochthonous and autochthonous production. Photosynthetic algae are autochthonous, while imported and dissolved organic matter from the catchment (allochthonous) is processed by microbes. In many streams, leaf litter and its microbial layer is consumed by several groups of “leaf-shredding, film-scraping, deposit-feeding and filter-feeding invertebrates”, and these are eaten by both invertebrate and vertebrate predators (Moss 2010). Nutrients and carbon cycles are affected by macroinvertebrates as they are the crucial link between primary producers, primary consumers, and top predators (Jayawardana 2011).

2.1.1. The Scale of Physical Structure in River Channels

In-stream macroinvertebrate distribution is governed by the availability of different habitats, food resources and biotic interaction (Giller & Malmqvist 1998). Substrate characteristics such as particle size (Pennak & Van Gerpen 1947; Bourassa & Morin 1995; Pedersen & Friberg 2007), stability (Stanford & Ward 1983; Downes, Glaister & Lake 1997), and habitat heterogeneity (Hynes 1970; Tolkamp 1980; Beisel, Usseglio-Polatera & Moreteau 2000; Boyero 2003) can all influence invertebrate community composition. Habitat stability is generally seen as being proportionate to particle size. Sand is a very unstable substrate, sandy sediment particles and organic matter are easily eroded by higher flow, making them less suitable than other biotopes for macroinvertebrates (Allan *et al.* 2012). Larger particle size substrates such as gravel and cobbles are more stable biotopes, important refuge for invertebrates during floods (Matthaei & Townsend 2000), and support higher number of macroinvertebrate taxa (including Ephemeroptera, Plecoptera, Tricoptera taxa) than sandy biotopes (Quinn & Hickey 1990; Maxted, Evans & Scarsbrook 2003; Timm 2003; Pan, Wang & Xu 2012). Refugia are spatially discrete patches within the channel bed substratum where hydraulic forces and shear stresses are lower, relative to the surrounding area (Lancaster *et al.* 2006). The occurence of invertebrates in refugia during disturbances increase the chance of survival and allows redistribution and collonisation post-disturbance (Lancaster & Belyea 1997; Hart & Finelli 1999).

Riffles have often been percieved as homogenous geomorphological units (Grant, Swanson & Wolman 1990). High diversity of aquatic macroinvertebrates have been found in riffles and high numbers (e.g. oligochaetes and chironomid larvae) in organic-rich sediments, reflecting the feeding modes of different taxa and how they process different carbon sources. Benke (1984) found that woody materials were heavily colonised, with higher taxa diversity than sand or mud. Retention and accumulation of leaf letter by woody materials also supported higher biomass and secondary productivity of macroinvertebrates (Entrekin *et al.* 2009). Such patterns of macroinvertebrate distribution and abundance according to in-stream patches have also been reported (Reice 1980; Bostelmann 2003; Beauger *et al.* 2006) and strengthen the value of heterogeneity for macroinvertebrate communities (Buss *et al.* 2004).

In-stream biotopes (formerly called functional habitats) are visually distinguishable, but small (50 cm^2 – 5 m^2 approximately) in-channel patches, made up of different mineral substrate, vegetation, and organic matter types, which form a dynamic mosaic structured by flow characteristics (Harper *et al.* 1995; Kemp, Harper & Crosa 1999). They are the result of predictable physical processes, and so conveniently sit between the forces which structure rivers and the biota (distinct macroinvertebrate assemblages) which inhabit them, as hydro-morpho-ecological units in river structure and function (Harper & Everard 1998).

The term “biotope” refers to the home of a species (or trait) assemblage as a physical and morphological unit. This term was adopted by Demars *et al.* (2012) in their paper for the first time, rather than the earlier terms “functional habitats” of (Harper 1995) in the same study or “mesohabitats” of Armitage, Pardo and Brown (1995) as the word ‘habitat’ implies something associated with a single species (e.g. the habitat template of Southwood 1977). Demars *et al.* (2012) linked 13 in-stream biotopes with their macroinvertebrates' biological traits (the 13 in-stream biotopes, with examples of positively associated trait category are illustrated in Figure 2.1).

Parallel developments in the fields of stream ecology and hydromorphology enabled 'biological' and 'physical' definitions of biotope to be linked through the 1990s (Kemp, Harper & Crosa 2000). Biotopes are distinct ecological units; each providing a unique physical and biological environment, and supporting a characteristic assemblage of macroinvertebrates (Kemp, Harper and Crosa (1999). They were also defined as the "interface between organisms and the physical processes of the river" by Harper and Everard (1998). Sixteen in-stream functional habitats were identified for the eastern England lowland rivers (Table 2.1) which together form the entire channel by (Harper 1995; Harper & Smith 1995). A natural river probably contains the entire set of in-stream functional habitats, it is likely that semi-natural reach of a lowland river can come close (Kemp 1999).

From hydromorphology, nine distinct 'flow biotopes' were the definition of in-stream physical habitat units according to surface flow type, characterised through hydraulic measurement (Padmore 1997) (

Table 2.2). The Froude number was the most reliable hydraulic variable to distinguish between them (Wadeson 1994; Gordon *et al.* 2004). In hydraulics, the Froude number is a dimensionless velocity/depth ratio, and it is used to define tranquil or sub-critical flow (Fr<1) and rapid or supercritical flow (Fr>1) (Chow 1959). Jowett (1993) found that velocity/depth ratio was the best discriminator of larger habitat units - riffle, run, and pool -, closely followed by the Froude number.

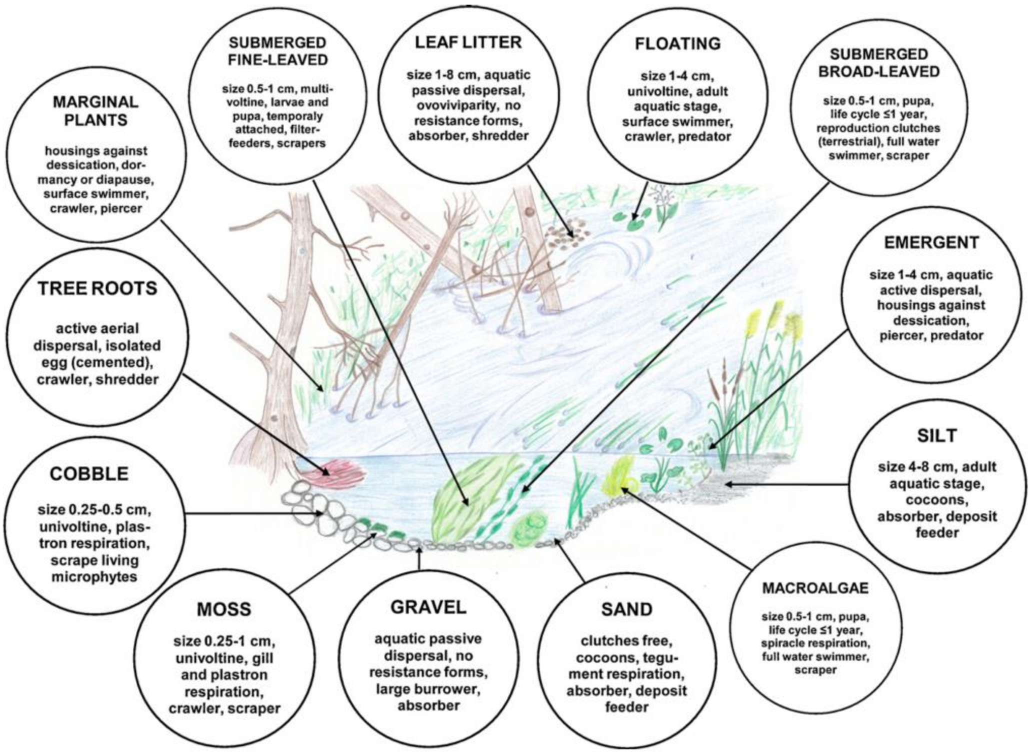


Figure 2.1. In-stream biotopes (capital letters) with examples of positively associated macroinvertebrate trait categories (Demars *et al.* 2012). 'Submerged fine-leaved', 'floating', 'submerged broad-leaved' and 'emergent' refer to macrophyte biotopes.

Table 2.1. The full list of biotopes (Harper 1995; Harper & Smith 1995).

Habitat	Code	Notes
Boulders/rock surfaces >256 mm	BR	Used instream by some filterers and in wet places (hygropetric zone)
Cobbles >64 mm	CO	Dominant substrate in some highly energy streams, or elsewhere in riffles
Gravel >2 mm	G	Dominance with above, and where cobbles have been removed (lowland streams)
Sand <2 mm	SA	Forming point bars, patches in riffle-pool transition, or dominant in some streams
Silt	SI	Deposited in pools, slacks, margins or off main channel
Tree root	R	Fine exposed roots or fibrous clumps of e.g. *Alnus, Salix, Acer*
Tree branches/vegetation	TV	Overhanging into stream, surface trapping non-woody materials
Marginal plant	MP	Rooted around (e.g. *Phalaris*) or below (e.g. *Rorippa*) normal water level
Leaf litter	LL	Deposited in pools, slacks, margins or as leaf packs in riffles
Woody material	WM	Waterlogged and rotting trees, logs, substantial branches and driftwood
Macrophytes, Emergent	ME	Significant aerial portion, e.g. *Sparganium* (usually grasses, rushes, reeds)
Macrophytes, Floating-leaved	MF	Leaves lying on water surface, e.g. *Nuphar* and some *Potamogeton* species
Macrophytes, Submerged, fine-leaved	MSF	Include fine leaves (e.g. *Zannichellia*) or dissected leaves (e.g. *Ranunculus*)
Macrophytes, Submerged, broad-leaved	MSB	Include strap-like leaves of e.g. *Butomus* and *Sparganium emersum*
Moss	M	Aquatic types, e.g. *Fontinalis*, *Rhynchostegium*
Macroalgae	MA	Cott, usually *Cladophora* and *Enteromorpha* on lowland rivers

Table 2.2. In-stream flow biotopes (Environment Agency 2003).

Flow biotope	code	Associated river feature (physical biotope)
Free fall	FF	Waterfall
Chute	CH	Step (of step-pool cascade)
Broken standing wave	BW	Rapid (whitewater)
Unbroken standing wave	UW	Riffle
Chaotic flow	CF	A mixture of rough flow types
Rippled	RP	Rub
Upwelling	UP	Boil
Smooth boundary turbulent	SM	Glide
No perceptible flow	NP	Pool/deadwater
No flow	DR	Dry river bed

Kemp, Harper and Crosa (2000) established the link between functional habitats (biologically defined habitat units) and flow biotopes (hydraulically defined habitat units) using Froude number. They observed non-random distribution of fifteen of the sixteen in-stream functional habitats (except woody materials) with Froude number. Eight of them - silt, roots, trailing vegetation, marginal plants, leaf litter, emergent macrophytes, floating-leaved macrophytes and submerged broad-leaved macrophytes - generally were found in low Froude number classes, while the remaining 7 functional habitats tended to be found in higher Froude numbers - boulders, cobbles, gravel, sand, submerged fine-leaved macrophytes, moss, and macroalgae. There was a gradient, with Froude number, going from sand to gravel to moss to macroalgae to cobbles to submerged, fine-leaved macrophytes. This provided a strong evidence for the control of functional habitats by hydraulic conditions. Smith, Harper and Barham (1991) found that distribution and frequency of functional habitat reflected the real physical functioning of the river ecosystem, mineral habitats consist of sediment separated into certain particle classes, and macrophytes separated into shape and location classes rather than species; they reflect the power spectrum of a river (Figure 2.2). Harper and Everard (1998) suggested that their distribution and frequency can be related to the principal power-related features such as discharge, the riffle-pool sequence and the meander pattern, in addition to changes in the riparian land use (Figure 2.3). Particular functional habitats tend to be associated with particular flow biotopes (Newson *et al.* 1998). The UK River Habitat Survey (RHS) developed by the Environment Agency for national river survey included these, and its data have been used by Harvey, Clifford and Gurnell (2008) to seek the linkages between flow biotopes, channel morphology (physical biotopes) and functional habitats. They found strong correlations between five flow biotopes [rippled flow, no perceptible flow, smooth boundary turbulent, unbroken standing waves, and chute flow] and functional habitats occurrence and frequency.

In-stream biotopes occurrence and frequency thus reflect the dominant geomorphological processes in the river channel and are therefore sensitive to anthropogenic impact such as physical or chemical degradation (Harper & Everard 1998; Newson *et al.* 1998), by the proportion of different biotopes in a river stretch. For example, a eutrophic river has higher macroalgae biotope; a structurally degraded river has smaller proportion of large sediment biotopes and higher proportion of fine sediment biotopes.

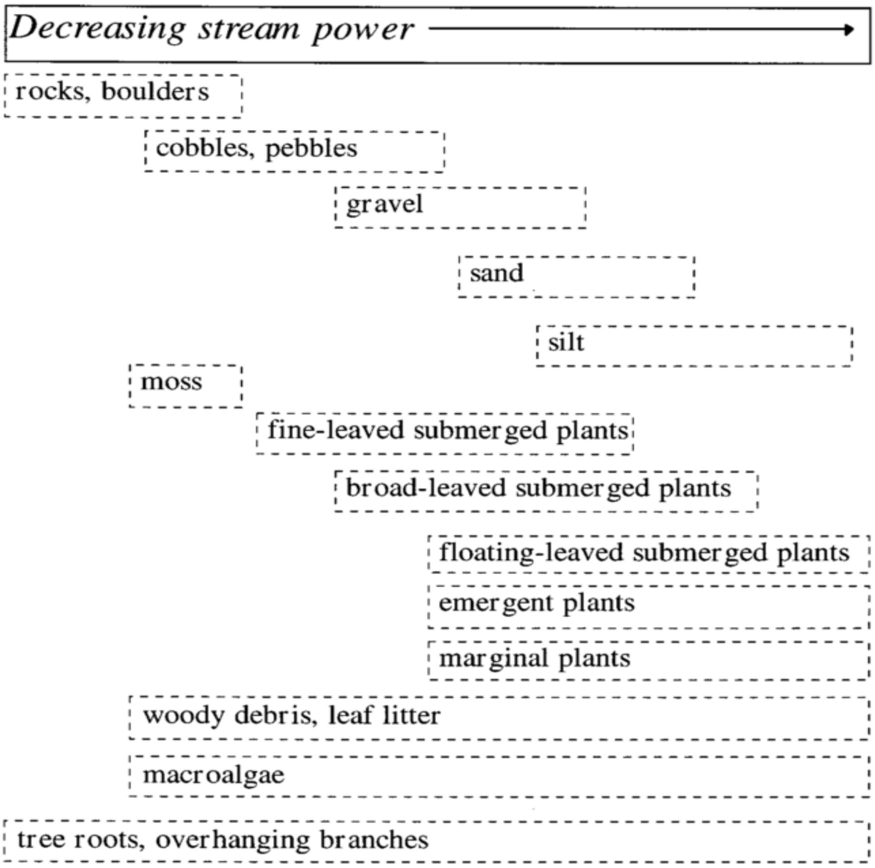


Figure 2.2. The dependence of in-stream biotopes upon stream power (Smith, Harper & Barham 1991).

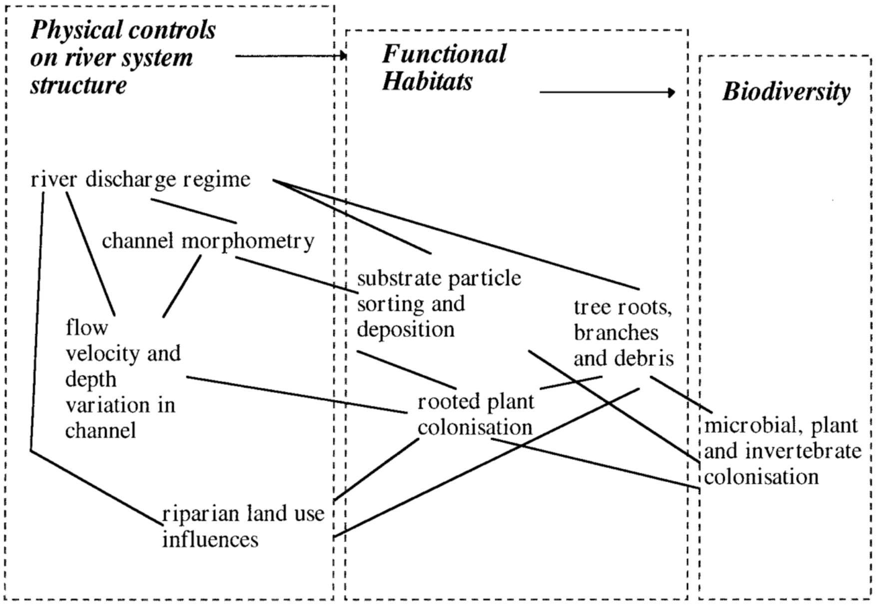


Figure 2.3. The important of in-stream biotopes at the interface between the geomorphological processes and human land uses in a river, and its in-stream biodiversity (Harper & Everard 1998).

2.2. Physical degradation and its negative ecological consequences

Hydromorphological, or in-stream habitat degradations, are changes to the natural structure and functioning of streams and rivers, such as alteration of natural flow regime through the installation of dams and weirs, modifications in the river bank structure, river channel slope and gradient (Garcia de Jalón *et al.* 2013). The consequence of these hydromorphological degradations is to create a "simplified, structurally-deficient, fragmented river system" (Ayres *et al.* 2014) that can negatively affect aquatic flora and fauna biodiversity (Garcia de Jalón *et al.* 2013; Ayres *et al.* 2014).

Globally, riverine ecosystems have been altered by man at different scales for several millennia, from alteration of the catchment-scale (e.g. landscape and land-use) to changes of the reach-scale and in-stream environment (e.g. channelisation and removal of large woody material) (Allan 2004; Vaughan *et al.* 2009) and ecology (WHO 2005). Fine sediment siltation is a major problem in many river and streams, especially in agricultural catchments (Glendell *et al.* 2014). Physical degradation and loss of complexity in river and stream ecosystems have been common in most parts of Europe, (Friberg 2010), threatening the ecological resilience and the sustainability of freshwater ecosystems to deliver goods and services that benefit people (WHO 2005).

Over the last 25 years, gross chemical and organic pollution pressures have significantly decreased in European water bodies as the result of wastewater treatment improvement and reduction in industrial effluents, so that hydromorphological degradation or elevated nutrient concentrations are now the most widespread pressure on European waters' ecological status, affecting more than 40% of all European rivers (EEA 2012). Hydromorphological pressures and in-stream habitat alteration are now the most common pressure and impacts for 48.2% (of 22 Member States) and 42.7% (of 16 Member States) of their river water bodies (Fehér *et al.* 2012). The main human-induced degradation activities, their physical pressures, and impacts on rivers habitats and flow alterations are shown in a conceptual overview by Fehér *et al.* (2012) in Figure 2.4.

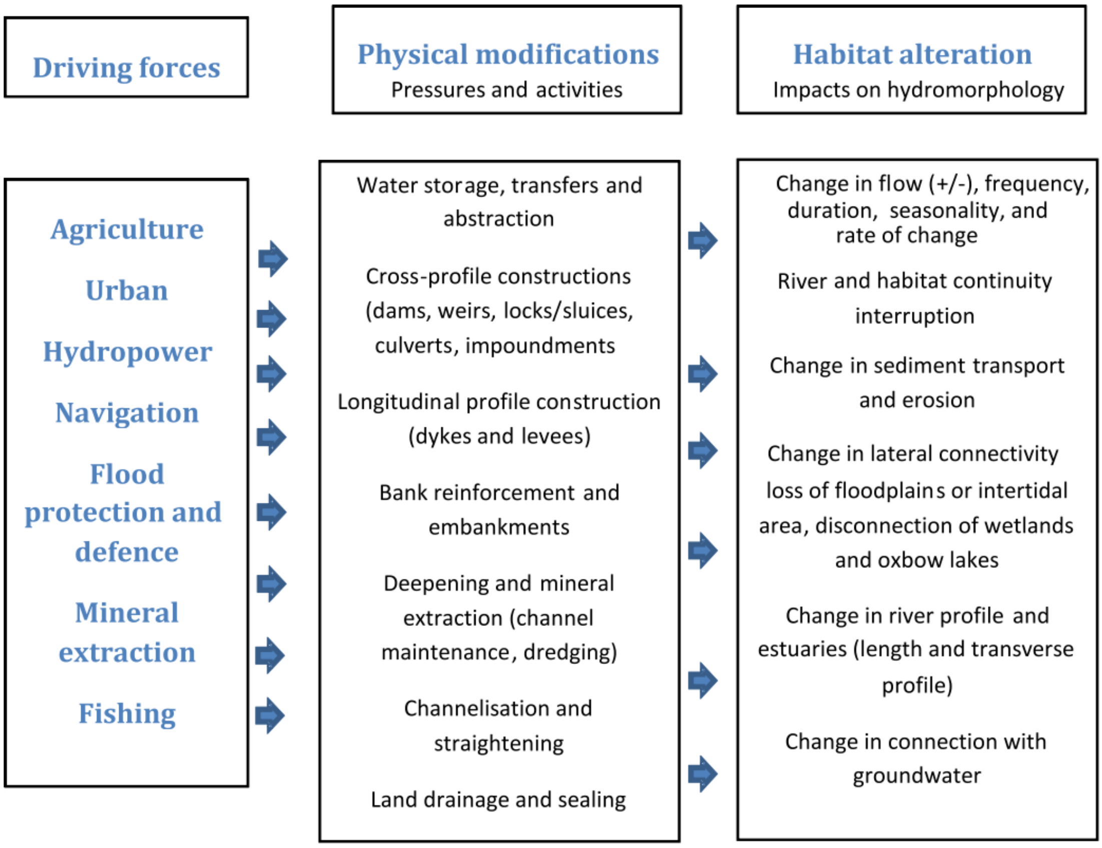


Figure 2.4. Conceptual overview of the relationship between drivers, hydromorphological pressures, and associated habitat and flow alterations. Source: (Fehér *et al.* 2012).

Analysis of the River Habitat Survey (RHS) by Raven *et al.* (1998) and the Scotland's Centre of Expertise for Waters (CREW) (Addy *et al.* 2016) provide useful information on the extent of physical degradations to the UK's river channels. More than 50% of England and Wales rivers have been physically degraded through reinforcement and reshaping (Maltby *et al.* 2011) – around 26,000 in-channel structures recorded in the river network (Environment Agency 2013), the majority of which are located in England. Loss of habitat complexity and river length are the common physical effects of those alterations. They have reduced lowland rivers' coarse substrates, shallow water, gently sloping banks, woody materials and leaf litter (Hladyz *et al.* 2011). In upland, high gradient rivers, channelisation has reduced river length, and often increased river gradient which has led to a prevalence of uniformly high hydraulic stress throughout the river channel (Mainstone & Wheeldon 2016).

2.2.1. Driving forces of river degradation and their negative ecological effects

2.2.1.1. Changing catchment land-use

In Europe, since the industrial revolution (ca. 1840), and particularly after the Second World War (1945) anthropogenic activities altered the landscape profoundly through intensive agricultural practices (Feld *et al.* 2011; Friberg *et al.* 2011). Catchment and floodplain clearance for agriculture, mineral excavation, and urbanisation have been the major causes of stream degradation. These have influenced stream and river ecosystems via increases in nutrient loading (Allan, Erickson & Fay 1997), greater solar energy flux (Hicks 1997), higher decomposition rates (Niyogi, Simon & Townsend 2003), and higher sedimentation rates (Bond & Lake 2003). They have changed both the hydrological (Potter 1991; Davies-Colley 1997) and sediment regimes (Zweig & Rabeni 2001), reduced the channel stability and subsequently produced a degraded, homogeneous river (Allan 2004). In Australia, more than 500,000 km^2 of forest and woodlands were cleared in the late 18^{th} century (Prosser *et al.* 2001), which increased catchment erosion rates and sediment delivery to streams, subsequently smothering spawning and nursery habitats (Hendry *et al.* 2003), or creating sand slugs (large, slow-moving accumulation of sediment) (Bond & Lake 2003).

Agricultural runoff, the major form of catchment land-use, affects river ecosystems by increasing nutrients and water turbidity (Henley *et al.* 2000). Consequent riverbed sedimentation impacts on the growth of benthic algae, macroinvertebrates and gravel-spawning fishes (Wood & Armitage 1997). Application of fertilisers used in agricultural lands affect stream ecosystems directly (Leonard *et al.* 1999), by widespread eutrophication (nutrient enrichment) of streams and rivers, which induces high growth of autotrophic communities such as algal blooms or macrophytes (Tilman, Kilham & Kilham 1982; Bakker *et al.* 2010), leading to oxygen depletion and pH changes (Hendry *et al.* 2003). Deficiency of oxygen in the water leads to the replacement of sensitive taxa such as oxygen-demanding fishes and invertebrates, by tolerant taxa (Hering *et al.* 2004; Furse *et al.* 2006). Pesticides are often contained within agricultural runoff that enters streams and negatively affects macroinvertebrate community. For example, Endosulfans are the main factor responsible for impairing macroinvertebrate communities in the cotton-growing regions of New South Wales (Hose *et al.* 2003).

2.2.1.2. Clearance of riparian vegetation

The extensive conversion of natural river catchments to agricultural land has often included removal of riparian vegetation. The riparian area is the transitional zone between riverbanks and floodplain that connect both aquatic and terrestrial ecosystems, both riparian area and floodplain significantly support biodiversity as they have many different type habitats (Naiman & Décamps 1997; Hladyz *et al.* 2011). The riparian zone is also the main source of organic matter, hence allochthonous energy, as small woody material from terrestrial vegetation to most stream ecosystems, especially in their upper reaches (Allan 1995).

Clearing of riparian zones for agriculture and urbanisation disrupts land-water linkages, leads to reduction in water quality, channel simplification, less stable flow and raised thermal regimes; it subsequently reduces biological integrity (Snyder *et al.* 2003). It increases the water temperature during daylight hours by the loss of shade that trees provided (Sovell *et al.* 2000). The amount of solar radiation available to the aquatic ecosystem is regulated by the surrounding riparian vegetation (Osborne & Kovacic 1993; Poole & Berman 2001). As riparian vegetation is changed or removed, the in-stream micro-climate changes and in-stream habitat will be unsuitable for many native species, thus changing the species assemblage (Poole & Berman 2001). A small difference in temperature (~2.0 °C) separates streams that can support young salmonids during their vulnerable life stage, and streams that will not support them (Jones *et al.* 2006). In cleared New Zealand pasture streams, daily water temperature has been recorded 6-7°C higher than adjacent uncleared streams (Quinn *et al.* 1997). More than 4°C difference in maximum temperature between shaded and unshaded streams has been recorded in agricultural streams in southeast Queensland and Western Australia (Rutherford *et al.* 2004). Increasing water temperature changes in-stream production, levels of dissolved oxygen and stream ecosystem carbon dynamics (Robertson *et al.* 1999). Shifts in lotic community structure of stream biota occur, as increasing temperature can provide a competitive advantage for warmer-tolerant species (Paul & Post 2001; Bear, McMahon & Zale 2007).

Riparian woodland in particular is crucial to river margin structure, morphology and dynamics, as it interacts with water flow and sediments to create and stabilise river margins (Gurnell 2013). Riparian woodland is also the source of in-stream large woody material (LWM) and organic matter (Laeser, Baxter & Fausch 2005). Their removal has led to a significant decrease of terrestrial litter input (Quinn *et al.* 1992), in-stream LWM and coarse organic matter (Gregory *et al.* 1991). In-stream wood is the main hydromorphic element in forested river channels (Diez, Elosegi & Pozo 2001). Clearing of woodland reduces in-stream habitat complexity as the opportunity for leaf litter to enter the stream is reduced and the transport rate increases (Lester & Boulton 2008). Pools become filled with fine sediment and riffles are eroded (Brooks *et al.* 2004) which negatively affects the taxonomic and functional diversity of fishes and macroinvertebrate communities (Gurnell, Gregory & Petts 1995; Stauffer, Goldstein & Newman 2000). Taxonomically, agricultural river catchments support fewer sensitive taxa species compared with natural forested catchments (Lenat & Crawford 1994; Wang *et al.* 1997; Genito, Gburek & Sharpley 2002) and functionally, the abundance of grazers increases with the loss of riparian forest as the energy source changed from autochthonous to allochthonous (Delong & Brusven 1998; Hladyz *et al.* 2011).

Livestock grazing practices have also altered the riparian and aquatic habitat (Myers & Swanson 1996), by decreasing the amount of canopy and the woody vegetation (Chapman & Knudsen 1980), changing the bank stability (Myers & Swanson 1991), and decreasing the recruitment of native species (Robertson & Rowling 2000). Stock trampling damages littoral margins and has a significant impact on the food web that rely on algae as a food source (Bunn, Davies & Winning 2003).

2.2.1.3. Channelisation

Stream channelisation for land drainage has occurred in all areas of the UK (Brock, Smith & Jarman 1999). This process involves artificial straightening, removing river meander bends, deepening and diversion of natural channels and may also involve lining channels with concrete or clay, construction of new drainage channels, embankments, bank protection and floodwalls, for the purpose of agricultural land drainage, navigation, and/or flood control (Brookes 1988; Brookes 1990). During the mid-20th Century, about 8,504 km of rivers were channelised in England and Wales (Brookes, Gregory & Dawson 1983). This caused shortening length, decreasing stream variability, with more uniform depths, velocities, and structural diversity (Hansen 1971; Shields, Knight & Cooper 1994; Brooks *et al.* 2004), widening and deepening the channel profile (Brooker 1985; Landwehr & Rhoads 2003; Moerke *et al.* 2004; Pedersen 2009). Channelized streams have less stable banks compared with natural streams due to lack of the riparian vegetation root matrix (Reily & Johnson 1982) and are susceptible to bank erosion. Thus, the sediment load has often been increased as the result of bank erosion in channelized rivers with negative effects upon the in-stream substrate and biological community (Kroes & Hupp 2010). Lower abundance and species richness of fish were observed in channelised sections of Bunyip river in Australia (Hortle & Lake 1983), attributed to decreased channel stability and sedimentation.

Straightening and increasing the gradient of streams and rivers generally increases flow velocity and causes channel widening or lowering (incision or entrenchment) (Rhoads 1990; Williamson, Smith & Quinn 1992; Landwehr & Rhoads 2003). Consequential lowering of the water table in the riparian zone has reduced growth of riparian vegetation (Reily & Johnson 1982). Channel incision also affects the lateral connectivity of streams and rivers with their floodplain, which limits the available habitat and potential resources for fish and invertebrates.

De-snagging or active removal of in-stream LWM as another mechanism of channelisation has also altered the in-stream environment. Active removal of in-stream LWM was used extensively until the late 1990s as it was thought it could help fish migration, assist land drainage and reduce flood risk (Addy *et al.* 2016). In Australia, de-snagging caused the loss of almost the entire natural wood load from many rivers (Gippel, Finlayson & O'Neill 1992). De-snagged rivers tend to be straighter, wider and less diverse (Gregory, Boyer & Gurnell 2003). In-stream habitat loss due to de-snagging has decreased fish populations (Collares-Pereira & Cowx 2004) and macroinvertebrate density and diversity (Nakamura & Yamada 2005).

2.2.1.4. Loss of river connectivity and fragmentation

River fragmentation is a discontinuity in any of the river's spatial dimensions (longitudinal, lateral or vertical) (Garcia de Jalón *et al.* 2013); such fragmentation disrupts the hydrological connectivity of the river's ecosystem (Pringle 2003), which negatively affect its physical and biotic components, as fragmentation interrupts both within and between habitat transfers of water, sediment, organic matter and organisms (Bunn & Arthington 2002). Variably river hydrology is important because high flows (flood flows) maintain river channel structure and connect floodplains together, medium flow control sediments and enhance fish spawning and migration, while low flows maintain minimum habitat for resident species (Acreman & Dunbar 2004).

Weir and dam construction are the main cause of longitudinal fragmentation. They have a profound impact on flow regimes, which are extremely variable naturally, both spatially and temporarily (Finlayson & McMahon 1988). Although a proportion of the flow is able to pass over weirs, the natural flow and sediment transport are disrupted. Weirs have also disrupted the dispersal and up- and downstream migration of fish and other aquatic organisms, especially when they span the entire width of a channel (Ayres *et al.* 2014; Addy *et al.* 2016). Branco *et al.* (2014) stated that construction of dams and weirs have severely impacted the Tagus River (Portugal) with a 48.4 – 54.4% reduction of river connectivity for fish species.

Storage of large quantities of water behind a dam, and consequent flow regulation imposes fundamental changes on fragmented river flow and sedimentation, which are the principal controls on fluvial morphodynamics (Church 1995). There are 596 dams in the UK at present (using a minimum height criterion of 15 metres) (Addy *et al.* 2016). Water is collected in artificial reservoirs and downstream flow is regulated for one or more purposes, e.g. water supply for urban areas, industrial plants, irrigation, flood control, or hydropower generation (Ward & Stanford 1979; Petts 1984). Artificial reservoirs typically lead to decreases of downstream water temperature, as dammed water is released mainly from the base of the storage, releasing hypolimnetic water, which is cooler in summer (Boulton *et al.* 2014). For example, lower water temperature (on average 5 °C) and decreased oxygen saturation were recorded downstream of Gordon dam in southwest Tasmania (Australia) compared to the upstream waters (Lake & Marchant 1990).

Artificial bank protection affects channel morphology and dynamics, it reduces marginal roughness, restricts the channel ability to migrate and channel width, and increases bed erosion (Winterbottom 2000). River embankments (e.g. using boulders, concrete or timber) to reduce channel lateral movement and protect land, settlement or infrastructure from flooding (e.g. roads and bridge) could increase downstream flood risk as they restrict a river's natural ability to erode and shift in response to floods (Raven *et al.* 2009). The occurrence of bank reinforcement is extensive in the UK (Raven *et al.* 1998). Consequently overbank flow occurrence is now regularly prevented, and river-floodplain hydrological connectivity has been severely limited. This impedes the natural transfer of water, sediment, and nutrient to and from floodplains (Tockner *et al.* 1999; Wyżga 2001; Antheunisse *et al.* 2006), leading to degradation of many aquatic ecosystems (Petts & Calow 1996; Nilsson & Svedmark 2002; Pedroli *et al.* 2002). In the absence of natural floodplain functioning has led to severe flooding of urban areas in the UK in recent years, leading to calls to provide 'room for rivers' given the recent extreme weather patterns and severe flooding in the UK and elsewhere (Hooijer *et al.* 2004; DEFRA 2005).

Vertical connectivity between surface and interstitial water can be fragmented by siltation processes which reduce the riverbed permeability and clog the pore spaces within gravels (Hancock 2002). In addition, increased instream fine sediment often leading to reduced macroinvertebrate diversity through reductions in the availability of suitable trophic resources and in-stream biotopes (Wood *et al.* 2016). Benthic algae can be smothered by siltation (Jones *et al.* 2014). Increasing fine sediment loads is probably the most important type of hydromorphological pressure for benthic algae communities (Friberg *et al.* 2016). This pushes the algal assemblage towards single-celled mobile taxa, as this unstable substrate is not suitable for the attachment of non-motile, and particularly chain-forming taxa that establish easily. This assemblage shift can be seen even where larger particles are covered with a layer of fine sediments (Dickman, Peart &

Yim 2005). Fine sediment accumulation thus leads to a decrease in algal taxon richness and biomass (Biggs, Smith & Duncan 1999; Matthaei, Guggelberger & Huber 2003).

2.2.1.5. Urbanisation

Urbanisation of river catchments has caused river hydromorphology to deteriorate (Arnold & Gibbons 1996; Allan 2004). It has enlarged river channels as a result of increased surface runoff and peak discharge (Arnold & Gibbons 1996) (Gregory 2006). Those physical changes affect the aquatic biota (Perkins *et al.* 2010) due to increasing water temperature while shade decreased (Galli 1990). In addition, they have caused decreased habitat stability, reduced diversity of benthic invertebrates (Horner *et al.* 1997; Yoder, Miltner & White 1999) and fish communities (Yoder, Miltner & White 1999).

Other alterations to in-stream habitat are caused through channel dredging and sand/gravel extraction (Garcia de Jalón *et al.* 2013). Sand and gravel extraction from rivers for construction purpose was commonplace between the 1930s and 1960s in Britain (Wishart, Warburton & Bracken 2008). This activity causes river bed incision (Kondolf 1997) and armouring (Rinaldi, Wyżga & Surian 2005), floodplain disconnection, and sometimes an entire change in channel style (Garcia de Jalón *et al.* 2013). River sediment mining also alters flood magnitude and frequency (Rinaldi, Wyżga & Surian 2005). Road runoff is a source of in-stream pollutant in urban rivers, often causing a significant increase of in-stream suspended sediment levels (Cornish 2001).

2.3. River rehabilitation ecology, techniques and their practical value

River rehabilitation has been an ever increasing technical activity in many countries, as a consequence of the recognition of the damage inadvertently caused by river modifications and effluents. The Clean Water Act was launched by the United States of America in 1972 to protect and improve the nation's freshwater resources (Senate 1972). The Water Framework Directive (WFD) was passed by the European Parliament in 2000 to achieve and maintain a good ecological quality for surface water in Europe (European Union 2000). The concept of river rehabilitation originated from these and other national efforts (Feld *et al.* 2011). It has thus been on the global agenda for more than 4 decades, and a large number of projects have been undertaken, particularly in Europe and North America (Ormerod 2004; Palmer *et al.* 2007; Feld *et al.* 2011).

Ecological rehabilitation has received increasing interest and funding over the past decades, as physical deterioration of aquatic ecosystems has intensified (Albertson *et al.* 2011). It has become a widely accepted activity in developed nations (Shields *et al.* 2003; Bernhardt *et al.* 2005), and has become common worldwide (National Research Council 1992; Cowx & Welcomme 1998). Implementing ecological rehabilitation measures in order to enhance biodiversity have become a multi-billion dollar industry worldwide since the 1990s (Bernhardt *et al.* 2005; Palmer, Hondula & Koch 2014) – over 1 billion US Dollars are now spent annually on aquatic habitat rehabilitation activities in the USA alone (Bernhardt *et al.* 2005). In Europe, similar efforts are underway to accelerate understanding and find the best ways to restore freshwater ecosystems (Morandi *et al.* 2014). In the UK, physical rehabilitation of rivers has been promoted by the formation of the EU-funded River Restoration Project (RRP) in 1992 together with partners in Denmark, and the formation of the UK River Restoration Centre http://www.therrc.co.uk/ (Mainstone & Holmes 2010).

The assumption that physical rehabilitation (which means increase of habitat heterogeneity) leads to increases in biodiversity and population density underlies most rehabilitation projects (Lepori *et al.* 2006; Roni *et al.* 2006a; Miller, Budy & Schmidt 2010). This assumption is sometimes called the "field of dreams" (i.e. if you build it, they will come) hypothesis, which has been the core paradigm in most projects (Palmer, Ambrose & Poff 1997). The natural positive relationship between increasing river bed physical diversity and taxon richness emerged through the pioneering work by Hutchinson (1959); in-stream mechanisms thought to underpin this relation were increase of refugia, space and food resources (Gurnell, Gregory & Petts 1995; Palmer, Menninger & Bernhardt 2010).

There are many different definitions of rehabilitation or restoration, from "*The completed structural and functional return to a pre-disturbed state*" (Cairns 1991), to "*the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed*" (Society for Ecological Restoration 2016). The term "restoration" has commonly been used by both practitioners and researchers to refer to all types of manipulations (e.g. improvement, enhancement, mitigation, new habitat creation, etc.). Roni, Hanson and Beechie (2008) however, used the term rehabilitation instead of restoration, in their global review of the physical and biological effectiveness of stream habitat rehabilitation measures, because they thought that most rehabilitation techniques do not truly restore a system into its original, pre-disturbance state. The complete restoration of lowland streams and rivers is rarely achievable as they are often nested within agricultural and urban areas, thus the rehabilitation of habitat diversity is done by re-creating morphological features (Pedersen *et al.* 2007). A global review, which compiled information on 644 rehabilitation projects by Palmer, Hondula and Koch (2014), revealed that the most common goals were increasing biodiversity, stabilising channels, improving riparian and in-stream habitat diversity, and improving water quality.

River rehabilitation process can be either active, like meandering of a straightened channel to modify its form and structure more rapidly, or passive by allowing the channel hydraulic forces to re-shape the river slowly (Gordon *et al.* 2004). Physical rehabilitation measures range from those carried out over distances of a few hundred metres at the individual reach-scale, such as riffle construction and introduction of large woody material (e.g. Edwards *et al.* 1984; Smock, Metzler & Gladden 1989; Harrison *et al.* 2004; Thompson 2015), to larger-scale projects that involve meandering of many kilometres of straightened river and reconnecting channel with floodplain (e.g. Biggs *et al.* 1998; Lorenz, Jahnig & Hering 2009; Winking 2015).

Rehabilitation is not simply the opposite of degradation, the relationship between rehabilitation and its ecological effects are likely to be differ from those identified for degradation (Moerke *et al.* 2004). An effective project requires diagnosing the primary barriers to ecological recovery, then identifying other stressors hierarchically (Feld *et al.* 2011). Streams and rivers lose their biodiversity and normal ecosystem processes as a consequence of multiple pressures; even under moderate impact levels, many sensitive species disappear quickly, while ecological process like self-purification, biomass production and decomposition may change significantly under severe degradation (Feld *et al.* 2011).

Earlier projects focused on structural rehabilitation rather than prioritising natural processes and functions by using techniques to rapidly change and improve physical habitats (Beechie *et al.* 2010). Most projects were and still are, performed with a primary focus on channel morphology and in-stream structure (e.g. channel width, depth, and slope) rather than on ecological function (Wortley, Hero & Howes 2013). Most UK projects are active, small-scale methods (Brookes 1996), focused on structural rehabilitation rather than process-based. According to the REFORM project's "inventory of restoration costs and benefits", 53% of the projects in the UK concern river planform alteration (meandering, width and depth variation), 19% in-channel structure and substrate, 9% lateral connectivity, 7% longitudinal connectivity, 7% riparian zone and 5% sediment flow quantity (Ayres *et al.* 2014). The most commonly used techniques in structural rehabilitation are the installation of flow deflectors (e.g. stones, concrete structures or LWM), boulders, rubble mats, and artificial riffles. These techniques were formerly popular due to a lack of funds, guidance, uncertainty over their effectiveness, and a lack of catchment-scale planning (Addy *et al.* 2016). There is now, however, emerging emphasis in river rehabilitation research to include the rehabilitation of ecological functions through prioritising techniques that encourage the self-recovery of degraded habitats and going beyond hydromorphological processes to include rehabilitation of ecological processes (Palmer, Hondula & Koch 2014). In turn, this can restore characteristic biodiversity (Beechie *et al.* 2010). Functional ecological rehabilitation includes restoring critical structural features (e.g. riparian vegetation), critical ecological processes such as nutrient dynamics (flux or efflux of nutrients) and the input of organic matter and productivity (Beechie *et al.* 2010; Bernhardt & Palmer 2011).

Addy *et al.* (2016) highlighted many direct and indirect actions that can be used to rehabilitate four main ecological process – lateral river movement, lateral river connectivity, longitudinal connectivity, riparian vegetation and in-channel wood – in physically degraded rivers and streams (Figure 2.5). Direct actions; such as removing physical structures that prevent or limited lateral movement of river channels, channel-floodplain connectivity, channel longitudinal connectivity, re-vegetating riparian areas and restoring in-stream LWM; or indirect actions such as changing catchment land-use to allow natural erosion and deposition, restoring up-stream sediment supply, or managing grazing pressures on the riparian area, can be used. Ideally, both direct and indirect actions should be used to satisfy the objectives of the four main ecological process. Interim measures such as adding in-stream LWM to enhance lateral channel movement, or restoring river-bed levels to enhance lateral connectivity could be used to accelerate the recovery of the ecological processes, and where societal constraints (e.g. threat to infrastructure or increased flood risk) exist, alternative 'last resort' measures such as adding deflectors, modifying flood defences, creating two-stage channel, modifying weirs, adding fish bypass structure, or sediment management should be used (Addy et al. 2016).

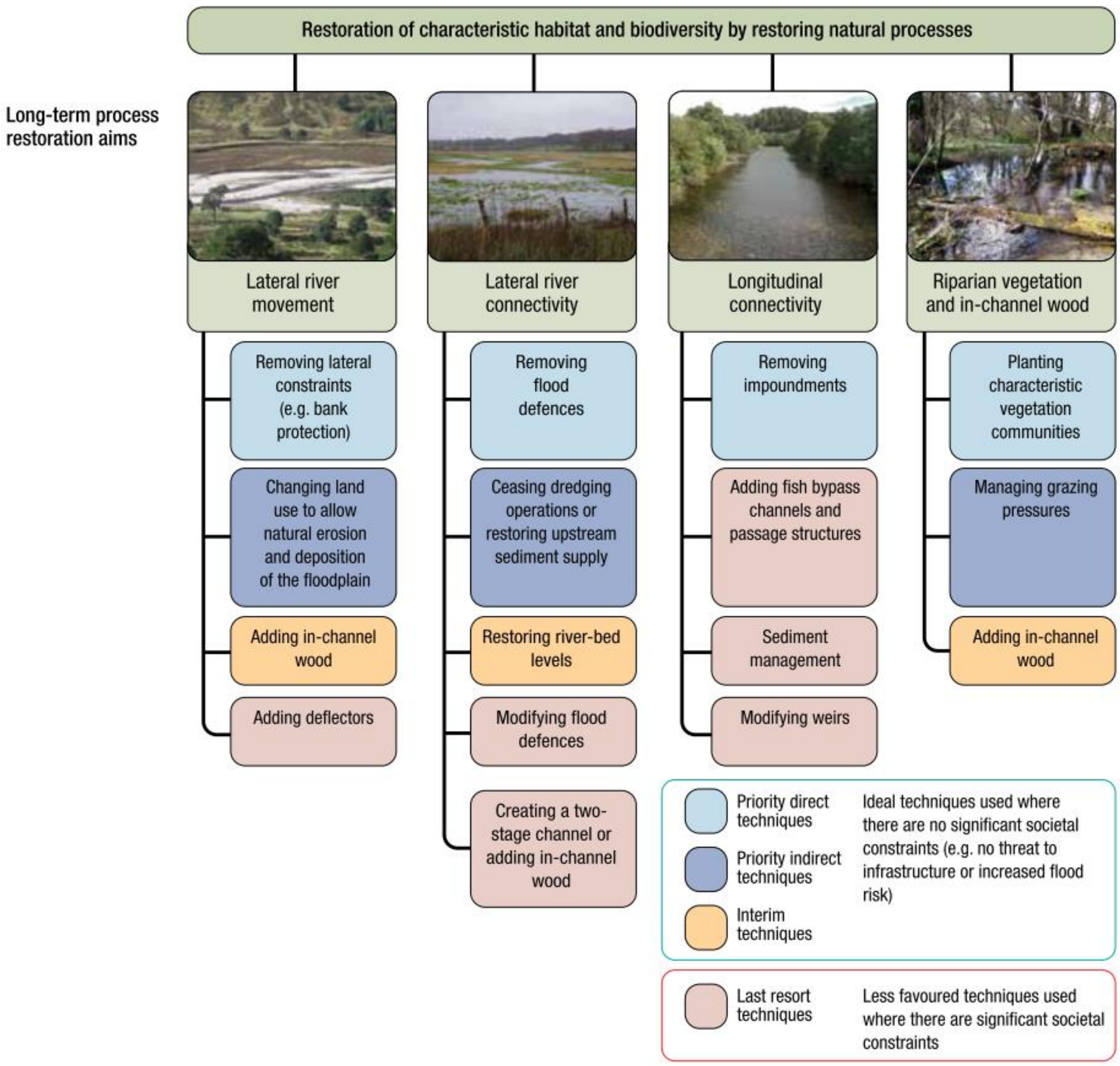


Figure 2.5. The process-focused aims of river rehabilitation projects and associated techniques to restore characteristic habitat, biodiversity and connectivity, adopted from (Addy *et al.* 2016).

2.3.1. Approaches to river rehabilitation and evidence of success

2.3.1.1. Re-meandering of rivers

Meanders are natural features of rivers in their middle courses, which create a dynamic balance of lateral erosion along the outside of a bend, deposition of sand and gravels along the inner bend with cobbles and boulders in riffles in between meander bends. This process continues along the water course to create and destroy meander loops continuously. When an old meander loop is cut off from the active channel, critical off-channel floodplain habitats, such as oxbow lakes, backwaters, and wetlands, are formed (Ayres *et al.* 2014).

Re-meandering of straightened river channels (e.g. creating a new meander course or reconnecting of cut-off meanders) is widely used as a rehabilitation measure in lowland areas (Feld *et al.* 2011; Kail *et al.* 2015). Historical maps or the remaining traces of a previous meander course in the floodplain are used for guiding this purpose (Addy *et al.* 2016), Reconnecting cut-off meander and side channels blocked off during river channelisation requires less excavation than cutting new meanders, and may involve the removal of any accumulated sediments with re-grading to fully reconnect with the main channel (Addy *et al.* 2016). Occasionally, some projects have included installing meanders where they were not historically feature of those channels (Walter & Merritts 2008).

This measure aims to change the shape (sinuosity and profile) of unnatural channelized river channels to a more natural or near-natural shape (Kondolf 2006), which will increase water retention, flow path length, and reduce channel depth incision (Ayres *et al.* 2014). Channel re-meandering could also be done passively through initiating lateral channel migration to “let the river do the work” (Ayres *et al.* 2014). Actively creating new meander and adding coarse substrata leads to immediate rehabilitation of some aspects of natural stream channel morphology (Friberg *et al.* 1994; Biggs *et al.* 1998; Pedersen *et al.* 2007). An improvement in the in-stream habitat complexity, channel morphology and in the amount of water passing onto floodplain have been observed (Kronvang *et al.* 1998; Sear, Briggs & Brookes 1998), but species abundance and diversity responses have been more variable. Small and short-term increases in macroinvertebrates, fish and aquatic vegetation abundance have been observed after re-meandering of a Danish stream (Friberg *et al.* 1994; Friberg *et al.* 1998), but the effects on fish were limited (Moerke &

Lamberti 2003; Pedersen *et al.* 2007). Macroinvertebrate density can recover to pre-rehabilitation levels within 1-2 years following rehabilitation (Friberg *et al.* 1994; Biggs *et al.* 1998; Pedersen *et al.* 2007), and recolonisation with increase in macroinvertebrate diversity (Jungwirth, Moog & Muhar 1993) is more possible if colonising population sources are present (Friberg *et al.* 1994).

2.3.1.2. Riffles installation and creating riffle-pool sequences

Coarse, well-oxygenated and permeable gravel substrate is essential for gravel spawning fish species; gravel spawning is considered as adaptation of fish to faster flowing conditions for protecting eggs and hatchling from becoming washed away (DeVries 1997; Jungwirth, Muhar & Schmutz 2000). Accumulation of fine sediments (less than 1 mm) has been reported to cause significant impacts on hatch and survival of fish larvae even at low proportions (Soulsby *et al.* 2001; Julien & Bergeron 2006; Heywood & Walling 2007). Artificial riffles imitate natural dynamic riffles to enhance flow heterogeneity (Brookes, Knight & Shields 1996). It is an appropriate rehabilitation technique to restore spawning habitat for fish, and habitat for rheophilic (flow water adapted) invertebrate species (Sarriquet, Bordenave & Marmonier 2007; Pedersen *et al.* 2009). Riffles and gravel bars can be rehabilitated either directly through the active addition of gravel, manipulations of the riverbed, or indirectly through re-establishing of natural flow, and the erosion and deposition sediment regime (Wheaton, Pasternack & Merz 2004). Active rehabilitation is necessary when the river peak-discharges and sediment transport have been degraded (Ayres *et al.* 2014) and may need post-project maintenance such as gravel cleaning, gravel addition, or installation of sand traps (Rubin, Glimsäter & Jarvi 2004; Meyer *et al.* 2008).

Installed riffles increased macroinvertebrate diversity, compared to degraded reaches (Edwards *et al.* 1984), up to the levels similar to natural riffles (Ebrahimnezhad & Harper 1997). Artificial riffles and gravel bars have shown non-measurable impacts on the fish communities in some studies (Pretty *et al.* 2003; Harrison *et al.* 2004), but can be successful in providing spawning habitat for gravel-spawning fish species, even under suboptimal environmental conditions (Barlaup *et al.* 2008; Goeller & Wolter 2015).

2.3.1.3. Rehabilitating channel lateral migration and floodplain connectivity

Removing or breaching of river embankments, levees, dikes or other engineering structures to re-establish river-floodplain re-connections and restore a more natural, dynamic, flood-pulsed hydrological regime with rehabilitated lateral migration of channels are an increasingly popular rehabilitation technique (Florsheim & Mount 2002; Blackwell, Maltby & Gerritsen 2006; Pescott & Wentworth 2011). These rehabilitation measures recover habitat complexity fairly quickly (Jungwirth, Muhar & Schmutz 2002; Muhar *et al.* 2004), enhancing floodplain biodiversity, improving nutrient-attenuation capacity, and providing temporary storage of flood water (Muhar, Schmutz & Jungwirth 1995; Bernhardt *et al.* 2005). A recent study suggested that river-floodplain hydrological connectivity increases after removal of embankments, to form a more natural flood-pulsed wetland ecotone, favouring conditions for enhanced flood storage, plant species composition and nutrient retention (Clilverd 2016). Reconnecting existing floodplain habitats has been effective in providing habitat for juvenile salmonids (Richards *et al.* 1992; Norman 1998; Roni *et al.* 2006b).

2.3.1.4. Rehabilitating channel longitudinal connectivity

Removing of barriers and re-establishing of longitudinal connectivity creates rapid habitat changes both upstream and downstream (Thomson *et al.* 2005) and has had positive effects on flow condition, sedimentation and water temperature (Bednarek 2001; Hart *et al.* 2002). It changes the river upstream from lentic to lotic, and hence causes positive changes in macroinvertebrate assemblages (Bushaw-Newton *et al.* 2002; Maloney *et al.* 2008). Re-establishing of river longitudinal connectivity facilitates passage of invertebrates and fishes (Gregory, Li & Li 2002; Doyle *et al.* 2005). Upstream of removed barriers created considerable variation in flow and water depth, which increased rocky bottom area, bank stability (Kanehl, Lyons & Nelson 1997), and sediment transport (Bushaw-Newton *et al.* 2002). In the case of large dams, regulated flow regimes need to be rehabilitated to govern erosion and sedimentation processes within the river channel (Greig, Sear & Carling 2005). Regulated flow regimes can be rehabilitated by recreating variable flow regimes through altering operational procedures of large dams, such as releasing of flushing flow to clean river-bed fine sediments and remove algae (Batalla & Vericat 2009).

Mitigation measures like increasing minimal flows, installing fish passages, or increasing dissolved oxygen levels provide only partial solutions, while complete removal of barriers offer the most complete and reliable means of restoring channels longitudinal connectivity (Kampa & Stein 2012). When full removal of a barrier is not possible, notches can be cut in the barrier crest to allow partial rehabilitation of water and sediment fluxes, in-stream habitat heterogeneity and biodiversity (Environment Agency 2013). Installation of fish passages like fish bypass channels or fish passes structure (e.g. ladders, locks or lifts) could enhance upstream migration of fish and access previously blocked habitats, but it is ecologically less beneficial than complete removal of the barriers (Environment Agency 2013).

Increase in the relative abundance of EPT taxa was recorded upstream of removed impoundment due to increase in flow and substrate particle size (Maloney *et al.* 2008), and fish biomass also increased (Kanehl, Lyons & Nelson 1997). Downstream of removed barriers where reservoir sediments are released however, there could be short-term decrease in productivity and diversity of aquatic biota (Bednarek 2001). For example, macroinvertebrate density decreased significantly with increasing sedimentation (Thomson *et al.* 2005). Intensive development in riparian and land plants was observed at the bottom of the Drzewieckie reservoir immediately after longitudinal rehabilitation by dam removal (Tszydel, Grzybkowska & Kruk 2009).

2.3.1.5. Adding in-channel LWM

LWM can be placed in streams to mimic the roles of naturally occurring wood as an interim measure before rehabilitated riparian trees have become established (Addy *et al.* 2016),. Installation of LWM could enhance river substrate diversity through enhancing frequency of pools and flow diversity (Larson, Booth & Morley 2001; Pretty *et al.* 2003; Brooks *et al.* 2004; Feld *et al.* 2011), bank stability (Levell & Chang 2008) and sediment retention (Quinn & Kwak 2000) at the rehabilitated-reach level, all of which enhance habitat heterogeneity (Baillie, Garrett & Evanson 2008; Lester & Boulton 2008; Miller, Budy & Schmidt 2010). LWM works to shape the stream's morphology, retain sediment, and construct in-stream habitat (Gregory *et al.* 1991; Maohua, Tarmi & Helenius 2002). Thus, they provide a key habitat for macroinvertebrate and fish communities (Roni & Quinn 2001; Brooks *et al.* 2004; Kail *et al.* 2007).

According to some previous studies, adding LWM increases the terrestrially derived organic matter (allochthonous), and making it available to stream biota (Johnson, Breneman & Richards 2003; Lepori *et al.* 2005). It can also change stream geomorphology through in-stream substrate sorting, which may expose gravel in the main channel and deposit sand along the banks of the channel (Kail 2003). Thus, changes in local geomorphology may lead to altered organic matter processing and macroinvertebrate production through increasing habitat stability and changing food availability for aquatic biota (Smock, Metzler & Gladden 1989; Lemly & Hilderbrand 2000; Benke & Wallace 2003).

River macroinvertebrate communities positively affected by introducing of LWM, they create a heterogeneous habitat structures and food sources that enhance the availability of a wide range of niches (Schneider & Winemiller 2008). Increases in invertebrate richness (Gerhard & Reich 2000; Johnson, Breneman & Richards 2003; Hrodey, Kalb & Sutton 2008; Lester & Boulton 2008; Miller, Budy & Schmidt 2010), abundance (Gerhard & Reich 2000; Lester, Wright & Jones-Lennon 2007; Coe *et al.* 2009) and diversity (Hrodey *et al.*, 2008) were observed in the presence of LWM. Smock, Metzler and Gladden (1989) found that contribution of the shredder feeding group to total macroinvertebrate community biomass increased with increasing the abundance of woody dams.

The positive effects of installed LWM on physical habitat heterogeneity and fish communities, especially salmonids is well documented (Pess *et al.* 2012). LWM enhances habitat that can be used by fish in both low-water flows (summer) and high-water flows. In summer, created pools and backwaters provide deep and cool water enough for fish to survive, and water to become oxygenated by mechanical mixing when the water flows over or under dams (Mossop & Bradford 2004). In winter, during flood condition, LWM creates areas of reduced flows to protect fishes from washing down-river. Fishes also use created habitat to hide from predators (Wing & Skaugset 2002). Increase in salmonid survival was observed in a system with the presence of LWM, due to the creation of essential habitat during both summer low-flows and winter floods (Johnson *et al.* 2005). In contrast, lateral flow deflectors made of concrete and large boulders put on the stream bed to enhance flow heterogeneity and channel meanders showed non-measurable impacts on the fish communities (Pretty *et al.* 2003; Harrison *et al.* 2004).

2.3.1.6. Rehabilitation of riparian vegetation

Riparian buffer strip is a land located between stream channel and the agricultural fields, it acts as a vegetated filter zone (Borin *et al.* 2010). This transition zone between terrestrial and aquatic ecosystem is essential for controlling runoff energy (holding back sediments) and nutrients (either in sediment particles or through chemical change in vegetation and soils) as well as the biotic interchange (Luke *et al.* 2007). Restoring riparian vegetation can decrease the influx of fine sediments, which need to be reduced or prevented in the first place (Wood & Armitage 1997; Pedersen & Friberg 2009). Undesirable sediment input can be reduced by changing land-use on the catchment scale (very difficult) and/or restoring sufficiently wide and mixed riparian vegetation on both sides of rivers (Barton, Taylor & Biette 1985; Castelle, Johnson & Conolly 1994). Restoring riparian vegetation communities can also reduce flood risk downstream through increasing the capacity of floodplains to store and slow flood waters (Thomas & Nisbet 2007; Dixon *et al.* 2016)

Riparian vegetation rehabilitation includes either active establishment of riparian buffer strip (Schultz *et al.* 1995; Northington & Hershey 2006; Sutton, Fisher & Gustafson 2010) or passive by allowing natural buffer re-establishment (where local seed sources are sufficient) by protection from large herbivores. This is either *via* fencing (Opperman & Merenlender 2004) or without fencing such as reducing stocking densities or setting water points away from the riparian area (McBride, Hession & Rizzo 2008; Pedraza, Giraldo & Chará 2008). The most effective kind is mixed buffers that consist of trees, shrubs and grass (Correll 2005), by planting native and appropriate species for the given environment (Addy *et al.* 2016). A sufficiently wide and mixed riparian vegetation on both sides of streams is needed (Barton, Taylor & Biette 1985; Castelle, Johnson & Conolly 1994). A minimum 15 m width on either sides of a stream is recommended for most conditions (Castelle, Johnson & Conolly 1994). A 25 – 60 m buffer width retained most of the fine sediments (Osborne & Kovacic 1993; Castelle, Johnson & Conolly 1994; Wenger 1999) while, at least 1-5 km length for first order and 10-20 km for fifth order streams were required to reduce water temperature to more typical reference condition (Parkyn *et al.* 2003).

Riparian buffer rehabilitation enhances in-stream habitat complexity (Opperman & Merenlender 2004), water quality (Dosskey 2001; Broadmeadow & Nisbet 2004), provides shade, decreases water temperatures (Castelle, Johnson & Conolly 1994; Opperman & Merenlender 2004), reduces fine sediments, and supplies in-stream LWM (Opperman & Merenlender 2004). Together these changes can enable the self-recovery of habitat heterogeneity and provide nutrients for the benefit of macroinvertebrate and fish communities (Addy *et al.* 2016). A meta-analysis study by Feld *et al.* (2011), showed clear evidence of the beneficial effect of riparian re-vegetation controlling water temperature, nutrient, in-stream physical habitats and sediments retention and increases of benthic macroinvertebrate richness (Castelle, Johnson & Conolly 1994; Broadmeadow & Nisbet 2004; Pedraza, Giraldo & Chará 2008; Becker & Robson 2009; Jowett, Richardson & Boubee 2009; Quinn *et al.* 2009). The major variables associated with riparian buffer rehabilitation and affected macroinvertebrate community structure were fine sediments, water temperature, supplied organic matter and LWM (Feld *et al.* 2011). Increase of fish richness and biomass (Penczak 1995), and macrophyte richness (Pedersen, Baattrup-Pedersen & Madsen 2006) were also documented after riparian rehabilitation.

2.3.1.7. Rehabilitation by the 'building blocks' of biotopes

In-stream biotopes are visually distinguishable, but small (50 cm^2 – 5 m^2 approximately) in-channel patches, made up of different mineral substrates, vegetation, or organic matter types, which form a dynamic mosaic structured by current speed and depth (Harper *et al.* 1995; Kemp, Harper & Crosa 1999). They are the result of predictable physical processes, and so conveniently sit between the forces which structure rivers and the biota (e.g. distinct macroinvertebrate assemblages) which inhabit them, as hydro-morpho-ecological units in river structure and function (Harper & Everard 1998). In-stream biotopes can thus be used as a simple building-block approach to rehabilitation (Harper, Smith & Barham 1992; Petersen, Petersen & Lacoursiere 1992; Kemp, Harper & Crosa 1999; Buffagni *et al.* 2000) as the interface between organisms and the physical processes of a stream as distinct units, recognisable and classifiable both on the basis of their physical and biological attributes. They can be rapidly and effectively mapped and indicate river condition (Kemp 1999; Kemp, Harper & Crosa 2000). Working at this level “makes [the system] easier to study, understand or manage” (Rabeni, Doisy & Galat 2002). It also “can be a cost-effective tool, and can increase reproductively and comparability of field results, and indices application” (Buffagni *et al.* 2000). The consideration of stream rehabilitation at in-stream biotope scale is important as it has proved to be useful in the UK river habitat survey RHS (Environment Agency 2003), and river management (Harper & Everard 1998).

This kind of river rehabilitation uses in-stream biotopes as the natural ‘jigsaw’ pieces that needs to be returned back to degraded river channels, in order to increase its heterogeneity, aiming to return natural features to a degraded channel reach. River rehabilitation through increasing in-stream biotope heterogeneity can be achieved by the design of a channel that mimics the natural physical state. This involves creating appropriately-spaced meanders and pool and riffle lengths with woody material installation, depending on hydromorphological data from its upstream or a nearby reference reach to advise the natural channel dimension, pattern, and profile for the rehabilitated reach (Rosgen 1994; Rosgen 1996; Doll *et al.* 2003). The river then responds by creating the diversity of current velocity, erosion-deposition process, and marginal berms that together maintain the biotopes. Thus, the rehabilitated channel planform, cross-section, and longitudinal profile are sustainable over time, and in-stream biotope heterogeneity and refuges can increase after the rehabilitated channel’s design has become more natural (Townsend & Hildrew 1994; Klein *et al.* 2007; Ernst *et al.* 2010).

2.3.2. *Does river rehabilitation work?*

Evaluating success of river rehabilitation projects, learning lessons, and sharing experiences are essential to understand and develop best rehabilitation measures (Addy *et al.* 2016). A practical monitoring guidance (PRAGMO) by the UK River Restoration Centre (RRC 2011) gives an overview and provides advice on commonly used monitoring methods for evaluating projects success. Monitoring and evaluation is considered to play a crucial role within the planning framework because it enables identification of stream rehabilitation project success by assessing outcomes against objectives (RRC 2011). It is difficult to assess to what extent rehabilitation has been successful without such comparison (Possingham 2012). Knowledge sharing websites at the European level such as REFORM http://wiki.reformrivers.eu, and RESTORE https://restorerivers.eu/wiki are making experiences easily accessible. Despite this, very few of the exponentially increasing number of rehabilitation projects have been monitored. However (Cowx *et al.* 2013; Wolter *et al.* 2013). Riverine fishes have been the main focus of in-stream habitat rehabilitation and used to measure ecological responses of rehabilitation (Rosi-Marshall, Moerke & Lamberti 2006), despite the vital role that macroinvertebrates play in maintaining stream ecosystem functions via formation and transportation of nutrients and energy. Macroinvertebrate communities' responses have less often been studied (Miller, Budy & Schmidt 2010). They are at middle trophic levels of freshwater food webs and can offer great information for indicating the trends of biological changes. They are influenced by alterations of the amounts of available colonisation area by rehabilitation activities more than fishes, as they typically move less than fishes instream (Gore, Crawford & Addison 1998).

Many meta-analysis reviews over the past decade have tried to synthesise general trends in river rehabilitation science (e.g. Bernhardt *et al.* 2005; Roni, Hanson & Beechie 2008; Miller, Budy & Schmidt 2010; Palmer, Menninger & Bernhardt 2010; Feld *et al.* 2011; Wolter *et al.* 2013; Palmer, Hondula & Koch 2014; Kail *et al.* 2015; Thompson 2015) (Table 2.3), but their outcome are rather conflicting, and there is no general agreement about the effectiveness of hydromorphological rehabilitation approaches on macroinvertebrate community.

The shortcoming of those review studies has not previously been examined, to the extent of asking which macroinvertebrate metrics were evaluated. It appears that insufficient objective data were often a barrier to determining the ecological effectiveness of rehabilitation projects. For example, Bernhardt *et al.* (2005) found, using the National River Restoration Science Synthesis (NRRSS) database, that only 10% of approximately 37,000 rehabilitation projects (in the USA) had any kind of pre- or post-rehabilitation monitoring. Thompson (2015), reviewed the National River Restoration Inventory (NRRI[1]) of the UK and RESTOR[2] of Europe data, found that the main aim of 90.5% of the 649 projects for which information was available was ecological rehabilitation; but 70% of projects provided no ecological monitoring information. Only 0.7% had used a proper study design (Before-After-Control-Impact) to demonstrate that ecological changes in the rehabilitated site were not due to natural variation.

Reviews mostly examined available literature qualitatively (e.g. Bernhardt *et al.* 2005; Palmer, Menninger & Bernhardt 2010; Feld *et al.* 2011; Wolter *et al.* 2013), in the extent to which rehabilitation projects have been monitored at all, or monitored for changes in aquatic community diversity or species richness, without quantifying the overall outcomes. Or they focused solely on macroinvertebrate community structural variables such as diversity or species richness as biological measures of success (e.g. Miller, Budy & Schmidt 2010), without an explicit evaluation of why those structural metrics were relevant measures of rehabilitation success. In addition, the lack of robustness in the conducted case-studies by Miller, Budy and Schmidt (2010) such as low quantity and poor quality of published data, and lack of rigorous study designs, was an important limitation. The review by Palmer, Hondula and Koch (2014) depended on much published data, which had not used multi-habitat sampling protocol (WFD) and where samples been collected from riffle habitat only (e.g. McClurg *et al.* 2007; Orzetti, Jones & Murphy 2010; Selvakumar, O'Connor & Struck 2010; Mackie *et al.* 2013; Petty *et al.* 2013; Scrimgeour, Jones & Tonn 2013).

[1] NRRI was launched by the River Restoration Centre (RRC) in the UK. It aims to develop river restoration processes through assessment and sharing of knowledge.
[2] RESTORE, a Europe-wide partnership has been established for exchanging river restoration information.

The latest quantitative meta-analysis review by (Kail *et al.* 2015), revealed that macroinvertebrate abundance/biomass metrics were more positively affected by in-stream rehabilitation process than its richness/diversity, but depended on a limited number of case studies (about 23 published papers, covering about 32 case studies), including studies that assessed rehabilitation effect on only one group of invertebrates e.g. Chironomidae (e.g. Spänhoff *et al.* 2006), or that assessed the effects of riffle installation with invertebrate samples only collected from the riffle habitat, which is not representative of all study reaches (e.g. Ebrahimnezhad & Harper 1997). In addition, the review combined both species richness and diversity as one response variable during their quantitative study, and the same for abundance and biomass. The number of case studies that assessed macroinvertebrate biomass is also very limited (only three case studies assessed macroinvertebrate community biomass).

Those ambiguous results, together with increasing calls for appropriate evaluation of rehabilitation projects, need a broader understanding to identify appropriate measures of rehabilitation success and a detailed review of all available evaluation studies, in order to coordinate future studies capable of detecting ecological changes.

Table 2.3. Meta-analyses reviewed on the effects of hydromorphological rehabilitation processes on macroinvertebrate communities.

Bernhardt *et al.* (2005)	Reported a synthesis of information on more than 37,000 projects in the NRRSS database, but there were insufficient objective data to determine the ecological effectiveness of the projects.
Roni, Hanson and Beechie (2008)	Reviewed 32 studies that examined responses of macroinvertebrates to in-stream rehabilitation processes. The results were highly variable and the information provided by the reviewed literature was limited so that they were unable to arrive at a firm conclusion.
Miller, Budy and Schmidt (2010)	Analysed 24 separate published studies of 89 rehabilitation projects across the world that were carried out between 1984 and 2009. They showed that increasing habitat heterogeneity may enhance benthic macroinvertebrate species richness but not diversity, with addition of large woody material (LWM) produced the greatest, while changes to density were negligible.
Palmer, Menninger and Bernhardt (2010)	The finding did not support the previous reviews; they found that physical habitat heterogeneity enhanced successfully, but only 2 out of 78 projects that they reviewed showed a significant increase in taxa richness to make rehabilitated reaches more similar to reference reaches.
Feld *et al.* (2011)	Reviewed available literature on the effect of river rehabilitation projects on fish, invertebrates, macrophytes, phytobenthos and algae in October 2010. A significant effect of adding LWM on macroinvertebrate community abundances and species richness was observed in some projects.
Wolter *et al.* (2013)	Highlighted an obvious need to collect new field data addressing the links between stream hydromorphology and aquatic biota.
Palmer, Hondula and Koch (2014)	Compiled information on 47 published studies that depended on macroinvertebrate metrics found that the rehabilitation effects so far were disappointing, measurable improvements variable by rehabilitation methods and monitoring techniques. They showed that biodiversity recovery was rare - only 16% of the most common type of projects (entire channel hydromorphological rehabilitation or in-stream hydromorphological rehabilitation) resulted in any improvements in biodiversity (e.g. Shannon index). The taxon richness of biotic communities (riparian vegetation, macroinvertebrate and fish assemblages) had improved as the result of these projects, while they concluded that taxon richness is not a particularly informative indicator of successful projects, and those improvements of taxon richness found post-rehabilitation were not characteristic of the reference site or the desired state of the stream.
Thompson (2015)	Reviewed 649 projects for which information was available in NRRI of the UK and RESTOR of Europe data, finding that 70% of projects provided no ecological monitoring information. Only 0.7% had used a proper study design (BACI) to demonstrate that ecological changes in the rehabilitated site were not due to natural variation.
Kail *et al.* (2015)	They found a high variability but an overall positive effect on macroinvertebrates, in-stream rehabilitation was more effective in increasing macroinvertebrate abundance and/or biomass than richness and/or diversity.

2.4. Evaluating stream rehabilitation projects: A new global literature review

2.4.1. Introduction

In this study, I am reviewing all recent rehabilitation projects that have shown increasing emphasis on monitoring their outcome functionally rather than structural outcomes. My aim is to update available knowledge on the effects of different types of river rehabilitation approaches on in-stream macroinvertebrate community function as well as their structure as a reliable means of assessing success in enhancing macroinvertebrate communities, and to develop a broad understanding of the pitfalls and areas to progress.

I have asked the following questions:

(1) To what extent has proper quantitative evaluation been done, in particular using the BACI design?

(2) How have macroinvertebrate samples been collected – e.g. has multi-habitat sampling protocol (WFD) which reflects the proportion of the microhabitat types (in-stream biotopes) that are present with ≥ 5% cover been applied?

(3) To which extent have measures of macroinvertebrate density, biomass, productivity, and functional traits been conducted as examples of processes of the ecosystem, in addition to structure?

(4) To what extent have hydromorphological rehabilitation activities increased habitat heterogeneity at the reach-level, and have they had an overall positive effect on macroinvertebrate community function as well as structure?

(5) Which macroinvertebrate metrics showed better responses (functional or structural)?

(6) Which rehabilitation techniques were more effective? and

(7) Did any factors constrain or limit rehabilitation outcomes?

2.4.2. Methods

I conducted an extensive review of the existing literature, focusing on peer-reviewed literature and readily available grey literature such as dissertations, theses, and case study reports. The search was not restricted to any particular journals. I searched Web of Science, Google Scholar, and SCOPUS by using the following keywords: (Restore* OR rehabilit* OR enhance* OR mitigate* OR reconfigurat* OR re-meander*) AND (aquatic habitat* OR reach* OR channel* OR stream* OR river*) AND (heterogeneity* OR LWD* OR habitat* OR instream*) AND (macroinvertebrate* OR invertebrate*). I compiled another search on British Library (EThOS) by using “Restoration and macroinvertebrates”, “rehabilitation and macroinvertebrates”, “re-meandering and macroinvertebrates”, “stream restoration”, “river restoration”, “stream rehabilitation”, “river rehabilitation”, “heterogeneity and macroinvertebrates”, “habitat and macroinvertebrates”, “LWD and macroinvertebrates”, “boulder addition and macroinvertebrates”, or “channel reconfiguration and macroinvertebrates” keywords. These searches were conducted from March 15th – April 15th 2016. I then examined each paper to determine whether the study included an evaluation of stream physical rehabilitation activity using macroinvertebrate community structure and function. Four criteria determined inclusion: (1) the paper must have evaluated a physical rehabilitation project that aimed at enhancing habitat heterogeneity, involving one or more rehabilitation measures such as channel reconfiguration, meandering, addition of artificial substrates like boulders or riffles, addition of LWM, modifying channel connectivity and/or re-vegetating the riparian zone; (2) the paper must have quantified macroinvertebrate community responses such as community composition, density, richness, diversity, biomass, productivity, and/or functional feeding group structure, richness, and/or diversity; (3) macroinvertebrate responses must have been quantified at the reach-scale, not at a single habitat within a stream (e.g. macroinvertebrate density on marginal plants or gravels with no information about the rest of the stream); (4) the study must have included a Before-After (BA), a Control-Impact (CI), or a Before-After, Control-Impact (BACI) design.

A number of papers were eliminated based on their abstract; all other papers were read in full. I also searched for related literature cited in every paper, especially former meta-analysis studies.

2.4.3. Results

Seventy seven papers published between 1984-2016, that reported outcomes of 359 independent projects met my criteria (Table 2.5). This included 28 of Kail *et al.* (2015)'s 32 case studies. Some projects were reported by more than one study; if so, the outcomes have been combined. For example, both Sundermann *et al.* (2011) and Haase *et al.* (2013) reported the impact of hydrological rehabilitation of 24 rivers in Germany on macroinvertebrate communities. Bushaw-Newton *et al.* (2002) and Thomson *et al.* (2005) both reported on the effects of a small dam removal on downstream macroinvertebrate assemblages in a Pennsylvania stream.

Each project was placed into one category depending on how the project was implemented (using categories of Palmer, Hondula and Koch (2014)). Categories were:

1) Entire-channel hydromorphological rehabilitation.
2) In-stream hydromorphological rehabilitation.
3) Longitudinal and lateral channel connectivity rehabilitation.
4) Riparian rehabilitation.

Entire-channel hydromorphological rehabilitation projects involved reconfiguring the channel completely, such as by re-meandering, widening, enhancing channel lateral connectivity within floodplains by raising/lowering the channel bed and often incorporated the addition of in-stream structures such as boulders, woody material, or gravel. In-stream hydromorphological rehabilitation projects were less intensive; they included changing in-stream structure without major channel manipulation, such as creating artificial riffles, decreasing bank erosion, or adding large woody material. Lateral connectivity rehabilitation projects involved channel-floodplain reconnection, and longitudinal connectivity projects aimed to enhance the channel longitudinal connectivity by removing small dams and weirs. Riparian rehabilitation projects involved revegetation of channel banks by planting native vegetation, removal of non-native vegetation or prevention of grazing activity.

2.4.3.1. Geographic distribution of the rehabilitation projects

The geographic distribution of rehabilitation projects showed that, despite the global literature search, the greatest number of projects originated from European countries

(60%), followed by USA (32%), and Australia (5%), while the remaining 3% of projects were in Canada (4 projects), New Zealand (4 projects), and Asia (2 projects) (Figure 2.6a).

2.4.3.2. Rehabilitation techniques applied

The most commonly used rehabilitation methods (Figure 2.6b) were entire channel and in-stream hydromorphological rehabilitation respectively - more than half of the rehabilitation projects (52% of total projects) and often incorporated the addition of in-stream structures such as artificial riffle installation, boulders or large woody material. In-stream hydromorphological methods without major channel reconfiguration, such as creating artificial riffles, adding woody material, or boulders were the second most commonly used method (38% of total projects). Projects that improved channel-floodplain or longitudinal connectivity by removing small dams and boulders comprised only 6% of total rehabilitation projects. Riparian rehabilitation projects either through replanting of river banks by native vegetation, fencing of banks to prevent grazing action of animals, or removal of non-native vegetation as a sole rehabilitation action, made up 4% of total projects.

Applied rehabilitation categories were very diverse, and many of techniques were used together. Entire-channel rehabilitation projects such as re-meandering and adding coarse substrates (artificial riffles) led to immediate rehabilitation of some features of natural stream channel morphology (e.g. Friberg *et al.* 1994; Biggs *et al.* 1998) and enhanced structural heterogeneity (e.g. Harrison *et al.* 2004). Removal of bank fixation, widening of the water course, and floodplain connection, led to more diverse substrate composition and floodplain habitat heterogeneity (e.g. Januschke *et al.* 2014).

In-stream rehabilitation projects, especially woody material installation techniques were more effective for enhancing macroinvertebrate community assemblages, especially density, biomass, FFGs and EPT, compared to other rehabilitation categories. However, failure of some rehabilitation projects to enhance physical and hydrological heterogeneity was regarded as the main factor to explain missing significant effects on macroinvertebrate community in many projects (e.g. Tullos *et al.* 2009; Violin *et al.* 2011; Leal 2012; Verdonschot *et al.* 2015). For example, Verdonschot *et al.* (2015) found that the 'missing effect' of 19 rehabilitation projects in 10 European countries assessed on macroinvertebrate richness and diversity, might be due to failure of the rehabilitation measure applied. They found that rehabilitation by remeandering and/or widening increased ‘visually appealing’ macrohabitat conditions, but had no significant effect on in-stream biotope diversity relevant for macroinvertebrate communities.

Catchment scale pressures that were not mitigated by in-stream rehabilitation, were also found to negatively affect recovery of stream macroinvertebrate taxa richness and diversity (e.g. Larson, Booth & Morley 2001; Harrison *et al.* 2004; Roni *et al.* 2006a; Louhi *et al.* 2011; McManamay, Orth & Dolloff 2013).

Longitudinal connectivity through removing of small dams and weirs had initial adverse effects on macroinvertebrate density due to the mobilisation of fine sediments from the upstream stagnant section, and full beneficial effects occurred once the fine sediments had been transported farther downstream, which seemed to take decades (Thomson *et al.* 2005). Bushaw-Newton *et al.* (2002) found that sediment transport increased downstream of removed dams, while at the upstream channel form changed and benthic biota assemblages shifted from lentic to lotic taxa and mean number of EPT nearly tripled within one year of the dam removal. Maloney *et al.* (2008) found that within two years relative abundance of EPT taxa increased upstream due to increase in flow and substrate particle size. Therefore, spatial and temporal aspects of the dam removal process are very important and need a more cautious approach than other rehabilitation methods. The deposition of fine sediment on courser substrate downstream of the removed impoundment could limit the availability of courser substrate preferred by EPT invertebrates and by fish for spawning. Regarding the effects of lateral connectivity projects, Paillex *et al.* (2015) studied the effects of floodplain connectivity on abundance and richness of aquatic macroinvertebrates by reconnection of 18 lateral floodplain channels to the Rhone River main channel. They found a significant increase in channel lateral connectivity two years after the rehabilitation, and benthic biota assemblages’ abundance and richness shifted from lentic to lotic taxa.

Riparian rehabilitation through re-vegetation has enhanced channel physical habitat diversity and in-stream substrate heterogeneity (Thompson & Parkinson 2011), alleviated water pollution (Wu *et al.* 2013), decreased water temperature (Becker & Robson 2009; Quinn *et al.* 2009), increased bank stability (Selvakumar, O’Connor & Struck 2009), and increased terrestrial food (Thompson & Parkinson 2011).

2.4.3.3. Applied study designs

264 projects (73%) used a Control-Impact (CI) design (Figure 2.6c) (also known as "space-for-time substitution design"), where a degraded reach within the same or an adjacent river system, and most often upstream of the rehabilitated section, was used as a control. It was selected to best represent the conditions of the rehabilitated reach prior to the rehabilitation process (e.g. Friberg *et al.* 2013; Haase *et al.* 2013; Dolph *et al.* 2015; Verdonschot *et al.* 2015). A second, but semi-natural, control reach was also used in some studies to compare with the changes and direction of rehabilitated reach after rehabilitation, sometimes called a reference reach for comparison with both the degraded and rehabilitated reaches (e.g. Friberg *et al.* 1998; Laasonen, Muotka & Kivijärvi 1998; Muotka *et al.* 2002; Ernst, Warren & Baldigo 2012; Pedersen, Kristensen & Friberg 2014; Winking 2015). The most comprehensive study design is Before-After-Control-Impact (BACI). In this design, hydromorphological and biological data of pre- and post-rehabilitation processes for both impact (rehabilitated) and nearby control reaches were compared. This design was used in 81 projects (23%) (e.g. Friberg *et al.* 1998; Renöfält *et al.* 2013; Paillex *et al.* 2015; Rios-Touma *et al.* 2015; Thompson 2015). The last and least common study design was just Before-After (BA), this design was used in 14 projects (4%). Some studies used this design to track the recovery of physical and biological features of rehabilitated reaches to pre-rehabilitation levels and/or assess improvements after rehabilitation (e.g. Jungwirth, Moog & Muhar 1993; Wu *et al.* 2013). 17% of all reviewed projects used a second, but semi-natural, control reach as the target state for macroinvertebrate community direction after rehabilitation (e.g. Laasonen, Muotka & Kivijärvi 1998; Muotka *et al.* 2002; Louhi *et al.* 2011; Stranko, Hilderbrand & Palmer 2012; Winking 2015). Partitioning the effects of rehabilitation outcomes from other sources of variance - especially seasonal and inter-annual variation was not possible as many projects evaluated by sampling only once (either during spring or summer). What was surprising is that 111 independent rehabilitation projects (in 6 published papers) were evaluated by sampling only once and without incorporating undisturbed control reaches (Harrison *et al.* 2004; Tullos *et al.* 2009; Jähnig *et al.* 2010; Haase *et al.* 2013; Thompson 2015; Verdonschot *et al.* 2015).

2.4.3.4. Biotic sample collection protocols

Most of the published papers that examined the largest number of independent rehabilitation projects (5 projects by Thompson (2015) to up to 26 projects by Jähnig *et al.* (2010)) compared post-rehabilitation samples with samples from their control reaches based on only one sampling visit per project (Harrison *et al.* 2004; Tullos *et al.* 2009; Jähnig *et al.* 2010; Stranko, Hilderbrand & Palmer 2012; Haase *et al.* 2013; Thompson 2015; Verdonschot *et al.* 2015; Winking 2015). Only two studies sampled rivers before and after rehabilitation for multiple years (Louhi *et al.* 2011; Paillex *et al.* 2015), and for at least 2 seasons of each year to account for seasonal variation that could affect macroinvertebrate community composition. Most of the evaluation studies sampled only riffle or riffle-pool habitats, which do not cover all available in-stream biotopes. Multi-habitat sampling protocol, of the official EU WFD, which reflect the proportion of the microhabitat types (in-stream biotopes) that are present with ≥5% cover was applied rarely (e.g. Pedersen *et al.* 2007; Jähnig *et al.* 2010; Louhi *et al.* 2011; Haase *et al.* 2013; Winking 2015).

2.4.3.5. Macroinvertebrate metrics depended on for monitoring the outcomes

The most common macroinvertebrate metrics used to quantitatively evaluate project outcomes as measured by macroinvertebrate community structure and function (Figure 2.6d) were:

Taxon richness (28% of the projects),

Density (individuals.m^{-2}) (23% of the projects),

Diversity (17% of the projects), and

Functional feeding groups FFGs% and/or FFGs richness (13% of the projects).

Ephemeroptera-Plecoptera-Tricoptera (EPT) % and/or EPT richness was used only in 6% of the projects, and Invertebrate Biological Index (BI) in 4% of the projects. Macroinvertebrate biomass (energy or mgDryMass m^{-2}) was used in 3% of projects, and secondary productivity (energy or mgDM.m^{-2}.year^{-1}) in 1% of the projects. Macroinvertebrate taxa evenness was used in 1% of projects. Other macroinvertebrate metrics - community composition ‘Bray-Curtis similarity index’, macroinvertebrate functional response group, the Proportion of Sediment-sensitive Invertebrates (PSI), and the Quantitative Macroinvertebrate Community Index (QMCI)- were used only in 4% of the projects. Macroinvertebrate community structural metrics (especially taxa richness) was widely used to assess the rehabilitation outcomes but functional metrics such as abundance, biomass, secondary productivity, FFG and EPT groups showed better responses, especially for in-stream hydromorphological projects. Significant improvements in macroinvertebrate abundance, biomass and secondary productivity were observed with increasing amounts of woody material that led to collection of organic matter and increased food availability (Smock, Metzler & Gladden 1989; Wallace, Webster & Meyer 1995; Entrekin *et al.* 2009; Dolph *et al.* 2015). Few studies tracked geomorphological rehabilitation impacts on macroinvertebrates productivity and only 3 studies used macroinvertebrate productivity as a functional metric (Wallace, Webster & Meyer 1995; Entrekin *et al.* 2009; Dolph *et al.* 2015).

2.4.3.6. Project ages at the time of evaluation

The ages of projects at the time of post-project monitoring were highly variable (Table 2.5). Hydromorphological and biological monitoring were performed in most of the studies, after one to three years following the rehabilitation activities. A few studies monitored projects for up to 10 years (e.g. Lorenz, Jahnig & Hering 2009; Jähnig *et al.* 2010; Stranko, Hilderbrand & Palmer 2012; Haase *et al.* 2013; Smith & Chadwick 2014), or even 20 years (e.g. Laasonen, Muotka & Kivijärvi 1998; Roni *et al.* 2006a; Louhi *et al.* 2011; Northington *et al.* 2011; Winking 2015). Little is known about the macroinvertebrate community recovery time scale (Tullos *et al.* 2009), but insufficient recovery time between rehabilitation activities and monitoring process was regarded as limiting factor for physical and biotic recovery in some projects (e.g. Becker & Robson 2009; Entrekin *et al.* 2009). Non-measurable effects on macroinvertebrate community, of 6 riparian revegetation projects after up to 8 years, was ascribed to a lack of sufficient time for recovery by Becker and Robson (2009). Entrekin *et al.* (2009) suggested that rehabilitated reaches are likely to require years to achieve measurable changes in channel geomorphology, organic matter retention and macroinvertebrate secondary productivity after LWM rehabilitation.

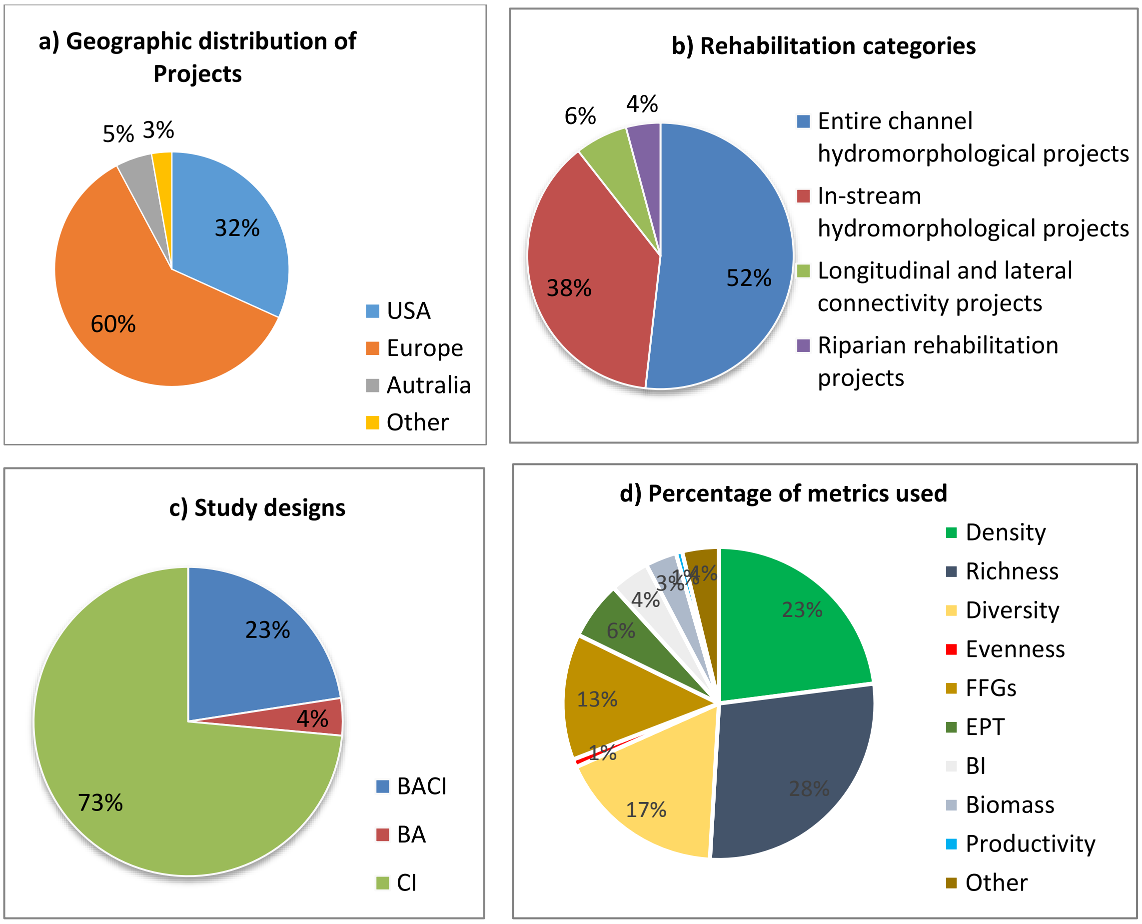


Figure 2.6. Summary of geographic distribution of rehabilitation projects, most common rehabilitation methods, study designs and most common macroinvertebrate metrics used to quantify the outcomes of rehabilitation for 359 independent rehabilitation projects. Projects were assigned into four groups according to the geographic distribution (a). 'Other' countries include Canada, New Zealand, China, and Japan. Each project's method of rehabilitation placed under one of four broader categories (b). Study designs used for monitoring the physical and biological outcomes of rehabilitation process (c) were Before-After-Control-Impact (BACI), Before-After (BA), and Control-Impact (CI). The percentage of macroinvertebrate metrics used to quantitatively evaluate projects outcomes (d).

2.4.3.7. Quantifying overall success rates of rehabilitation projects

In what follows, I summarise the overall success rates of rehabilitation projects recording significant biological enhancement according to the four main rehabilitation categories (as above).

The success rates of rehabilitation projects recording significant enhancement in each macroinvertebrate metric and the absolute number of projects monitored with respect to each metric are summarised in Table 2.4. The list of reviewed studies arranged according to the hydromorphological rehabilitation categories and their biotic metrics used to synthesise the percentages of significant increases of metrics is in Table 2.6.

2.4.3.7.1. Entire-channel hydromorphological rehabilitation projects

Entire-channel rehabilitation of streams by re-meandering the straightened and simplified channels, creating artificial riffle-pool sequences, removal of bank fixation, widening of the water course, and floodplain connection showed obvious improvements in channel morphology, and physical habitat complexity (e.g. Friberg *et al.* 1994; Biggs *et al.* 1998; Friberg *et al.* 1998; Purcell, Friedrich & Resh 2002; Moerke *et al.* 2004; Januschke *et al.* 2014). While the effects on macroinvertebrate communities were limited (Table 2.5). The percentage of entire channel hydromorphological rehabilitation projects that reported significant increase in macroinvertebrate density was 10%, taxon richness 10%, diversity 12% and evenness 14% (Table 2.4). The effects on functional metrics such as FFGs and EPT richness and composition were not much greater, with only 16-11% of projects showing significant enhancement. Other rarely used metrics such as Proportion of Sediment-sensitive Invertebrates (PSI), Bray-Curtis Similarity Index showed some enhancement, while Regional Invertebrate Biotic Index (BI), and total biomass results were not significant.

2.4.3.7.2. In-stream hydromorphological rehabilitation projects

The in-stream physical diversity of rehabilitated reaches was generally enhanced in comparison with their nearby physically damaged sites and/or with their pre-rehabilitation status. Only a few projects were not successful (e.g. Sudduth & Meyer 2006; Leal 2012; McManamay, Orth & Dolloff 2013; Thompson 2015). The biotic effectiveness of the in-stream rehabilitation measures applied however was limited (Table 2.5). The effects on macroinvertebrate richness and diversity were not better than those of entire channel hydromorphological rehabilitation projects (Table 2.4). The percentage of projects that reported increased macroinvertebrate taxon richness was 14%, diversity 4% and evenness 0%. Functional metrics showed better responses - macroinvertebrate total abundance increased in 21% of projects, biomass in 52%, FFGs in 20%, EPT in 24% and productivity in 71%. These increases mainly arose from the woody material projects.

2.4.3.7.3. Longitudinal and lateral connectivity projects

A limited number of studies about rehabilitation of connectivity (5 published papers; covering 3 longitudinal, and 20 lateral connectivity projects) showed that macroinvertebrate abundance increased in 87%, taxa richness in 91% of them. The overall outcomes of the 3 longitudinal connectivity projects were negative for the macroinvertebrate community downstream of the removed impoundment, but positive for the upstream reach's community (Table 2.4).

2.4.3.7.4. Riparian rehabilitation projects

Six published papers compared physical and biological structure of 15 independent rehabilitation projects using BA or CI study design. The variables that showed the largest changes, and affected the macroinvertebrate communities following riparian buffer rehabilitation, were fine sediment reduced, water temperature decreased, and supplied organic matter increased. Macroinvertebrate community structure showed some statistically significant enhancement (Table 2.4). Taxon richness increased significantly in 18% of projects (Jowett, Richardson & Boubee 2009; Wu *et al.* 2013), while, total biomass (Wu *et al.* 2013), EPT richness, EPT density, and BI (Jowett, Richardson & Boubee 2009; Quinn *et al.* 2009; Selvakumar, O'Connor & Struck 2009) showed improvements in a higher proportion of studies.

Table 2.4. The outcomes of stream or river rehabilitation projects as assessed by macroinvertebrate community parameters. Projects are placed under four categories according to the rehabilitation methods. They are listed as a percent of projects recording significant improvement in macroinvertebrate density (Individual.m^{-2}), taxa richness, diversity, evenness, biomass (energy or mgDM m^{-2}), functional feeding groups FFGs%, FFGs richness, Ephemeroptera-Plecoptera-Tricoptera (EPT)%, EPT richness, Invertebrate Biological Index (BI), secondary productivity (energy or mgDM.m^{-2}.$year^{-1}$), or other parameters (e.g. Proportion of Sediment-sensitive Invertebrates[1] (PSI); Quantitative Macroinvertebrate Community Index[2] (QMCI); macroinvertebrate functional response group[3] ; community composition by using B-C similarity index[4]).

Parameters used to assess success of rehabilitation project	Rehabilitation category							
	Entire-channel hydromorphological		In-stream hydromorphological		Longitudinal and lateral connectivity		Riparian rehabilitation	
	Percentage of projects recording significant improvement	Number of projects	Percentage of projects recording significant improvement	Number of projects	Percentage of projects recording significant improvement	Number of projects	Percentage of projects recording significant improvement	Number of projects
Density	10%	91	21%	123	87%	23	0%	11
Richness	10%	157	14%	112	91%	22	18%	11
Diversity	12%	109	4%	78	0%	1	-	0
Evenness	14%	7	0%	2	-	0	-	0
Biomass	0%	8	52%	23	-	0	25%	4
FFG	16%	70	20%	71	-	0	-	0
EPT	11%	38	24%	21	100%	2	80%	4
BI	20%	20	5%	20	-	0	80%	4
Productivity	-	0	71%	7	-	0	-	0
Other	44%	18	0%	21	-	0	100%	2

[1] Extence, C.A., Chadd, R.P., England, J., Dunbar, M.J., Wood, P.J. & Taylor, E.D. (2013) The assessment of fine sediment accumulation in rivers using macroinvertebrate community response. *River Research and Applications,* **29,** 17-55.

[2] Quinn, J.M., Croker, G.F., Smith, B.J. & Bellingham, M.A. (2009) Integrated catchment management effects on flow, habitat, instream vegetation and macroinvertebrates in Waikato, New Zealand, hill-country streams. *New Zealand Journal of Marine and Freshwater Research,* **43,** 775-802.

[3] Januschke, K., Jähnig, S.C., Lorenz, A.W. & Hering, D. (2014) Mountain river restoration measures and their succession: Effects on river morphology, local species pool, and functional composition of three organism groups. *Ecological Indicators,* **38,** 243-255.

[4] Winking, C. (2015) Ecological evaluation of restored former sewage channels in the urbanised Emscher catchment. PhD thesis PhD, Universität Duisburg-Essen, Germany.

2.4.4. Discussion

This review has a number of important implications for future practice of stream hydromorphological rehabilitation projects and monitoring of their success: 1) rehabilitation projects should aim at rehabilitating ecosystem functions, not be based solely on community structure; 2) addressing larger scale barriers at catchment scale such as land use, erosion and water pollution is essential for success; 3) well-designed monitoring (e.g. BACI design) is required to detect any physical and biological changes; 4) biotic samples should be collected to represent all available in-stream biotopes, sampling of only gravel or riffle area is generally not representative of all available habitats; 5) incorporating undisturbed (semi-natural) reaches in the study design as target states of rehabilitation to track the direction of macroinvertebrate community structure and function changes is highly necessary; 6) biotic data should be collected over sufficient time frames to partition the outcomes of rehabilitation treatment from other confounding pressures such as seasonal variations; 7) using a broader range of macroinvertebrate metrics as response variables (not only taxa richness or diversity) could improve our understanding of the relationship between created habitat heterogeneity and any enhancement of macroinvertebrate community composition, structure and function.

Infancy of stream rehabilitation science (Palmer, Hondula & Koch 2014) indicate the urgent need for more and better studies to addressing the links between hydromorphology and stream biota (Louhi *et al.* 2011; Wolter *et al.* 2013). In the proceeding chapters (Ch. 3 - 5) I address the above limitations, especially conducting the evaluation of stream rehabilitation projects. I assess the success of two rehabilitation projects in enhancing the rehabilitated reaches' morphology, in-stream biotope diversity and macroinvertebrate assemblages, both structurally and functionally. In Chapter 6, I discuss the suitability of sampling and evaluating at in-stream biotope level for future widespread use.

Table 2.5. Summary of published studies on the effects of rehabilitation projects on habitat heterogeneity and macroinvertebrate community structure and function. Project's age includes the age of rehabilitated projects in years at the time of monitoring. Study designs; Control-Impact (CI), Before-After (BA) or Before-After-Control-Impact.

Reference Location (No. of Projects)	Rehabilitation technique	Study design (project's age)	Key Finding
Edwards *et al.* (1984) Ohio, USA (1)	Artificial riffle and pool construction	CI (6)	Different depths and velocities were provided. Significant difference in family richness was recorded; macroinvertebrate abundance and family richness were higher in natural and rehabilitated (artificial riffles and pools) versus channelised area.
Smock, Metzler and Gladden (1989) Virginia, USA (2)	Woody material addition	CI (1)	Macroinvertebrate abundance and biomass increased with increasing the number of woody material that has led to collection of organic matter and increased food availability, and contribution of shredder feeding group to biomass increased with increasing the abundance of dams.
Jungwirth, Moog and Muhar (1993) Lower Austria (1)	Channel reconfiguration	BA (3)	Project increased spatial variance in depths and velocities to provide a wider range of substrate types. Significant increase in macroinvertebrate species richness recorded, while biomass decreased.
Tikkanen *et al.* (1994) Finland (1)	Boulder addition	BA (1)	Slight increase in bed roughness and mean particle size. Slight decrease in abundance immediately after rehabilitation, no measurable effect on species richness.
Friberg *et al.* (1994) Denmark (1)	Remeandering	BACI (2)	Proposed that density and diversity increased after two years of remeandering, recovery of biota community after rehabilitation process needs one to two years
Wallace, Webster and Meyer (1995) North Carolina, USA (1)	Woody material added to the downstream of three riffles within the stream.	BA (4)	At LWM addition sites, stream depth and organic matter increased, current velocity decreased, sand and silt covered the cobble substratum. Abundance, biomass, and secondary production increased significantly after rehabilitation. Abundance, biomass, and secondary production of scrapers and filterers decreased, while collectors and predators increased, no change in overall shredder biomass.
Hilderbrand *et al.* (1997) West Virginia, USA (2)	Woody material addition to compare the differences with systematic or random placement of pieces.	BA (2)	Systematic placement had a lower effect on erosion and score rates than random placement. No changes in total abundance, some functional group increased with the pool areas.
Biggs *et al.* (1998) Denmark (1), UK (1)	Re-meandering, gravel and cobble addition	CI (1)	Dramatic increase in channel meandering and substrate heterogeneity. Non-significant increase in species richness or abundance.
Friberg *et al.* (1998) Denmark (1)	Channel reconfiguration, re-meandering, gravel and rock material addition	BACI (6)	Immediate rehabilitation of natural stream channel morphology observed. Non-significant increase in species richness or abundance.

Laasonen, Muotka and Kivijärvi (1998) Finland (9)	Boulder addition, flow deflector, excavation and channel enlargement	CI (<1-16)	Bed roughness higher in rehabilitated than unrehabilitated reach, more different depths and flows present in rehabilitated reach. No difference in richness or abundance between rehabilitated and channelized sections.
Gørtz (1998) Denmark (1)	Gravel, boulder addition	CI (4)	Resulted in deeper and narrower stream with a higher flow velocity near the bottom and a coarser substrate. Macroinvertebrate abundance increased and became similar to the natural reach, with no change in diversity
Gerhard and Reich (2000) Germany (2)	Woody material addition	CI (4)	Rehabilitated reaches had more functional habitat patches per metre than unrehabilitated. Abundance, species richness and diversity increased in Joseklein stream, with no increase in Lude stream.
Larson, Booth and Morley (2001) Washington, USA (6)	Woody material addition	CI (2-10)	Channel complexity significantly increased. No change in benthic index of biotic integrity (B-IBI).
Muotka and Laasonen (2002) Finland (4)	Boulder weir and deflector	BACI (3)	Substrate heterogeneity increased, retention efficiency was higher in rehabilitated in comparison with channelized, but lower than in natural streams. Only algae-feeding invertebrate shredder density increased.
Purcell, Friedrich and Resh (2002) California, USA (1)	Channel restructuring, addition of step pools, rocks, riparian revegetation and opening up of a culvert stream	CI (3)	Channel complexity increased by meanders, step pools. Buffer vegetation increased. Index of biotic integrity and taxa richness improved in treated reach relative to control reach.
Muotka *et al.* (2002) Finland (3)	Enhancing habitat heterogeneity through boulder addition, flow deflector, excavation and channel enlargement	CI (4-8)	Higher leaf retention was in natural and 8 years old rehabilitated reach. Detritivores and shredder FFGs did not differ among reaches.
Bushaw-Newton *et al.* (2002) Thomson *et al.* (2005) Pennsylvania, USA (1)	Dam removal	BACI (1)	Sediment transport downstream caused habitat alteration, macroinvertebrate assemblage shifted from lentic to lotic taxa. Dam removal caused reduction in the macroinvertebrate density, but the effect was temporary. Changes in macroinvertebrates density and richness were non-significant. Mean number of EPT nearly tripled within one year in the upstream of the removed dam.
Haapala, Muotka and Laasonen (2003) Finland (2)	Boulder weir addition	BA (2)	Channel complexity was higher in rehabilitated reaches. No consistent differences in macroinvertebrate structure between channelized and rehabilitated reaches.

Negishi and Richardson (2003) Canada (1)	Boulder deflector	BACI (1)	Habitat heterogeneity increased in comparison with pre-rehabilitation and the reference reach. Macroinvertebrate abundances increased 280% in the rehabilitated reach and converged with those of reference reach, Detritivores taxa numerically dominated the macroinvertebrate community.
Pretty and Dobson (2004) UK (3)	Woody material addition	BA (2)	Log addition enhanced detrital standing stocks. Macroinvertebrate total abundance, taxon richness were significantly increased in rehabilitated reach, the significant response was most marked for detritivores group.
Harrison *et al.* (2004) UK (13)	7 with riffle construction, 6 with flow deflector	CI (4-9)	Flow and depth heterogeneity increased. Diversity and richness slightly differed (non-significantly) between rehabilitated and control reaches; the difference was between macrophyta and benthic habitats
Korsu (2004) Finland (1)	Boulder addition	BA (<1)	Invertebrate recolonized rehabilitated reach to pre-project level within 2 weeks of disturbance, relatively fast recovery of invertebrate can be in winter. Moss biotope (bryophytes) is important for invertebrate as a habitat and refugee.
Moerke *et al.* (2004) Indiana, USA (2)	Re-meandering, boulder and log addition, riffle-pool construction, sediment reduction and riparian re-vegetation	BACI (5)	Habitat improved after one year of rehabilitation, with more pools and less fine sediment. After five year of rehabilitation the density of macroinvertebrates remain higher than unrehabilitated reach, with no increase in diversity.
Lepori *et al.* (2005) Sweden (7)	Boulder addition and channel restructuring; remove bank armoring, widening	CI (3-8)	Higher habitat heterogeneity in rehabilitated to unrehabilitated reach. No changes in macroinvertebrates diversity and richness.
Roni *et al.* (2006a) Oregon, USA (13)	Boulder weir placement, and log addition	CI (1-20)	Pool area, number of LWM, boulders, and pools were significantly higher in rehabilitated site and the control site. No changes in abundance, richness, EPT%, FFGs% or IBI were observed.
Lepori *et al.* (2006) Sweden (3)	Boulder addition, channel widening.	CI (4-6)	Current velocity decreased, woody material entrapment by introduces boulders, and leave retention was higher in stream margins, while non-significant changes in macroinvertebrate biomass between rehabilitated and channelized reaches was observed.
Rosi-Marshall, Moerke and Lamberti (2006) Michigan, USA (2)	Enhancing in-stream hydromorphology through underbank cover and pool-creating structures.	BACI (1)	Channel depth and organic matter retention increased, macroinvertebrate density, diversity, and FFG composition did not response significantly to the rehabilitation.

Sudduth and Meyer (2006) Georgia, USA (4)	Enhancing in-stream hydromorphology through bank stabilisation.	CI (1-9)	Percentage of organic habitat did not improved, macroinvertebrate total abundance, diversity, richness, biomass, FFG composition, abundance, and biomass changes were non-significant.
Lester, Wright and Jones-Lennon (2007) Australia (8)	Woody material addition	BACI (1)	Wood increased storage of organic matter and sediments, improved bed and bank stability. Macroinvertebrate density and richness significantly increased, treated streams had greater family richness and greater richness of all functional feeding groups. Richness increased in all wood, benthic and edge habitats.
Pedersen *et al.* (2007) Denmark (1)	Re-meandering and gravel addition	BACI (1)	Macrophyte recolonized the reach after rehabilitation. Macroinvertebrates rapidly colonized the rehabilitated reach and total abundance, species richness, EPT% and richness, changes were non-significant. Community diversity increased, only Heptageniidae abundance increased significantly.
Sarriquet, Bordenave and Marmonier (2007) France (1)	Gravel addition	CI (3)	No change in invertebrate assemblage density and taxonomic richness were observed.
De Vaate *et al.* (2007) Netherland (3)	Secondary channel construction	CI (3)	Former channel substrate changed from silt to sand bottom, macroinvertebrate species richness increased rapidly following habitat development.
Nakano and Nakamura (2008) Japan (1)	Re-meandering, adding boulder	CI (2)	Significant differences in depths, velocities and sediments habitats observed. Rehabilitated and natural reaches had significantly higher density and taxa richness than the control reach.
Maloney *et al.* (2008) Illinois, USA (1)	Dam removal	BACI (3)	Habitat improved, flow rate and substrate particle size increased, channel width and depth decreased. No change to overall macroinvertebrate assemblage structure, EPT% increased within two years of removal.
Becker and Robson (2009) Australia (6)	Willow removal, riparian re-vegetation.	CI (1-8)	Revegetated sites were warmer and had a higher light intensity compared with older revegetated and natural site. Density and richness of macroinvertebrates did not vary among site types.
Quinn *et al.* (2009) New Zealand (2)	Riparian re-vegetation with native plants and exclusion of livestock	BACI (1-6)	After rehabilitation channel width, water depth and water temperature reduced, macroinvertebrate density significantly decreased, EPT richness increased significantly in one reaches. EPT density, IBI, and quantitative macroinvertebrate community index increased significantly.
Lorenz, Jahnig and Hering (2009) German (2)	Re-meandering, floodplain connection, wood and small cobbles added.	CI (1-10)	Significant increase in habitat heterogeneity. Slight change in macroinvertebrate density, diversity and richness.

Tullos *et al.* (2009) North Carolina, USA (24)	Channel reconfiguration	CI (1- 4)	Non-significant difference in habitat feature and channel complexity between rehabilitated and control sites. Shannon genus diversity increased significantly in urban streams, with no significant changes rural and agricultural streams.
Jowett, Richardson and Boubee (2009) New Zealand (2)	Riparian re-vegetation, fencing to exclude livestock.	CI (1-8)	Macroinvertebrate communities, EPT richness, and EPT% become more similar to those of reference sites (native forest) in one case study.
Herbst and Kane (2009) Sierra Nevada, Spain (1)	Channel reconstruction, adding rook substrate and erosion control fabric, and willow planting	BACI (2)	Deposition of fine sediments and sand increased in the downstream of rehabilitation reach in one year after rehabilitation, while was similar to pre-project in second year. Macroinvertebrate community and trophic structure significantly increased after rehabilitation, diversity and composition of sensitive taxa (EPT) and shredders increased, while tolerant taxa and filter-feeders decreased
Selvakumar, O'Connor and Struck (2009) Virginia, USA (1)	Bank stabilisation through bioengineering structures and bank revegetation.	BACI (2)	Instream structure improved, and significant changes in some invertebrate indexes, and EPT taxa were recorded after rehabilitation.
Entrekin *et al.* (2009) Michigan, USA (3)	Woody material addition	BACI (2)	Significant increase (22%) of macroinvertebrate biomass and secondary production was recorded in one rehabilitated reach, while the changes in other two reaches were non-significant in comparison to values before logs addition.
Coe *et al.* (2009) Washington, USA (2)	Woody material addition	CI (2)	Macroinvertebrate density was significantly higher on woody material than on cobbles, wood substrate increase density of invertebrates at reach level.
Chin *et al.* (2010) Texas, USA (3)	Channel stability via Riffle and steps construction, riparian re-vegetation along gradient banks.	BA/CI (2)	Measurable changes detected in channel characteristics and habitat condition, channel cross-section area increased. Significant increase in taxa richness, EPT%, and grazers' %.
Jähnig *et al.* (2010) Austria, Czech republic, Germany, Italy, and Netherlands (26)	Re-meandering, remove of bank fixation, adding gravel, boulder and woody material.	CI (3-12)	Habitat diversity was improved and higher in rehabilitated reaches, while macroinvertebrate density, richness, diversity, and evenness changes were non-significant.
Louhi *et al.* (2011) Finland (6) Finland (15)	boulder ridges and flow deflector, and woody material addition	BACI (3) CI (15-17)	Stream habitat diversity increased, while post-rehabilitation density and richness as a result of adding boulder ridges and flow deflectors across the channels significantly decreased. Feeding groups did not show significant response to rehabilitation.
Thompson and Parkinson (2011)	Riparian re-vegetation	CI (15)	Habitat heterogeneity was higher in rehabilitated reaches, and macroinvertebrate density and biomass changed after rehabilitation.

Australia (3)			
Testa, Douglas Shields and Cooper (2011) Mississippi, USA (1)	Woody material addition	BACI (2)	Woody substrate tripled after rehabilitation, while macroinvertebrate density and family richness changes were non-significant.
Northington *et al.* (2011) Virginia, USA (6)	Natural channel design, adding in-stream structure, riparian re-vegetation	CI (1-20)	Total taxa richness changes were not significant, and EPT richness was significantly higher in unrehabilitated reaches.
Selego *et al.* (2011) Virginia, USA (1)	In-stream rehabilitation through adding logs, gravel and riparian re-vegetation.	BACI (1)	after rehabilitation macroinvertebrate community composition, IBI and density became more similar to reference reach, and collector-filterers and scraper become most dominant
Schiff, Benoit and Macbroom (2011) New York, USA (1)	Re-meandering, boulder, and woody material addition, bank stabilisation through fibre rolls, rock wing deflectors and tree revetments.	CI (2-5)	Small improvements in local habitat observed, with non-significant improvement in macroinvertebrate density and richness was observed.
Albertson *et al.* (2011) California, USA (1)	Channel reconfiguration, re-meandering, removal of fine sediment and introducing of gravel.	CI (1)	Macroinvertebrate density and biomass declined after rehabilitation, while richness and evenness of rehabilitated reach were significantly increased in comparison with unrehabilitated reach.
Violin *et al.* (2011) North Carolina, USA (4)	Channel rehabilitation	CI (1-7)	No significant improvement in reach-scale habitat features. Natural reaches had significantly higher taxa richness than degraded and rehabilitated reaches in winter samples. EPT species richness was higher in natural reach and significantly differed with the degraded and rehabilitated reaches in both winter and summer seasons.
Clark (2011) Australia (1)	Bank stability, riparian re-vegetation and riffle construction	CI (1)	Macroinvertebrate diversity, richness, abundance and predator % in rehabilitated site were similar to that of reference site, while the environmental variables were no significantly differed between rehabilitated and degraded sites in spring. Higher number of sensitive taxa was in the natural sites.
Leal (2012) California, USA (1)	Woody material addition	CI (1)	Smaller substrate particle size were found across rehabilitated site, no significant difference between other habitat features such as canopy cover, algae, tree roots, and emergent vegetation %. Lower invertebrate abundance and diversity associated with LWM in several months of the first year after rehabilitation. Non-significant improvement of macroinvertebrates density or richness was recorded.

Ernst, Warren and Baldigo (2012) New York, USA (5)	Natural channel design restructuring.	CI (1-5)	Bank stability and macroinvertebrate Gatherer% increased significantly. While, abundance, richness, EPT richness, Chironomidae%, and all other FFGs% changes were not significant.
Stranko, Hilderbrand and Palmer (2012) Maryland, USA (15)	Channel reconstruction, tree planting, and removing concreates.	CI (5-10)	Macroinvertebrate biotic index (BI) index, number of genera, intolerant genera, mayfly genera, and stonefly genera were similar to unrehabilitated reaches.
Extence *et al.* (2013) UK (2)	Weir removing, channel narrowing, mechanical removal of fine sediment and introducing of gravel.	BACI (3)	Proportion of Sediment-sensitive Invertebrates (PSI) increased subsequently at rehabilitated sites as the number of the taxa associated with coarse substrate quickly colonised the rehabilitated habitat.
McManamay, Orth and Dolloff (2013) North Carolina, USA (2)	Gravel addition	BACI (1)	Gravel washed down by water current, taxonomic composition shifted, increased macroinvertebrate richness and density were not sustained, and the response is specific to individual taxa or particular functional feeding groups.
Haase *et al.* (2013) Sundermann *et al.* (2011) Germany (24)	Removal of bank fixation, adding flow deflectors, woody material, creating of new channel, and connectivity.	CI (1-12)	Rehabilitated sections had significantly higher spatial diversity index SDI value and higher variance of river width and depth. Macroinvertebrate composition, density, richness, evenness, diversity, dominance and FFGs changes were not significant.
Wu *et al.* (2013) China (1)	Riparian re-vegetation	BA (1)	Vegetation cover area, species richness, and diversity increased after rehabilitation. Macroinvertebrate richness and biomass increased significantly.
Renöfält *et al.* (2013) Sweden (1)	Dam removal	BACI (3.5)	Sediment deposition increased significantly after removing the dam, macroinvertebrate density decreased after rehabilitation but was not significant, while number of taxa significantly decreased.
Friberg *et al.* (2013) Denmark (1)	Re-meandering, adding coarse substrate.	CI (19)	Corse substrate added during rehabilitation still after 19 years can be separated from other habitats. No evidence of long-term positive effects of rehabilitation on macroinvertebrate community composition.
Smith and Chadwick (2014) UK (8)	Improving flow condition, re-meandering.	CI (2-10)	No difference in the macroinvertebrate (litter decomposer) density, richness or biomass was found between rehabilitated and unrehabilitated reaches.
Januschke *et al.* (2014) Germany (3)	Removing of bank fixation, widening, floodplain connection	CI (7- 9)	Rehabilitated reaches had more diverse substrate composition, floodplain habitat heterogeneity increased. Macroinvertebrate species composition was variable over time in rehabilitated than unrehabilitated reaches.
Erwin (2014) Canada (3)	In-stream habitat manipulation, enhancing	BACI (1)	Changes in macroinvertebrate abundance and diversity were not significant.

	longitudinal connectivity for fish passage by creating pool-weir and choke-pool structure.		
Pedersen, Kristensen and Friberg (2014) Denmark (6)	Re-meandering, pebble and gravel addition.	CI (3)	Gravel substrate is introduced without considering flow or stream power, which not provided sufficient habitat conditions for macroinvertebrate assemblages. Macroinvertebrate density, richness, diversity, evenness, EPT density, and EPT richness did not related significantly with increasing substrate heterogeneity.
Mueller, Pander and Geist (2014) Germany (6)	Boulder and gravel addition	BACI (1)	Macroinvertebrate community composition changed after rehabilitation, overall density, richness, Shannon diversity, evenness, and FFGs changes were non-significant.
Koebel, Bousquin and Colee (2014) Florida, USA (1)	Continues flow establishment.	BACI (3)	River habitat significantly changed after flow rehabilitation, Collector-filterer density and biomass increased significantly after the rehabilitation
Rios-Touma *et al.* (2015) Oregon, USA (3)	Re-meandering, boulders and woody material addition, floodplain reconnection, and riparian re-vegetation	BACI (4)	Differences in substrate, large wood pieces, and canopy cover after rehabilitation was not significant, Macroinvertebrate richness increased significantly after rehabilitation, diversity increased after rehabilitation, but both were still lower compared with reference streams, FFGs diversity increased significantly but was still lower than the reference streams.
Paillex *et al.* (2015) France (20)	Floodplain reconnection	BACI (4)	Lateral connectivity increased significantly, lotic invertebrate density and richness increased after 2 and 4 years of lateral reconnection.
Winking (2015) Germany (13)	Remove of concrete bed, near natural channel and riparian area construction, wastewater free.	CI (1-5/9-20)	Macroinvertebrate community composition of old rehabilitated sites (9-20 years old) was more similar to the reference sites, while the younger sites (1-5) were well separated from the reference sites. 7 sites' (connected to the upstream natural site) community composition enhanced and significantly became similar to reference sites, while other 6 sites' (un connected with the reference site) significantly differed from reference sites.
Thompson (2015) UK (5)	Woody material addition	BACI (1)	Reach-scale geomorphology changes were not significant. Macroinvertebrate abundance and biomass were higher significantly within LWM habitat. At reach-scale, biomass was significantly higher in rehabilitated reaches than unrehabilitated, while, density and richness, diversity, and FFGs composition was not significant.
Dolph *et al.* (2015) Minnesota, USA (3)	Adding boulder, woody material, and riparian re-vegetation.	CI (1)	No significant improvement in taxa richness and EPT abundance%. While, macroinvertebrate density, number of EPT taxa significantly increased, biomass duplicated in rehabilitated reaches and production 2 to 3 times higher in rehabilitated reaches (significantly increased), collector-filterers production were dominant.

Verdonschot *et al.* (2015) 10 European countries (19)	Channel widening, removal of bank fixation, re-meandering, lateral sides reconnecting, and adding in-stream structures.	CI (3-18)	Effects on overall macroinvertebrate total richness, diversity, and EPT richness and diversity were not significant. The limited effect on macroinvertebrate overall reflect the limited effect of most rehabilitation measures on biotope composition and diversity. They found positive relationships between macroinvertebrate responses and effect of rehabilitation on biotope diversity and patchiness. The effects on macroinvertebrates could be related to changes in the cover of specific biotopes in the rehabilitated sections.

Table 2.6. Reference used to calculate rehabilitation success in each of four categories of rehabilitation measures (A, entire-channel hydromorphological rehabilitation projects; B, in-stream hydromorphological rehabilitation projects; C, lateral and longitudinal connectivity projects; D, riparian rehabilitation projects). Other macroinvertebrate metrics include: Proportion of Sediment-sensitive Invertebrates (PSI); Quantitative Macroinvertebrate Community Index (QMCI); Community composition (using Bray-Curtis Similarity index); and macroinvertebrate functional response group. 1= metrics depended on in each study.

Reference Location (No. of projects)	Rehabilitation measure	Density	Richness	Diversity	Evenness	Biomass	FFG%, FFG richness	EPT%, EPT richness	Biotic Index (BI)	Productivity	Other
Friberg *et al.* (1994) Denmark (1)	A	1	1	1							
Biggs *et al.* (1998) Denmark (1), UK (1)	A	1	1								
Friberg *et al.* (1998) Denmark (1)	A	1	1	1							
Laasonen, Muotka and Kivijärvi (1998) Finland (9)	A	1	1								
Gerhard and Reich (2000) Germany (2)	A	1	1								
Muotka and Laasonen (2002) Finland (4)	A	1					1				
Purcell, Friedrich and Resh (2002) California, USA (1)	A	1	1					1	1		
Muotka *et al.* (2002) Finland (3)	A	1					1				
Lepori *et al.* (2005) Sweden (7)	A	1	1	1							
Moerke *et al.* (2004) Indiana, USA (2)	A	1		1							
Pedersen *et al.* (2007) Denmark (1)	A	1	1	1				1			
De Vaate *et al.* (2007) Netherland (3)	A		1								
Nakano and Nakamura (2008) Japan (1)	A	1	1								
Lorenz, Jahnig and Hering (2009) German (2)	A	1	1	1							
Tullos *et al.* (2009) North Carolina, USA (24)	A		1	1			1				
Herbst and Kane (2009) Sierra Nevada (1)	A		1	1			1	1			
Chin *et al.* (2010) Texas, USA (3)	A		1				1	1			
Jähnig *et al.* (2010) Austria, Czech republic, Germany, Italy, and Netherlands (14)	A	1	1	1							
Northington *et al.* (2011) Virginia, USA (6)	A		1					1			
Schiff, Benoit and Macbroom (2011)	A	1	1					1			

New York, USA (1)											
Albertson *et al.* (2011) California, USA (1)	A	1	1		1	1					
Violin *et al.* (2011) North Carolina, USA (4)	A		1					1	1		
Ernst, Warren and Baldigo (2012) New York, USA (5)	A	1	1				1	1			
Stranko, Hilderbrand and Palmer (2012) Maryland, USA (15)	A		1						1		
Extence *et al.* (2013) UK (2)	A										PSI
Haase *et al.* (2013) Sundermann *et al.* (2011) Germany (21)	A	1	1	1			1				
Friberg *et al.* (2013) Denmark (1)	A			1							
Januschke *et al.* (2014) Germany (3)	A										Functional response group
Pedersen, Kristensen and Friberg (2014) Denmark (6)	A	1	1	1	1		1				
Smith and Chadwick (2014) UK (7)	A	1	1			1					
Rios-Touma *et al.* (2015) Oregon, USA (3)	A		1	1			1				
Winking (2015) Germany (13)	A										B-C Similarity
Verdonschot *et al.* (2015) 10 European Countries (16)	A		1	1				1			
Edwards *et al.* (1984) Ohio, USA (1)	B	1	1								
Smock, Metzler and Gladden (1989) Virginia, USA (2)	B	1				1					
Jungwirth, Moog and Muhar (1993) Lower Austria (1)	B		1			1					
Tikkanen *et al.* (1994) Finland (1)	B	1	1								
Wallace, Webster and Meyer (1995) North Carolina, USA (1)	B	1				1	1			1	
Hilderbrand *et al.* (1997) West Virginia, USA (2)	B	1					1				
Gørtz (1998) Denmark (1)	B	1	1	1							
Larson, Booth and Morley (2001) Washington, USA (6)	B								1		
Pretty and Dobson (2004) UK (3)	B	1	1								
Haapala, Muotka and Laasonen (2003) Finland (2)	B	1									
Negishi and Richardson (2003) Canada (1)	B	1	1	1							
Harrison *et al.* (2004) UK (13)	B	1	1	1							

Korsu (2004) Finland (1)	B	1									
Roni *et al.* (2006a) Oregon, USA (13)	B	1	1				1	1	1		
Lepori *et al.* (2006) Sweden (3)	B					1					
Rosi-Marshall, Moerke and Lamberti (2006) Michigan, USA (3)	B	1		1			1				
Sudduth and Meyer (2006) Georgia, USA (4)	B	1	1	1		1	1				
Lester, Wright and Jones-Lennon (2007) Australia (8)	B	1	1				1				
Sarriquet, Bordenave and Marmonier (2007) France (1)	B	1	1								
Entrekin *et al.* (2009) Michigan, USA (3)	B	1	1			1		1		1	
Coe *et al.* (2009) Washington, USA (2)	B	1									
Jähnig *et al.* (2010) 6 European countries (12)	B	1	1	1							
Louhi *et al.* (2011) Finland (21)	B	1	1	1			1				B-C Similarity
Testa, Douglas Shields and Cooper (2011) Mississippi, USA (1)	B	1	1								
Selego *et al.* (2011) Virginia, USA (1)	B	1						1	1		
Clark (2011) Australia (1)	B	1	1	1			1	1			
Leal (2012) California, USA (1)	B	1	1								
McManamay, Orth and Dolloff (2013) North Carolina, USA (2)	B	1	1	1	1						
Haase *et al.* (2013) Sundermann *et al.* (2011) Germany (3)	B	1	1	1			1		1		
Smith and Chadwick (2014) UK (1)	B	1	1			1					
Erwin (2014) Canada (3)	B	1		1							
Mueller, Pander and Geist (2014) Germany (6)	B	1	1	1	1		1				
Koebel, Bousquin and Colee (2014) Florida, USA (1)	B						1				
Thompson (2015) UK (5)	B	1	1	1		1	1				
Dolph *et al.* (2015) Minnesota, USA (3)	B	1	1			1	1			1	
Verdonschot *et al.* (2015) European Countries (3)	B		1	1				1			
Paillex *et al.* (2015)	C	1	1								

France (20)											
Maloney *et al.* (2008) Illinois, USA (1)	C	1		1				1			
Bushaw-Newton *et al.* (2002) Thomson *et al.* (2005) Pennsylvania, USA (1)	C	1	1					1			
(Renöfält *et al.* (2013)) Sweden (1)	C	1	1								
Becker and Robson (2009) Australia (6)	D	1	1								
Jowett, Richardson and Boubee (2009) New Zealand (2)	D		1					1	1		
Quinn *et al.* (2009) New Zealand (2)	D	1	1					1	1		QMCI, B-C similarity
Selvakumar, O'Connor and Struck (2009) Virginia, USA (1)	D							1	1		
Thompson and Parkinson (2011) Australia (3)	D	1				1					
Wu *et al.* (2013) China (1)	D		1			1					

Chapter 3. Rehabilitation of Rolleston Brook using Large Woody Material

3.1. Introduction

River channel morphological complexity is extremely important for in-stream biotope heterogeneity. Rivers with complex and heterogeneous physical structure tend to have more biodiversity than simply structured ones (Downes, Lake & Schreiber 1995). Morphological complexity is described as variation in channel morphology, flow velocity, in-stream substrate composition and vegetation characteristics of the river channel (Bartley & Rutherfurd 1999). Variable channel morphology refers to both longitudinal variation of the bed profile and the cross sectional surface morphology. Channel morphology and flow velocity control each other: specific morphological forms are associated with specific flow types and *vice versa*. In-stream substrate composition refers to the in-stream inorganic substrates [classified as different biotopes according to their grain size], and vegetation characteristics include both in-stream and riparian macrophytes, and algal biotopes.

A naturally complex fluvial system has been described as having "high heterogeneity in channel width and depth (such as shallow riffles, deep pools, runs, secondary channels, flooded backwaters, sand or gravel bars, and islands), abundant large woody material (LWM; such as snags, root wads, log jams, brush piles), coarse bottom substrate (gravel, cobbles, boulders), overhanging vegetation, undercut banks, and aquatic macrophytes" (Hughes, Larsen & Omernik 1986).

LWM contributes to a wide range of structural, functional and biological processes in riverine ecosystems (Gregory, Boyer & Gurnell 2003). Stable LWM pieces are primary agents of control on stream channel morphology in forested streams (Montgomery *et al.* 2003). Their presence can enhance physical habitat complexity (heterogeneity) through creation of areas of local sedimentation and deposition as a result of altered flow patterns (Triska & Cromack Jr 1980; Gippel 1995). Organic matter trapped within LWM dams, and nutrient storage in sediments behind dams decrease spiralling lengths, and increase nutrient and energy availability for invertebrates, thus potentially increasing invertebrate secondary production (Smock, Metzler & Gladden 1989). LWM can create habitat for invertebrates that may be rare elsewhere in the system (Godfrey & Middlebrook 2007), and it enhances macroinvertebrate production by providing a stable biotope in unstable sandy bottom streams (Benke *et al.* 1985; Collier & Halliday 2000).

A wide range of geomorphological functions of LWM pieces over a wide range of spatial scales is illustrated (Figure 3.1; from Baillie (2011). When a LWM piece is installed parallel to the stream bank edge; it can armour the bank, increase its stability and constrict flow. Stable LWM spanning the stream channel creates a step along the channel profile, decreases elevation, and provides sites of energy dissipation (Bilby 1981; Montgomery *et al.* 2003; Comiti *et al.* 2008). It also can apply strong controls on sediment retention, and regulate sediment movements through the channel system (Mosley 1981; Montgomery *et al.* 2003). LWM enhances pool formation, particularly in alluvial river ecosystems; it was associated with the formation of 70-80% of all pools in those US rivers studied (Montgomery *et al.* 1995; Richmond & Fauseh 1995; Webb & Erskine 2003). When a LWM piece does not completely span the stream channel; it works as a flow deflector. Deflected flow may undercut the channel bank, widen out the channel, and mobilise sediments. Sufficient quantity of flow deflectors can significantly increase hydraulic roughness, which affects flow velocity, stream power and shear stress in the stream channel (Montgomery *et al.* 2003; Wondzell *et al.* 2009).

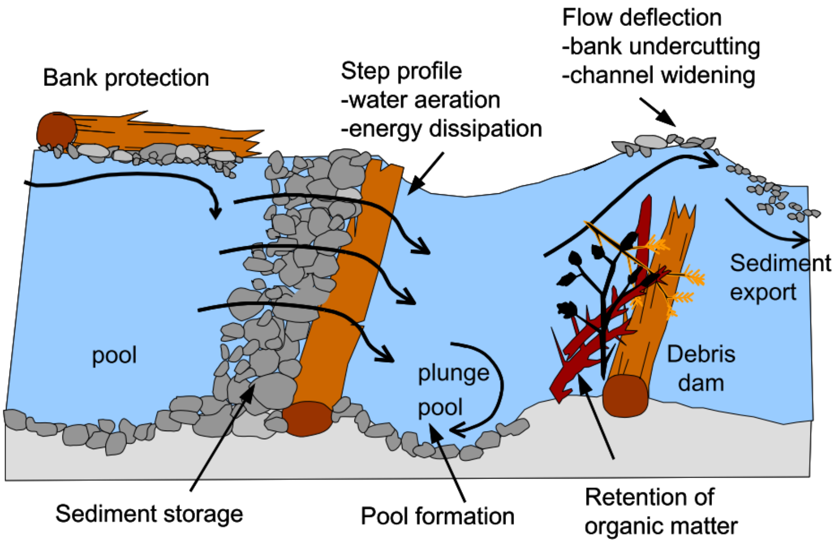


Figure 3.1. Influence of large woody materials on geomorphological processes in streams, adopted from Baillie (2011).

For centuries, anthropogenic changes have reduced the hydromorphological complexity of streams and rivers. Changes such as channelisation, straightening of meandered reaches, logging, flow regulation (dams), mining and agriculture acted to disturb streams' natural hydraulic, geomorphologic, and biological conditions and thus complexity (Bartley & Rutherfurd 1999). The natural morphology of many streams has therefore become less complex, and subsequently their biotic communities have been strongly altered, in many cases depleted (Sparks 1995), or made more uniform with less biodiversity (Wallace, Webster & Meyer 1995).

Recently, rehabilitation ecology has grown as a scientific discipline with significant applied importance for environment managers and policy makers (Ormerod 2003). The introduction of the European Water Framework Directive (WFD) required EU countries to achieve at least 'Good Ecological Status' of streams and rivers by 2015, and introduced a new phase of managing European rivers (Muhar *et al.* 2015). LWM is increasingly used in rehabilitation projects to improve the hydromorphological and ecological status of physically degraded streams and rivers (Kail *et al.* 2007). Current vogues in river rehabilitation are to attempt to mimic natural physical structures of streams (Thompson 2015). Adding LWM seems to have an important effect on channel structure and functioning, acting as an "ecosystem engineer" increasing habitat heterogeneity through alteration of geomorphic, hydraulic and sediment retention process (Thorp & Covich 2001; Corenblit *et al.* 2007). Although accumulation of installed LWM can increase local flood risk by redirecting water onto floodplains, this can reduce flood peaks downstream (Gippel *et al.* 1996).

Many studies have reported positive effects of installed LWM on channel morphology, current velocity, sediment retention, pool creation, leaf litter retention and nutrient dynamics (e.g. Smock, Metzler & Gladden 1989; Hilderbrand *et al.* 1997; Larson, Booth & Morley 2001; Roni *et al.* 2006; Lester, Wright & Jones-Lennon 2007), but biological improvement has often been limited. The biotic responses to LWM installation (especially changes in macroinvertebrate diversity and richness - which are commonly used as biodiversity tools in monitoring studies) are thus still not clear. Here, I have collected literature studies that used Before/After (BA), Control/Impacted (CI) or both (BACI) study designs to assess outcomes and responses of macroinvertebrate community structure and diversity to projects that added large wood materials as a sole rehabilitation measure (Table 3.1). I have located 13 published papers (see Chapter 2, for criteria that determined study inclusion), and evaluated the outcomes of 49 independent projects. Overall, biologically positive responses were limited. Only 11/49 projects recorded an increase in taxa richness/diversity, 15/49 projects recorded an increase in macroinvertebrate density and, of the 11/49 projects that assessed macroinvertebrate biomass as a response variable, only 4 reported increased macroinvertebrates biomass (Smock, Metzler & Gladden 1989; Wallace, Webster & Meyer 1995; Entrekin *et al.* 2009).

The disparity in the biological results among studies could result from three possible causes a) failure of LWM treatment to enhance physical and hydrological heterogeneity; b) insufficient recovery time or c) inappropriate study designs or monitored metrics. Failure to improve the physical habitat and channel complexity was recorded as the limiting factor in 6 rehabilitation projects by Leal (2012) and Thompson (2015). The long recovery time of physical and biological structures following LWM treatment also limits the power of some studies in detecting possible effects on macroinvertebrate communities. Entrekin *et al.* (2009) suggest that rehabilitated reaches are likely to require years to achieve measurable changes in channel geomorphology, organic matter retention and macroinvertebrate community.

Using a more appropriate study design, able to partition the effects of treatment from natural sources of variation (e.g. seasonal and inter-annual variability) is still not common. The dearth of pre-installation data has pushed researchers to use a surrogate for pre-installation data, a Control-Impact (CI) study design, in more than half of the LWM projects described in Table 3.1, which can be misleading (Miller, Budy & Schmidt 2010) and “render [supposed] impacts on macroinvertebrates questionable” (Feld *et al.* 2011). This approach might confound responses to rehabilitation activities with differences between macroinvertebrate communities (Laasonen, Muotka & Kivijärvi 1998; Negishi & Richardson 2003) because macroinvertebrate community metrics vary naturally at small spatial scales for reasons unrelated to rehabilitation activities (Negishi & Richardson 2003; Miller, Budy & Schmidt 2010).

Monitoring of rehabilitation outcomes needs to consider the direction - not only the change - of biotic communities (Downes *et al.* 2002). Assessing LWM installation effectiveness needs rigorous study design using pre-installation data to assess inherent differences between control and rehabilitated reaches. Only 9/48 of the projects described in Table 3.1 used undisturbed control reaches to represent the target state of rehabilitation (Smock, Metzler & Gladden 1989; Gerhard & Reich 2000; Thompson 2015) and thus can better account for other confounding sources of variance (partition the rehabilitation effects from other confounding source of variance) and provide more conclusive evidence for the rehabilitation treatment significance on macroinvertebrate community (Miller, Budy & Schmidt 2010; Feld *et al.* 2011). Macroinvertebrate taxa richness and diversity were commonly used monitoring metrics, but density and biomass - which showed some significant responses - were rarely used.

My study is to assess ecological effects of installed LWMs in a small rural headwater stream, using in-stream biotopes and their macroinvertebrate assemblages as a tool to assess the ecological effectiveness, as in-stream biotopes with their macroinvertebrate assemblages are regarded as a useful way of linking macroinvertebrate ecology and river hydromorphology (Demars *et al.* 2012). The study quantifies the short-term effects and positive outcomes of using LWM to rehabilitate a previously straightened headwater tributary of the River Welland (Rolleston Brook- Leicestershire). A natural reach was used as the theoretical goal of the rehabilitation, data from it were used as benchmarks for the level of recovery of the rehabilitated reach (following Hughes, Larsen & Omernik 1986).

I have addressed major limitations of previous studies by using multi-habitat sampling at the in-stream biotope level, in a BACI study design. Data were collected for six seasons (2 years) after the LWM installation. A broad range of physical and biological metrics (not only taxa richness or diversity) were used as response variables to assess morphological complexity and biological improvement of the rehabilitated reach. Seasonal changes in stream morphology (depth, width, in-stream biotope number and percentage of area covered) were recorded in both reaches; once before the installation process, then seasonally. Multi-habitat macroinvertebrate samples were collected in three replicates at the finest scale (all in-stream biotopes that comprised at least 1% of the total study reach area were sampled) in spring 2014, and after the rehabilitation for six successive seasons (16 months).

Table 3.1. Summary of published studies addressing the effects of LWM rehabilitation projects on habitat heterogeneity and macroinvertebrate community structure and function. A project's age is given as the age in years at the time of monitoring by the study authors. Study designs; Control-Impact (CI), Before-After (BA) or Before-After-Control-Impact (BACI). LWM, Large Woody Material; EPT%, Ephemeroptera, Plecoptera, Trichoptera index; FFGs%, Functional Feeding Groups index.

Reference Location (No. of projects)	Study design (project's age)	Key finding
Smock, Metzler and Gladden (1989) Virginia, USA (2)	CI (1)	Macroinvertebrate abundance and biomass increased with an increase in the number of woody material because there was increased collection of organic matter and increased food availability. The contribution of shredders to biomass increased with increasing the abundance of dams.
Wallace, Webster and Meyer (1995) North Carolina, USA (1)	BA (4)	At LWM addition sites, stream depth and organic matter increased, current velocity decreased, sand and silt covered the cobble substratum. Macroinvertebrate abundance, biomass, and secondary production increased significantly after rehabilitation. Abundance, biomass, and secondary production of scrapers and filterers decreased, while collectors and predators increased, no change in overall shredder biomass.
Hilderbrand *et al.* (1997) West Virginia, USA (2)	BA (2)	Systematic placement had a lower effect on erosion and score rates than random placement. There were no changes in total abundance of macroinvertebrates in either stream. Ephemeroptera abundance increased significantly with increasing pool area.
Gerhard and Reich (2000) Germany (2)	CI (4)	Rehabilitated reaches had more functional habitat patches per m metre than unrehabilitated. Abundance, species richness and diversity increased in Joseklein stream, but not in Lude stream.
Larson, Booth and Morley (2001) Washington, USA (6)	CI (2-10)	Channel complexity significantly increased. There was no change in benthic index of biotic integrity (B-IBI).
Pretty and Dobson (2004) UK (3)	BA (2)	Log addition enhanced detrital standing stocks. Macroinvertebrate total abundance and taxon richness were significantly increased in rehabilitated reaches The response was most marked for detritivores.
Roni *et al.* (2006) Oregon, USA (13)	CI (1-20)	Pool area, number of LWM, boulders, and pools were significantly higher in rehabilitated sites than the control sites. There were no changes in species abundance, richness, EPT%, FFGs% or IBI.
Lester, Wright and Jones-Lennon (2007) Australia (8)	BACI (1)	Wood increased storage of organic matter and sediments, improved bed and bank stability. Macroinvertebrate density and richness significantly increased. Treated streams had greater family richness and greater richness of all functional feeding groups. Richness increased in all wood, benthic and edge habitats.
Entrekin *et al.* (2009) Michigan, USA (3)	BACI (2)	Significant increase (22%) of macroinvertebrate biomass and secondary production was recorded in one rehabilitated reach, while there were no significant changes in other two reaches in comparison to values before logs addition.
Coe *et al.* (2009) Washington, USA (2)	CI (2)	Macroinvertebrate density was significantly higher on woody material than on cobbles. Wood substrate increased density of invertebrates at reach level.
Testa, Douglas Shields and Cooper (2011)	BACI (2)	Woody substrate tripled after rehabilitation, while there were no significant changes in macroinvertebrate density and family richness.

Mississippi, USA (1)		
Leal (2012) California, USA (1)	CI (1)	Smaller substrate particle sizes were found across rehabilitated site. There were no significant changes in other habitat features such as canopy cover, algae, tree roots, and emergent vegetation. Lower invertebrate abundance and diversity were associated with LWM in several months of the first year after rehabilitation. There was no significant improvement of macroinvertebrates density or richness.
Thompson (2015) UK (5)	BACI (1)	There were no significant reach-scale geomorphology changes. Macroinvertebrate abundance and biomass were significantly higher within LWM habitat. At reach-scale, biomass was significantly higher in rehabilitated reaches than unrehabilitated, but there were no significant changes in density and richness, diversity, and FFG composition.

3.2. Aim and objectives

This study aimed to explore the role of installed LWM in a small rural stream in enhancing stream hydromorphology and macroinvertebrate community composition, structure and function.

The following methodological hypotheses were designed to test the assumed effects of installed LWM:

a) Rehabilitation will improve the rehabilitated reach hydromorphology by increasing exposed coarse substrate and retaining leaf-litter, and this should be reflected by changes in the macroinvertebrate community.
b) Using a broader range of macroinvertebrate metrics (structural and functional) will help to understand the ecological effects of LWM installation better than could be achieved by using only diversity and/or richness measures.
c) Using a BACI study design and collecting samples over six successive seasons will help to follow the direction of the rehabilitation action, and partition the effects off from other confounding factors.

The specific ecological hypotheses were (expected reasons for them in brackets):

1) Installed LWM will enhance morphological complexity and physical heterogeneity (through increasing the depositional zone, trapping silt, increasing erosion from adjacent habitats, enhancing leaf litter retention, creating pool-riffle sequences, changing stream depth and width, altering in-stream biotope number, and diversity).
2) Macroinvertebrate Total Density (individuals m^{-2}), Total Biomass (mgDM m^{-2}), Taxon Richness, Taxon Diversity, Evenness, EPT Richness, EPT Diversity, EPT Count%, and EPT Biomass% will be enhanced in the rehabilitated reach compared with comparable measures made before rehabilitation, and the rehabilitated reach macroinvertebrate community metrics will resemble those of the natural reach.
3) Non-Tanypodinae Chironomidae Count% and Chironomidae Biomass% will decrease (due to reduction in silt biotope coverage area), while EPT Count% and EPT Biomass% will increase (due to increase in coarser biotopes area).

4) Macroinvertebrate community taxonomic composition (based on Count m^{-2}, and Biomass m^{-2}) will be improved by enhanced physical heterogeneity in the rehabilitated reach compared with the pre-rehabilitation situation, and will resemble that of the natural reach (as LWM will provide food and shelter for different macroinvertebrate assemblages).
5) Macroinvertebrate functional feeding groups' density and biomass will respond to the morphological enhancements. Shredders and scrapers feeding macroinvertebrates will increase, while deposit-feeders and filter-feeders will decrease. The rehabilitated reach FFGs structure will resemble those of the natural reach.
6) Macroinvertebrate FFGs composition (based on Count m^{-2}, and Biomass m^{-2}) will differ between before and after (as installed LWM will control and rearrange the occurrence and frequency of organic and inorganic biotopes). Rehabilitated reach FFGs composition will resemble those of the natural reach.

3.3. Materials and methods

3.3.1. Study reaches and LWM installation

The study was carried out on the Rolleston Brook; a headwater tributary of the Welland River, at Rolleston, Leicestershire (52.603564 N, -0.913059 W). Artificially straightening and over-deepening were the two main types of physical degradation on the Rolleston Brook. They have led to a characteristic imbalance in the in-stream biotope appearance and frequency. The entire reach was covered by fine-grained sediments. It apparently had low retention capacity of leaf litter and small woody material, due to low amounts of in-stream LWM. In addition, the entire channel reach was disconnected from its floodplain and marginal plants by a steep river bank. The channel longitudinal connectivity was also disrupted due to the presence of four concrete structures (Figure 3.2). The reach lacked hydromorphological variability and biodiversity.

In order to enhance the channel complexity, biotope heterogeneity and biodiversity, LWMs were installed in the impacted reach during summer 2014. LWM is often defined as pieces larger than 10 cm diameter and 1 m in length, although this definition may vary between studies (Baillie 2011). Installing LWM started at the downstream end of the reach and progressed upstream. The LWM installation process took three weeks. A 375 m reach was divided into 5 sections (Figure 3.3). LWM was installed (Figure 3.4): a) parallel to the flow (from one or both sides) to narrow the channel, reduce ponding upstream of the obstructions, and enhance the water flow; b) perpendicular (70-90°) to the channel to create meander patterns and promote riffle-pool sequences, increase hydraulic roughness (which affects flow velocity, stream power and appearance of new biotope); c) downstream faced (30°) as deflectors to kick flow over to one side to promote bank scour for outer meander bend development; d) as wing deflectors from both sides spanning the stream channel to create steps along the channel profile, regulate sediment movements through the channel system, and enhance leaf litter retention. The distance between each LWM installation was 6.5 - 9.1 m, which was equal to 5 - 7 times the average channel width. Deflectors stretched out from the bank to at least half-way across the low flow channel. In the first section, there was a fallen tree that had caused bank scour and created an outer meander, and tree roots that had caused bed scour with pool development, both of which were incorporated into the 5-7 channel widths sequence of LWM installation (Figure 3.5).

Figure 3.2. Concrete obstructions are affecting the channel longitudinal connectivity. a) First obstruction structure which was too high caused the upstream flow to be sluggish and ponded. b) A concrete track (white arrow) which had silted up. c) Upstream And d) downstream views of the second obstruction. The upstream end of the pipe has silted up and barely visible, the downstream end of the pipe was further obstructed by concrete sills, the channel was over widened and the flow was ponded. Photos of spring 2014.

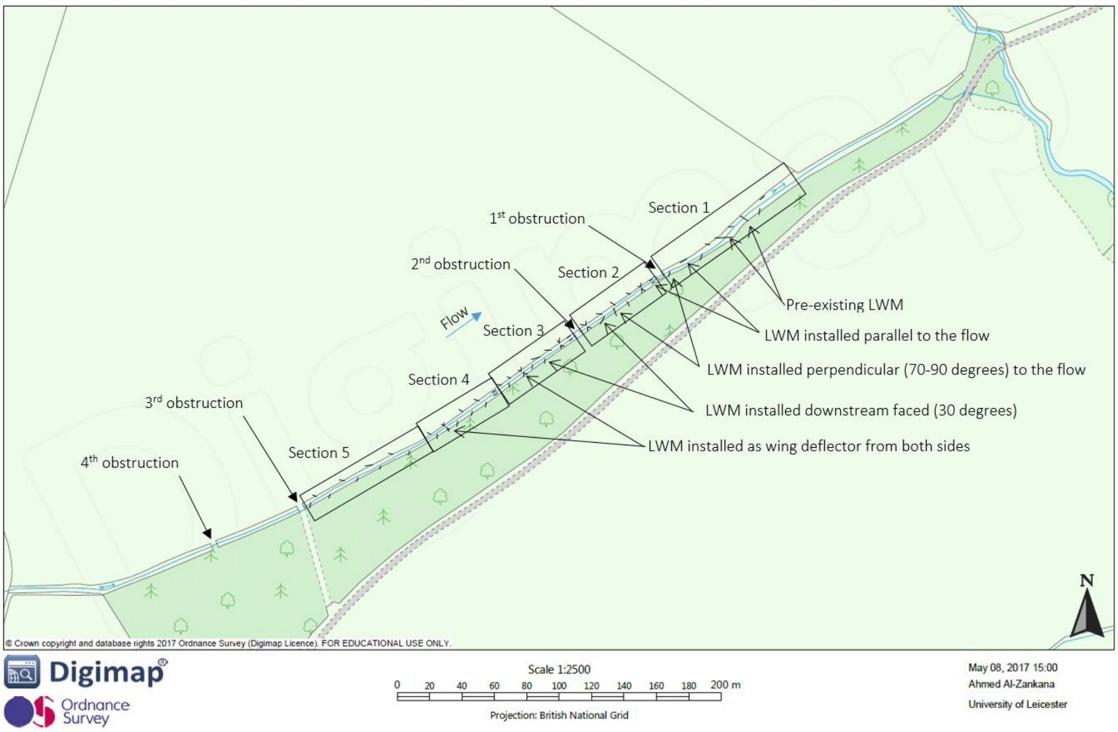


Figure 3.3. Map of the impacted reach shows positions and ways of LWM installation.

Figure 3.4. LWM installed to enhance the reach hydromorphological features. a) Installed LWM parallel to the channel to squeeze the channel. b) LWM installed as lateral deflector to enhance channel meandering and riffle-pool sequence, picture c) installed LWM spanning the channel to create a step along the channel profile, regulate sediment movements through the channel system, and increase water depth and the water retention capacity within the channel, and enhanced leaf litter retention. Photos of spring 2015.

Figure 3.5. The natural woody material in the rehabilitated reach. a) A fallen tree has caused bank scour, creating an outer meander, retained small woody material and leaves. b) Water flowing over tree roots has scoured the bed and created a pool.

About a 220 m reach of the impacted tributary (Rehabilitated Reach hereafter) was compared with a 220 m reach of a nearby natural tributary (Natural Reach hereafter) (Figure 3.6), selected as a control reach because it retains an original configuration (Figure 3.7) characterised by meanders, LWM dams, riffle-pool sequences and a wide range of organic and inorganic biotopes.

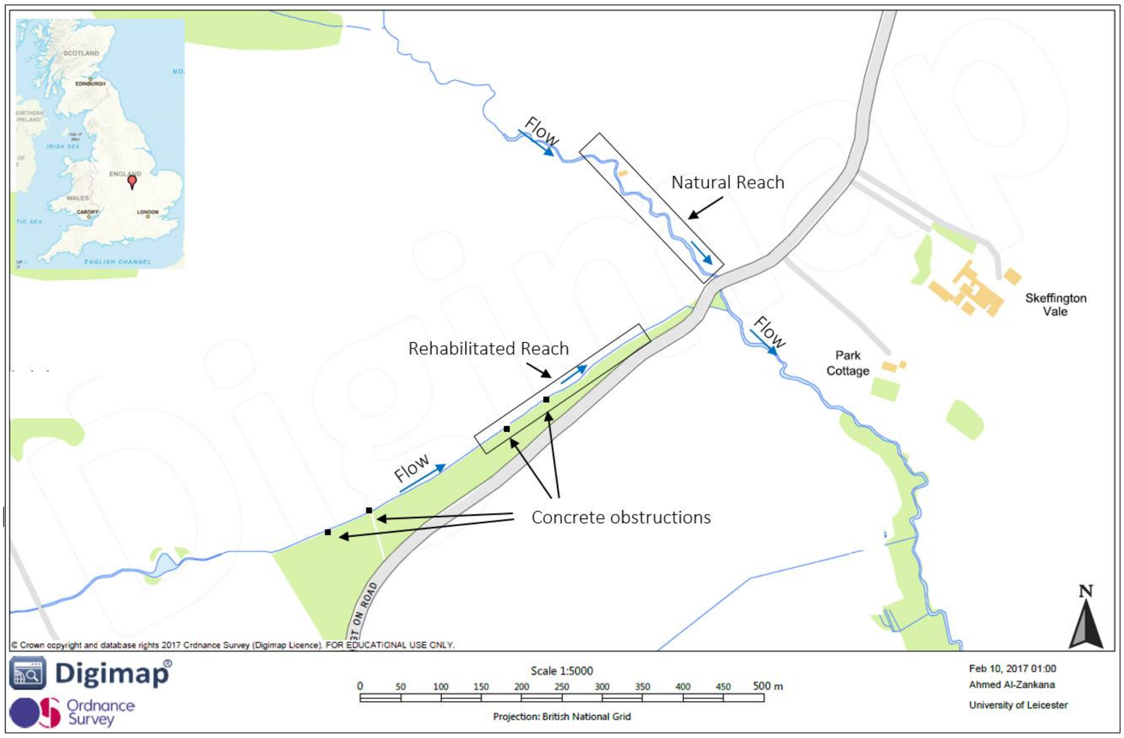


Figure 3.6. Map of study reaches.

Figure 3.7. Natural tributary of Rolleston Brook. a) A naturally fallen tree created a riffle-pool habitat and exposed sediments. b) A meander and riffle-pool sequence with marginal plants and macroalgae biotopes. c) The mineral habitat mosaic and log jams. Photos of spring 2015.

3.3.2. Surveying channel morphological features and mapping in-stream biotopes

Before the installation of LWM, the study reaches were surveyed and mapped in mid-April 2014. Channel width and depth were measured every 5m; the depth was measured to the nearest cm at the centre of each 5m cross section. The cover of each available in-stream biotope was estimated. In-stream biotopes were estimated using lateral transects spaced every 5m (perpendicular to the flow). The area of leaf litter and small wood was quantified by measuring the length and width of accumulated organic matter parallel and perpendicular to the stream channel. The total number of biotopes and their coverage area for each 5m transect were calculated following Entrekin *et al.* (2009). In-stream biotopes were – boulders, cobbles, gravel, sand, clay, soft silt (with organic matter), tree roots, marginal plants, woody material, and leaf litter. All transect measures were summed to give reach-level parameters and total wet surface area for each study reach. In-stream biotopes were visually identified and named as above (according to Demars *et al.* (2012)). Study reaches were surveyed and mapped seasonally in the 1st and 2nd years after the installation (2015-2016). Seasonal surveys were spring 2014 (before LWM installation), and six successive seasons after the installation process (winter 2015, spring 2015, summer 2015, autumn 2015, winter 2016 and spring 2016).

Based on the data from the reach-level morphological survey and in-stream biotope mapping, three parameters were calculated to describe the morphological condition of the study reaches –

a) in-stream biotope diversity by Shannon-Wiener diversity index (SWI) (Shannon & Weaver 1949), following Kemp (1999) and Poppe *et al.* (2015), named “SWI_biotope” hereafter. This diversity index depends on both species richness and dominance. Greater values of the Shannon index refer to higher numbers of species and greater equitability. Here, the number of in-stream biotopes (rather than the number of invertebrate species), and the biotope proportions (instead of species densities) have been used.

b) The coefficient of variation of channel water depth and width (CV_depth, CV_width) were calculated from all the measurements made along the reach. Coefficient of variation is defined as the ratio of the standard deviation to the mean.

3.3.3. Sampling and preservation of macroinvertebrates

In the middle of March and May 2014, before the installation process started, macroinvertebrate samples were collected from both reaches. Three replicate samples were taken from all existing biotopes (each covering ≥1% area of the river bed) within the two reaches. Samples were collected using a Surber sampler (500 µm mesh size and area of 0.09 m^2, Figure 3.8). After installation, samples were collected on an approximately 28 day schedule for one year (13 samples during 2015, from 22nd January to 24th December), and on three sampling visits during the second year after the rehabilitation (January, March, and May 2016). Repeated sampling accounted for shifts in macroinvertebrate assemblage composition and changes that may occur throughout the year. Repeated samples were grouped seasonally following Extence *et al.* (2013). Table 3.2 shows sampling dates.

Table 3.2. Macroinvertebrate sampling dates according to the study reaches.

Year	Season	Abbreviation	Natural reach	Rehabilitated reach
2014	Spring	Sp.14	11th March	13th March
			13th May	15th May
2015	Winter	Wi.15	22nd January	22nd January
			19th February	19th February
	Spring	Sp.15	19th March	19th March
			16th April	17th April
			14th May	15th May
	Summer	Su.15	12th June	13th June
			8th July	9th July
			7th August	8th August
	Autumn	Au.15	5th September	5th September
			2nd October	2nd October
			30th October	30th October
			27th November	27th November
	Winter	Wi.16	24th December	24th December
2016			22nd January	22nd January
	Spring	Sp.16	16th March	16th March
			12th May	12th May

The Surber sampler was used to sample all biotopes, starting at the downstream end of each reach and proceeding upstream to minimise any disturbance that could affect quantitative sampling. The stream bed within the sampler frame to a depth of 5 cm was disturbed for 30 s, and all material was retained and washed in the sampler's net to cause the organisms to be entrained into the flow and captured within the net (following Worrall 2012). Shoots of marginal plants were shaken within the sampler frame to obtain free-swimming invertebrates, then stems were cut and the plant directly removed to a plastic collection bucket (following Demars *et al.* 2012). Although large woody material dams can be an important habitat for macroinvertebrates (Smock, Gilinsky & Stoneburner 1985), the installed LWM contributed little as a habitat in the impact reach, especially during low flow seasons, as most of it was above the water level. They were therefore not sampled for macroinvertebrates (following Kedzierski & Smock 2001).

Samples were placed in 2.5 litre plastic buckets, labelled and returned to the laboratory. They were stored in a cold room at 4° C, and sorted into major groups within 48 h. Soft sediment samples were washed by tap water on a 500 µm sieve to remove excess clay and silt (following Maloney *et al.* 2008). Organic material was placed into plastic trays and checked for attached invertebrates, especially cased caddisflies, snails and flatworms. Processed samples were then transferred into a white plastic sorting tray and covered with water. Invertebrate specimens were extracted from the sorting tray and placed in 50 ml sealable plastic sample tubes containing 75% ethanol and kept separately for later taxonomic identification and counting. To ensure consistent sampling effort, samples were collected from both reaches within the same week (usually on the same day), following the same protocol.

Figure 3.8. Surber sampler (30.5 * 30.5cm).

3.3.4. Identification and counting of macroinvertebrate specimens

Macroinvertebrate specimens collected from each sampled biotope were identified and counted in the laboratory. Specimens were identified to the lowest possible taxonomic level (either species or genus), with the exception of Oligochaeta, Coleoptera, Diptera and early Limnephilidae instars, which were identified to family level. Chironomidae were identified to sub-family level. Specimens were morphologically identified using standard UK lotic invertebrate taxonomic keys and guidance books – (Soar & Williamson 1925; Soar & Williamson 1927; Soar & Williamson 1929; Mann & Watson 1954; Hynes, Macan & Williams 1960; Brinkhurst 1971; Gledhill, Sutcliffe & Williams 1976; Hynes 1977; Macan & Cooper 1977; Elliott & Mann 1979; Cranston 1982; Croft 1986; Elliott, Humpesch & Macan 1988; Wallace, Wallace & Philipson 1990; Edington & Hildrew 1995; Killeen, Aldridge & Oliver 2004; Wallace 2006; Greenhalgh & Ovenden 2007; Elliott 2009; Elliott & Humpesch 2010; Dobson *et al.* 2012; Waringer & Graf 2013). Identification was carried out under a dissecting microscope with a light source. The number of individuals per sample of each identified taxon was recorded in an Excel spreadsheet for each sampled biotope. An identically structured multivariate taxa count list was used to record data for all biotopes and replicated samples.

3.3.5. Assessing biomass

Macroinvertebrate population biomass (mg Dry Mass sample^{-1}) was estimated according to published size-specific mass regressions (Appendix 1), in addition to direct estimation for worms and some insect larva. Population biomass assessment requires both population density (number of individuals sample^{-1}), and dry-mass (mg DM) of each individual organism within the population.

Population of each species was divided into different size-classes according to the body length or head-capsule width. Body length was measured to the nearest 0.5 mm, and head capsule width to the nearest 0.1 mm. Length was measured by using an ocular micrometer for small specimens or a sheet of 1 mm graph paper placed directly on the dissecting-microscope's stage for the large specimens. Head capsule width (HW) was measured across the widest part of the head. Body length (BL) was measured as the distance between the anterior of the head to the posterior of the last abdominal segment (after Poepperl 1998). In addition, for two species, other linear body dimensions were used: these were for *Gammarus pulex* the length of first thoracic segment (TL), and for *Asellus* spp. the length of the Pleotelson (PL). Tricoptera larval head capsule width at eye level was measured to the nearest 0.2 mm (after Ross & Wallace 1983).

Dry-mass of each individual organism was then estimated according to the published size-specific dry-mass regression for the same or closely related taxa in European streams and rivers (Meyer 1989; Wenzel, Meyer & Schwoerbel 1990; Burgherr & Meyer 1997; Poepperl 1998; González, Basaguren & Pozo 2002; Giustini *et al.* 2008), or regressions available for North American (Smock 1980; Benke *et al.* 1999) or New Zealand (Towers, Henderson & Veltman 1994) macroinvertebrates when regressions were not available for European streams (after Thompson 2015). If more than one regression was available for same species, a regression was selected according to; geographical area (preferentially UK regressions, if not, then European or North American); aquatic ecosystem (lotic system, then lentic); number of individuals (n) used to create the regression (higher number preferred); and higher regression coefficient (r^2). Where higher level regressions (e.g. at family level) were required, those derived from several genera were used in preference to those derived from fewer or a single genus. Size-specific biomass (mgDM sample^{-1}) for each size group was calculated by multiplying the size-specific dry-mass (mgDM) with the density (number of individual sample^{-1}) of the size-group, then the biomasses of all the size groups were summed to obtain the population biomass (mgDM sample^{-1}) for each in-stream biotope. Dry-mass was determined for individuals of Oligochaeta and Nematomorpha (*Gordius aquaticus*) worms and Neuropteran larva (insect) directly. Specimens were placed in pre-weighed aluminium foil boats and dried in an oven for 24 h at 60°C, followed by cooling to room temperature in a desiccator before being weighed on an analytical balance with 0.01 mg precision (following Rodriguez & Verdonschot 2002; Benke & Huryn 2006). For worms, 10 individuals (where possible) of each family sampled were selected randomly, dried and weighed (from same biotope replicates). Multiple individuals were sometimes combined as some species were too small to weigh singly (e.g. Naididae). Mean individual dry-mass of worms for each biotope was measured by dividing total dry-mass of each possible 10 individuals by 10 or by total number of dried individuals when the number of individuals was less than 10. Population biomass of each taxon sample^{-1} was determined by multiplying the mean individual dry-mass and the number of individual sample^{-1}. The list of regressions and length parameters that were used and relevant references are available in Appendix 1.

3.3.6. Feeding strategy assignment

Macroinvertebrate abundance and biomass data for each biotope were assigned to eight feeding strategies (Table 3.3) (hereafter called Functional Feeding Groups FFGs) according to (Tachet *et al.* 2010). Each taxon was coded using a “fuzzy coding” approach on the basis of the extent to which it displayed the traits (Appendix 2). Taxon affinities for each group were fuzzy coded from zero (no affinity) to three (strong affinity). This approach allows taxa to exhibit feeding groups to different degrees, and avoids the obligate assignment of a taxon to a single FFG which may lead to inaccurate characterisation of biological or ecological taxa profiles (Chevene, Doleadec & Chessel 1994), because many taxa display multi-faced behaviour depending upon, for example, the specific conditions and resource availability (Usseglio-Polatera *et al.* 2000). The affinity codes of the functional feeding habit trait of each taxon were converted into a trait matrix. The sum of the affinity scores within the trait matrix for each taxon must equal 1.0 (e.g. the affinity codes of the eight feeding habit trait groups of the Dipteran Stratiomyidae were converted from (0, 2, 3, 1, 0, 0, 1, 0) to (0, 0.2857, 0.4286, 0.14285, 0, 0, 0.14285, 0). Feeding habit trait information was available for most taxa at species or genus level, except for Diptera and Oligochaeta, for which different systematic levels were used; genus but also subfamily or family. Curculionidae (Coleoptera), Muscidae (Diptera), and Empididae (Diptera) were assigned to FFGs according to (Merritt & Cummins 1996). Acari taxa were assigned into the predator group according to (Lugthart & Wallace 1992). Most Limnephilidae taxa were assigned as shredders following Dangles (2002).

The abundance of each taxon was multiplied by its fuzzy-coded feeding habit proportion at the in-stream biotope level. These values were then summed across all recorded different taxa (following Bolam & Eggleton 2014) to produce FFG abundance measures. Biomass data were used in the same way to derive FFG biomasses.

Table 3.3. Macroinvertebrate functional feeding group (FFG) types, adopted from Chevene, Doleadec and Chessel (1994).

No.	Group descriptor
1	Absorber
2	Deposit feeder
3	Shredder
4	Scraper
5	Filter feeder
6	Piercer (plant or animals)
7	Predator (carver/engulfer/swallower)
8	Parasite

3.3.7. Calculating reach-level macroinvertebrate community composition

For each sampled biotope, each of the three samples collected was used to generate a separate list of: taxa count sample^{-1} (T_{count}), taxa biomass sample^{-1} ($T_{biomass}$), FFG count sample^{-1} (FFG_{count}), and FFG biomass sample^{-1} ($FFG_{biomass}$). They were named following Jähnig *et al.* (2010), as;

a) biotope-specific T_{count} ,
b) biotope-specific $T_{biomass}$,
c) biotope-specific FFG_{count} , and
d) biotope-specific $FFG_{biomass}$,

Reach-level values of these four multivariate parameters were calculated according to the relative coverage area of each sampled in-stream biotope in the given reach. The reach-level variable lists were created by summing biotope-specific values that were weighted by their availability percentage (following Huryn & Wallace 1987; Lugthart & Wallace 1992; Kedzierski & Smock 2001; Pedersen *et al.* 2007; Jähnig *et al.* 2010). One of the three replicate data lists from each sampled biotope was selected randomly, multiplied by its coverage % of the streambed, then summed to give one replicate data list of the given parameter at the reach-level. This step was repeated two more times to create second and third lists. Thus, each reach had three separate lists of T_{count}, $T_{biomass}$, FFG_{count} and $FFG_{biomass}$. They were named

a) reach-level T_{count} ,
b) reach-level $T_{biomass}$,
c) reach-level FFG_{count} , and
d) reach-level $FFG_{biomass}$

Figure 3.9 shows as an example the steps involved in the calculation of the reach-level T_{count} for the natural tributary of the Rolleston Brook in winter 2015. Before the biotic samples were collected, the study reach was surveyed and mapped to assess the relative percentage of each available biotope's coverage of the streambed. Seven different biotopes each comprised at least 1% of the reach streambed (first row of Figure 3.9: boulders (BR), cobbles (CO), gravel (G), sand (SA), clay (CL), tree root (R), and leaf litter (LL). 21 samples were collected from the reach (3 replicates from each biotope, numbered 1-3 in the second row of Figure 3.9), sorted and specimens identified to the lowest possible taxonomic groups to create three separate lists of macroinvertebrate count/sample at the biotope-level for each biotope (third row in Figure 3.9). The 21 biotope-specific T_{count} lists were divided into 3 groups, each group with one replicate (selected randomly) from each of the 7 sampled biotopes (fourth row of Figure 3.9). Each biotope-specific T_{count} data list for the first group was weighted by the corresponding biotope percentage, the biotope values then summed (these two steps indicated by x%+ in the fourth row of Figure 3.9) to give one replicate reach-level T_{count} data list (G1 at the bottom right of Figure 3.9). The same steps were repeated for the second and third groups, to generate the second and third replicates of the reach-level T_{count} (G2, G3 in Figure 3.9).

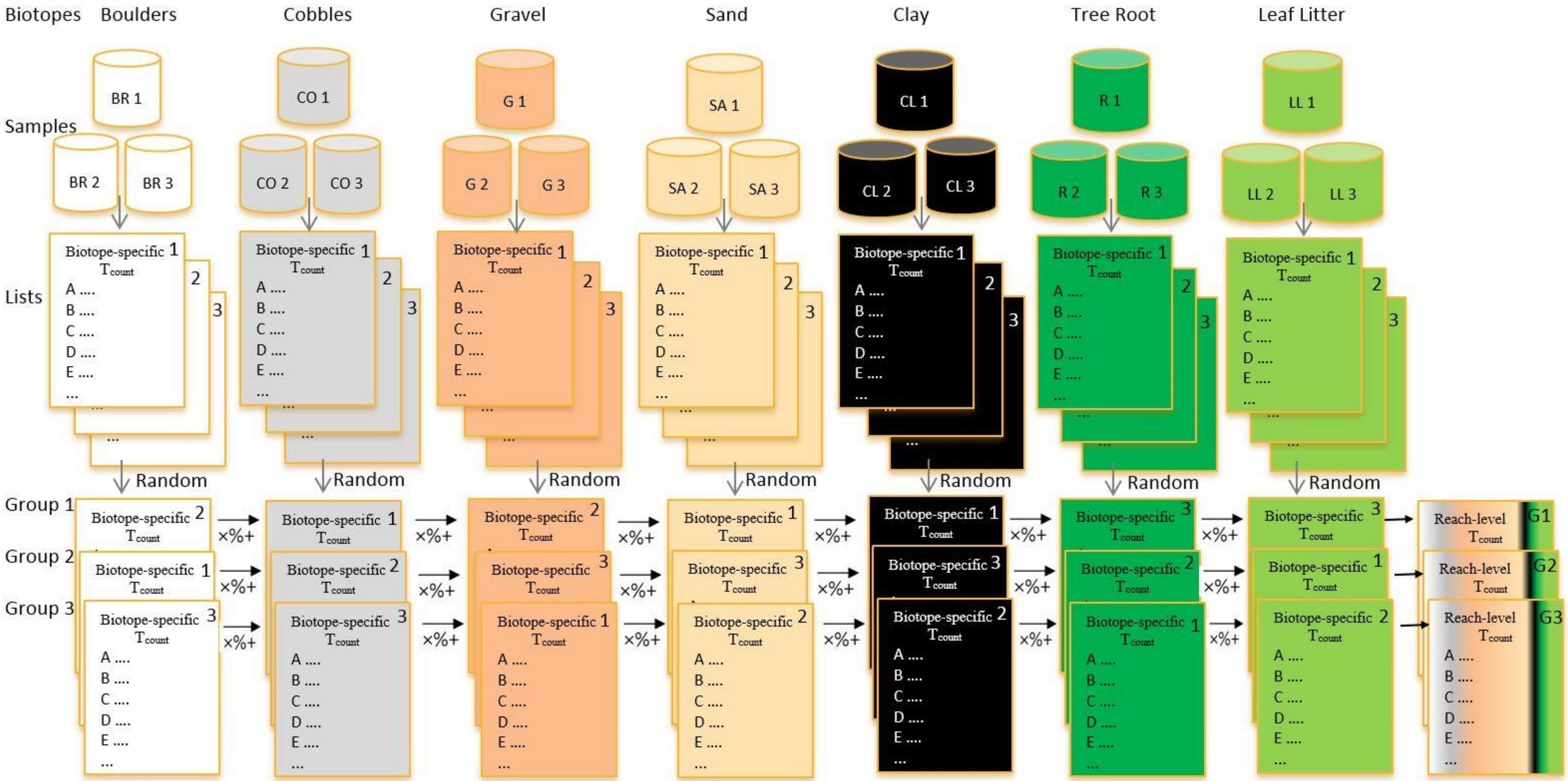


Figure 3.9. Diagram shows calculation of the reach-level T_{count} data list from the biotope-specific T_{count} data lists. BR, Boulders, CO, Cobbles, G, Gravel, SA, Sand, CL, Clay, R, Tree Root, LL, Leaf Litter. A, B, C, D, E … refer to the name of macroinvertebrate taxa. 1, 2, 3 refer to the number of replicates.

3.3.8. Calculating reach-level macroinvertebrate univariate metrics

Reach-level univariate metrics were calculated using PRIMER software (version 7; Primer-E Ltd., Plymouth, England). The multivariate reach-level T_{count} data lists were used to generate eight community structure and diversity metrics [Total Density (individuals sample^{-1}) (N), Taxa Richness (d), Evenness (Pielou's 'J′), Taxa Diversity (Shannon-Wiener 'H′), EPT Richness, EPT Count%, EPT Diversity, and Chironomidae Count%]. The reach-level $T_{biomass}$ data lists were used to calculate Total Biomass (mgDM sample^{-1}), EPT Biomass%; and Chironomidae Biomass%. The reach-level FFG_{count} and $FFG_{biomass}$ data lists were used to calculate the percentage of density and biomass of each FFG, (following Tullos *et al.* 2009). Density, biomass, richness, evenness, and diversity metrics were calculated using the DIVERSE program. Relative percentages were calculated using the 'standardise' option of the same software.

3.3.9. Data analysis

Channel morphological metrics and in-stream substrate composition (biotope coverage area relative percentages) were normalised, Euclidean distance matrices were then calculated and used in one-way ANOSIM (Analysis of Similarity) (Clarke *et al.* 2014). This tested for differences in morphological variables and substrate composition between both reaches in a control-impact (C-I) design, depending on reach-level data collected over five successive seasons (winter, spring, summer, autumn 2015, and winter 2016) within the first and second years after LWM installation. Greater global R values in ANOSIM indicate greater separation in ordination space. R values >0.5 illustrate clear differences between reaches with some degree of overlap (Clarke & Gorley 2015), values ≥0.6 shows a significant difference. Significance values of $P<0.05$ were accepted. Principal component analysis (PCA) was conducted to visualise which metrics or variables separated the study reaches. PCA results were ordinated by reaches, and variables contributing >0.5 Spearman's rank correlation (ρ) were included as vectors (following Clark 2011).

Macroinvertebrate univariate metrics (Total Density and Total Biomass) and community composition data were pooled to show values per square meter before the data analysis.

Permutational ANOVA (PERMANOVA) (Anderson, Gorley & Clarke 2008) was used to perform both univariate and multivariate analyses (following Eddy & Roman 2016).

Reaches were compared seasonally before and after LWM installation. I first created the Euclidean distance matrix to calculate distances between samples for each univariate metric separately. Metrics were ln(x), ln(x+1), Sqrt(x), or Asin(x) transformed (Table 3.4) prior to the analysis to normalise the data distribution and satisfy the PerANOVA test requirement, where applicable. Two-way PerANOVA design with *Reach type* (fixed factor, two levels: control, impact) and *Seasons* (fixed factor, seven levels: Sp.14, Wi.15, Sp.15, Su.15, Au.15, Wi.16, Sp.16) were used for running a BACI design test and all possible pair-wise tests. Since the design was unbalanced, a Type III test for sum of squares (SS) was used. All PerANOVA tests used 9999 random permutations under a reduced model. When there were too few possible permutations (<100) to obtain a reasonable test, a P value was calculated using 9999 Monte Carlo draws from the appropriate asymptotic permutation distribution (Anderson & Robinson 2003). Spatial and temporal differences were visualised using box plots.

Macroinvertebrate community composition differences were tested by performing the same PERMANOVA designs, depending on the reach-levels T_{count}, $T_{biomass}$, FFG_{count}, and $FFG_{biomass}$ data matrices (pooled to show values per square meter). All matrices were fourth-root transformed prior to the analysis to normalise the data distributions. This down-weighed the influence of numerically dominant taxa, and prevent masking of less abundant taxa. 2D non-metric multidimensional scaling (nMDS) ordination plots with Bray-Curtis dissimilarity coefficients were used to visualise significant differences. Bray-Curtis distance was chosen because it is not biased by joint absence (coincident occurrence of null values in the samples being compared). In nMDS analysis, a stress ≤0.2 gives a potentially useful picture of the data structure, while a stress ≤0.1 corresponds to a good ordination with no prospect of misleading interpretation (Clarke *et al.* 2014)

A similarity percentage procedure (SIMPER) was used to determine which taxa or FFGs accounted for the dissimilarities in any significant spatial or temporal measures, with exclusion of taxa or FFGs that contributed less than 30% of the dissimilarity (following Johnson *et al.* 2010; Gosch *et al.* 2014). These analyses were visualised using shade plots.

The relationships between channel morphological variables and macroinvertebrate univariate metrics were analysed using distance-based linear modelling (DISTLM) following Eddy and Roman (2016) and Heerhartz *et al.* (2016). This analysis was performed after normalising of morphological variables. Euclidean distance matrices of all univariate metrics used for the previously described PERMANOVA analyses were used separately. Sequential tests were used to determine which combinations of morphological variables best explained variability in the response variable. Each sequential test was performed with a step-wise selection procedure using Akaike's Information Criteria (AIC). This analysis partitions the variability of the macroinvertebrate community metrics along best-fit axes and then tests the morphological variables that are most closely related to these axes. The relationship between morphological variables and biological metrics were determined using Spearman's rank correlation (ρ).

BIOENV analysis (Clarke & Ainsworth 1993) was used to investigate relationships between patterns in macroinvertebrate community composition and morphological variables. The test selected a maximum of five morphological variables from Euclidian distance resemblance matrices that contribute the best Spearman's rank correlation (ρ) with each of T_{count}, $T_{biomass}$, FFG_{count}, and $FFG_{biomass}$ data Bray-Curtis similarity matrices.

All analyses were carried out using PRIMER v.7 software program (Clarke & Gorley 2015) and the PERMANOVA+ add-on package (Anderson, Gorley & Clarke 2008).

Table 3.4. Univariate macroinvertebrate community metrics transformations.

Univariate metrics	Transformation
Total Density (N)	ln(N)
Taxa Richness (d)	None
Evenness (J´)	Asin(J')
Taxa Diversity (H´)	Sqrt(H')
EPT Richness	None
EPT Count %	None
EPT Diversity	None
Chironomidae Count %	None
Total Biomass	ln(TB)
EPT Biomass %	None
Chironomidae Biomass %	None
FFGs Count	Sqrt(C)
FFGs Biomass	Sqrt(B)

3.4. Results

3.4.1. Channel morphological metrics and in-stream biotope structure

During first post-rehabilitation year, installed LWM enhanced the rehabilitated reach's morphological complexity and physical heterogeneity through increasing the depositional zone, trapping silt, increasing erosion from adjacent habitats, enhancing leaf litter retention, creating pool-riffle sequences, changing stream depth and width and altering in-stream biotope number and diversity. Current speed diversity was enhanced because installed LWM created steps along the channel profile, and thus sequences of riffle-pool (Figure 3.10). They increased the hydraulic roughness of the rehabilitated reach, and enhanced water and leaf litter retention. Rehabilitated reach morphological metrics were positively affected. Coefficient of variation of channel water depth and width (CV_depth, and CV_width), Wet surface area (m^2) were increased. Number of in-stream biotopes and the Biotope Diversity (SWI_biotope) were increased due to the appearance of a new organic biotope (leaf litter) and retention of sediment by installed LWM. Silty materials were trapped behind the installed LWM, so clear patches of cobbles and gravels appeared downstream (Figure 3.11). However, in the second post-rehabilitation spring (Sp.16), the installed LWM had been washed away during a preceding flood event. They were trapped by the concrete barriers, blocked the channel and caused further longitudinal dis-connectivity to the reach (Figure 3.12). Trapped silty materials scattered and covered cobbles and gravels patches (Figure 3.13), and retained leaf-litters either washed out to the channel banks or downstream. Thus, measured channel morphological metrics and in-stream biotope% declined. Therefore, Sp.16 morphological data were not included in the between reach statistical analysis. Statistical analysis was based on post-rehabilitation reach-level data collected during five successive seasons (Wi.15-Wi.16).

Statistically, the positive effects of the installed LWM were not enough to enhance the rehabilitated reach channel morphology and in-stream biotope composition to become similar to the natural reach. Analysis of Similarities (ANOSIM) testing on channel morphological metrics and in-stream biotope composition (Biotope%) revealed that significant differences between reaches remained (Global R=0.64 and 0.968 respectively, P<0.008).

Figure 3.10. Two sections of the rehabilitated reach, before (2014) and after the LWM installation (2015 and 2016). a) Upstream to the first concrete obstruction, the installed LWM created steps along the channel, riffle-pool sequence, and increased leaf-litter retention in spring 2015. b) Downstream to the first concrete obstruction, installed LWM affected the channel morphology, increased in-stream biotope mosaic and leaf-litter retention in spring 2015. In spring 2016, installed LWM washed away and the rehabilitated reach lost most of the positive hydromorphological outcomes.

Figure 3.11. Seasonal variations in morphological metrics. a) Coefficient of variation of water depth. b) Coefficient of variation of water width. c) Wet surface area. d) Number of in-stream biotopes. e) Shannon-Wiener diversity index of in-stream biotopes. Sp.14, spring 2014 (before LWM installation); Wi.15, winter 2015; Sp.15, spring 2015; Su.15, summer 2015; Au.15, autumn 2015; Wi.16, winter 2016; and Sp.16, spring 2016 (after LWM installation).

Figure 3.12. Installed LWM washed down in spring 2016 by a flood. a) The upstream end of the second concreate obstruction, trapped LWM, leaf-litter, soft sediments blocked the pipe and affected the flow continuity. b) Washed down LWM trapped by the second obstruction. c) The naturally fallen tree trapped LWM. Photos of spring 2016.

Figure 3.13. The second concrete obstruction affected the rehabilitated reach longitudinal connectivity. a) The upstream of the obstruction, ponded and all in-stream biotopes silted. b) The blocked upstream end of the obstruction trapped installed LWM. c) The downstream of the obstruction, the flow is interrupted. Photos of spring 2016.

The study reaches' channel morphological metrics compared using Principal Components Analysis (PCA) are shown in Figure 3.14, PC1 to PC2 described 89.5% of the variation between both reaches. Clear separation between reaches was explained by having a higher Number of in-stream Biotopes and higher Biotope Diversity in the natural reach than the rehabilitated reach. PC1 captured 58.3% of the variance. Both the Number of in-stream Biotopes (ρ=-0.636) and Biotope Diversity (ρ=-0.613) were highly associated with PC1. The clear separation between the seasonal data explained by PC2 which captured 31.2% of the variance. Wet surface area (ρ=-0.889) was highly related to PC2 and explained within reach seasonal variations (Appendix 3.1).

In-stream biotope % PC1 to PC2 described 96.5% of between reach variations. PC1 captured 92.9% of the variance and clearly has separated both reaches (Figure 3.14). The rehabilitated reach had higher coverage of silt biotope (ρ=0.791) than the natural reach. (Appendix 3.2). A summary of channel morphological metrics measured at the reach-level for both reaches and in-stream biotope composition is included in Appendix 3.3 and Appendix 3.4 respectively.

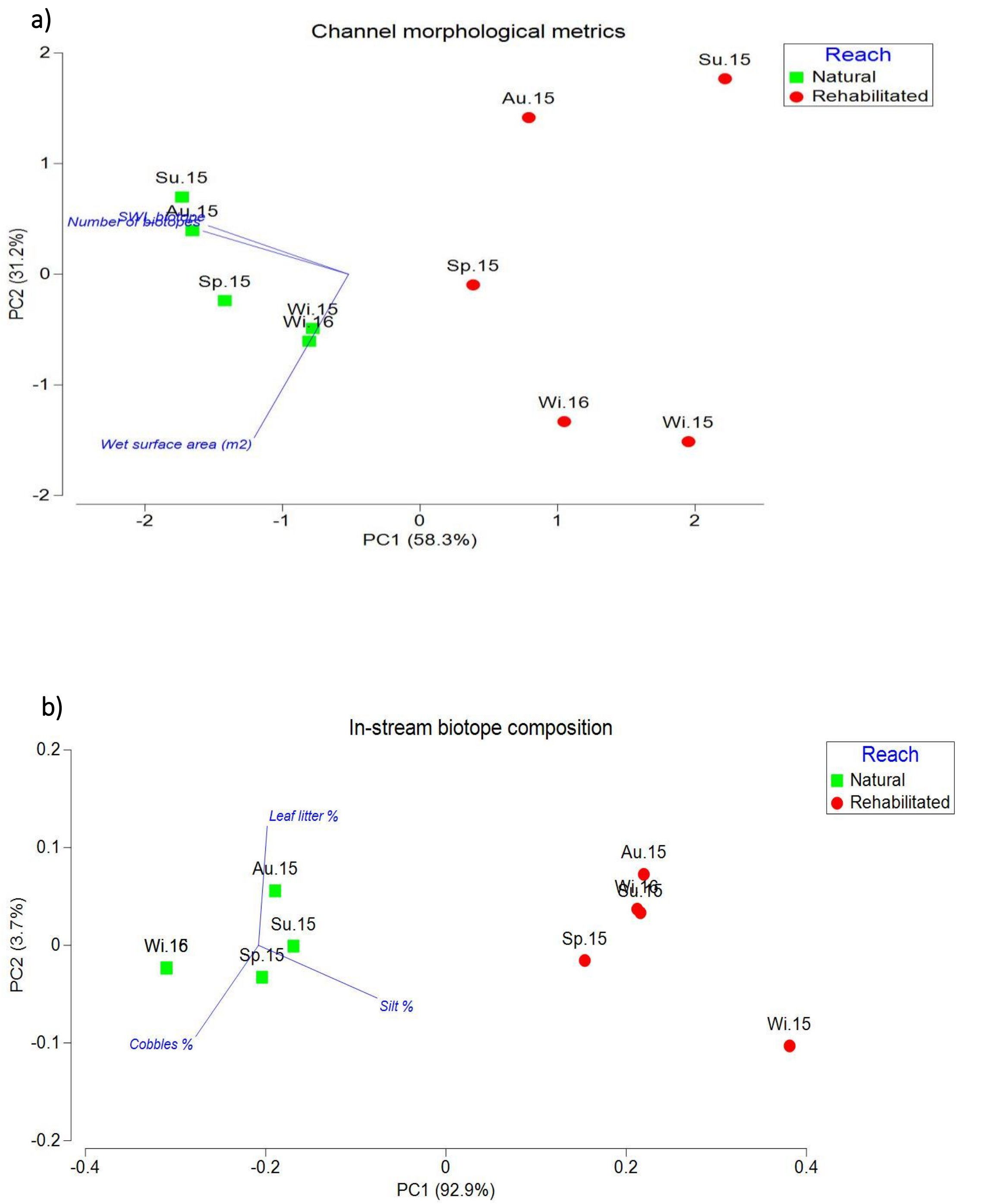


Figure 3.14. PCA ordination plots showing seasonal trends of a) channel morphological metrics, and b) in-stream biotope composition, depending on reach-level data measured over five successive seasons during the first and second years after LWM installation in both natural and rehabilitated reaches. Wi.15, winter 2015; Sp.15, spring 2015; Su.15, summer 2015; Au.15, autumn 2015; and Wi.16, winter 2016.

3.4.2. Macroinvertebrate community structure and diversity metrics

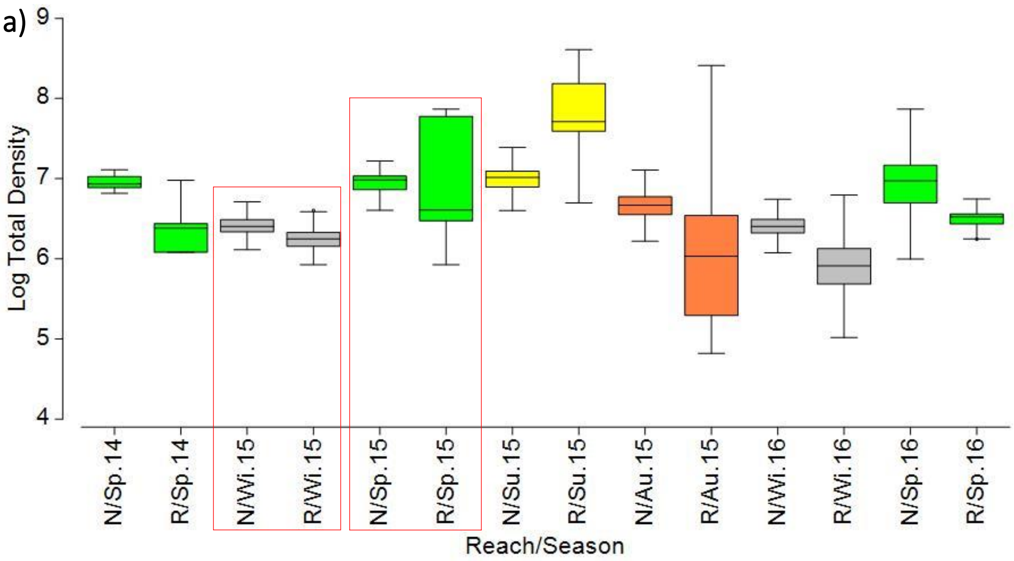
Before the LWM installation process, in spring 2014 (Sp.14), both reaches differed significantly ($P>0.05$) in all measured macroinvertebrate community univariate metrics (Figure 3.15; Figure 3.16; Figure 3.17; Figure 3.18; Appendix 3.5). The natural reach had a higher Total Density (individual m^{-2}), Total Biomass (mgDM m^{-2}), Taxon Richness, Taxon Diversity, Evenness, EPT Richness, EPT Diversity, EPT Count%, and EPT Biomass%. The degraded reach had a higher Chironomidae Count% and Chironomidae Biomass % (Table 3.5).

During first post-rehabilitation year, LWM installation led to significant increases ($P<0.05$) in the rehabilitated reach's macroinvertebrate Total Density (individuals m^{-2}), Total Biomass (mgDM m^{-2}), Taxa Richness, EPT Count%, and EPT Biomass%. However, Taxon Diversity, Evenness, EPT Richness and EPT Diversity did not show any significant responses to the rehabilitation process (Appendix 3.6). The positive influences of the installed LWM were lost by the second post-rehabilitation spring (Sp.16). Macroinvertebrate Total Density, Total Biomass, and Taxa Richness had declined significantly ($P<0.05$). Macroinvertebrate Total Biomass (mgDM m^{-2}) (Figure 3.15 b) increased significantly during both first and second post-rehabilitation years (Sp.15 compared with Sp.14 ($P=0.0003$), and Wi.16 compared with Wi.15 ($P=0.0193$). Even though it had declined in Sp.16 compared with Sp.15 it was still higher than Sp.14 ($P=0.0024$).

Chironomidae Count% and Chironomidae Biomass% both decreased significantly during the second post-rehabilitation year (Wi16, and Sp.16) (Figure 3.18). Sp.16 had lower Chironomidae Count% and Chironomidae Biomass % ($P=0.0028$) compared with Sp.14, and Wi.16 had lower Chironomidae Count% and Chironomidae Biomass% ($P=0.0022$ & $P=0.0392$ respectively) than Wi.15.

The rehabilitated reach became similar to the natural reach in Wi.15 and Sp.15 by Total Density (individual m^{-2}) (Figure 3.15 a), and in Wi.15 and Au.15 by EPT Biomass% (Figure 3.18 a).

a)



b)

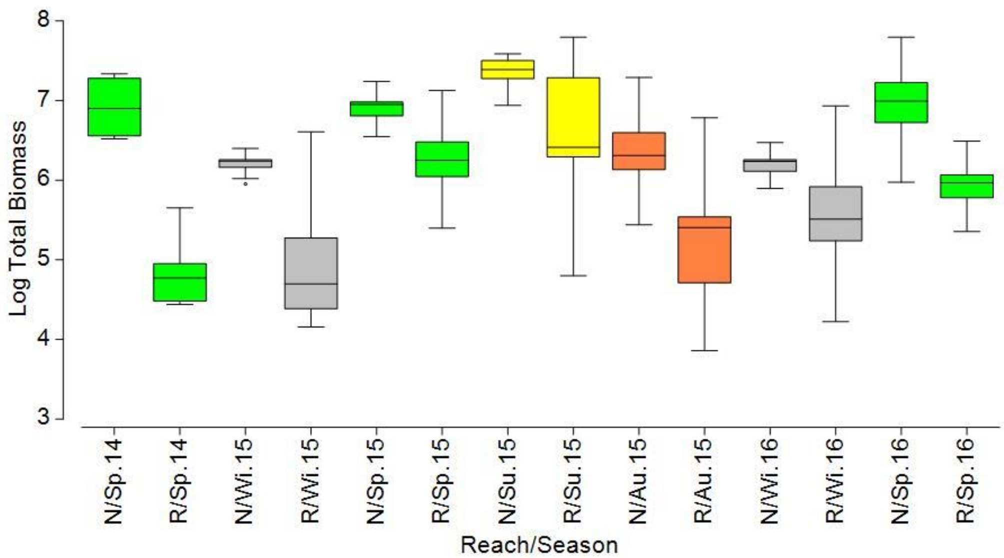


Figure 3.15. Seasonal variations in macroinvertebrate community structure according to the study reaches, a) Total Density; b) Total Biomass. N, Natural reach; R, Rehabilitated reach. Red rectangles indicate the non-significant difference between both reaches.

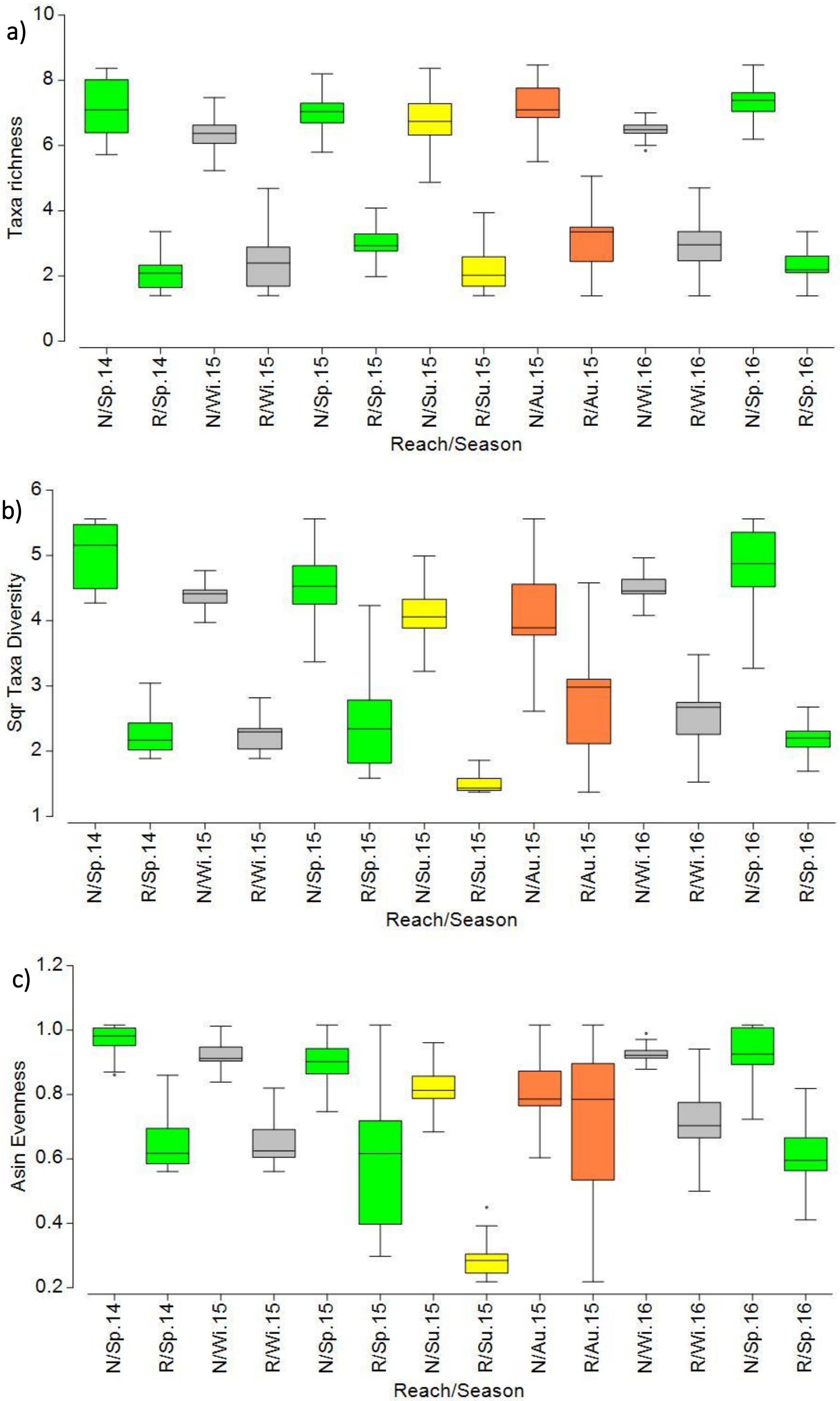


Figure 3.16. Seasonal variations in macroinvertebrate community structure according to the study reaches, a) Taxa Richness; b) Taxa Diversity; c) Evenness. N, Natural reach; R, Rehabilitated reach.

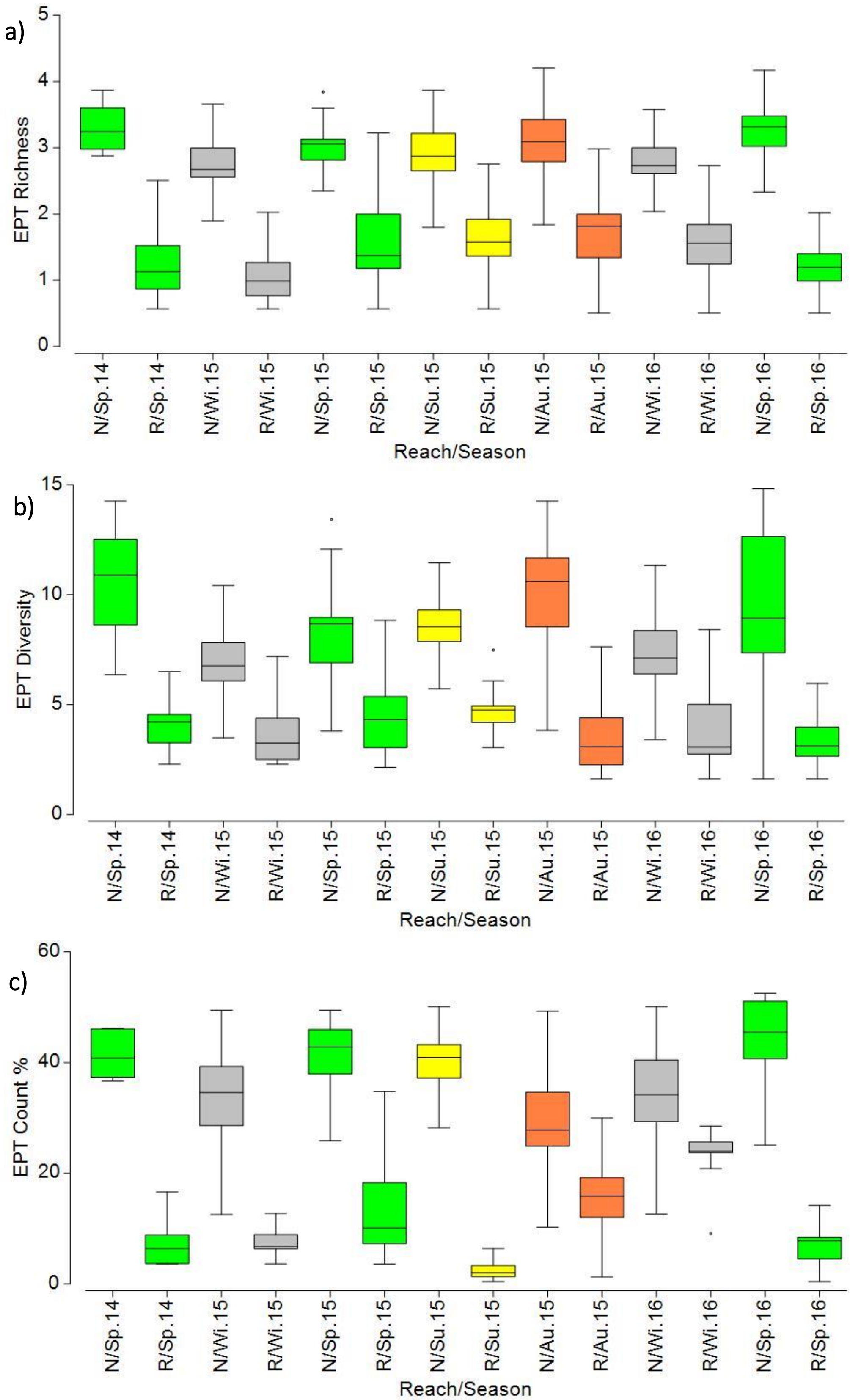


Figure 3.17. Seasonal variations in macroinvertebrate community structure according to the study reaches, a) EPT Richness; b) EPT Diversity; c) EPT Count%. N, Natural reach; R, Rehabilitated reach.

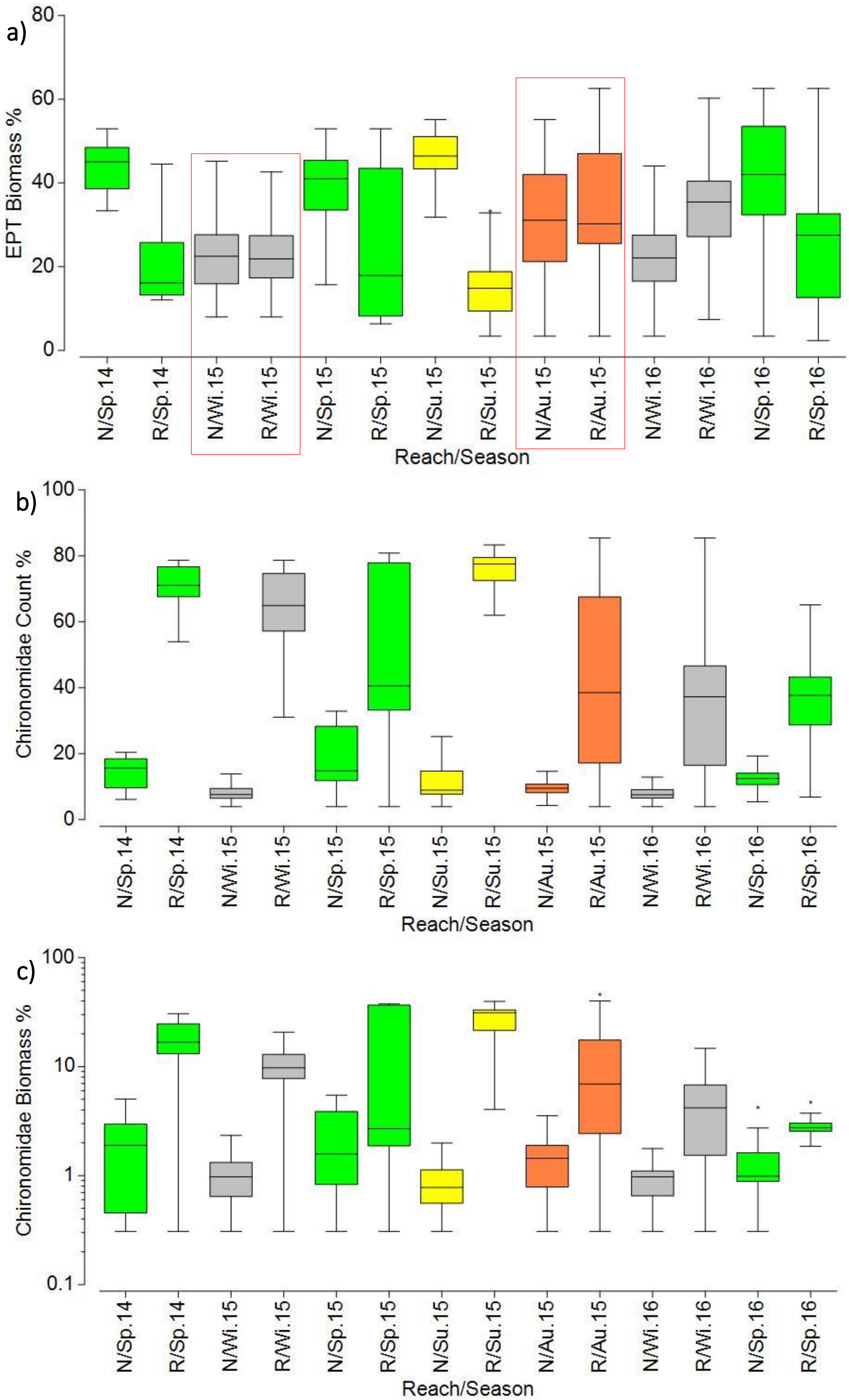


Figure 3.18. Seasonal variations in macroinvertebrate community structure according to the study reaches, a) EPT Biomass %; b) Chironomidae Count %; c) Chironomidae Biomass %. N, Natural reach; R, Rehabilitated reach. Red rectangles indicate the non-significant difference between both reaches

Table 3.5. Mean and standard deviation (±SD) of macroinvertebrate community structural and functional metrics. N, Natural reach; R, Rehabilitated reach. The grey shading means reaches become similar in the given metrics during the given season

	Status	Before LWM installation		After LWM installation											
	Year	2014		2015								2016			
	Season	Spring		Winter		Spring		Summer		Autumn		Winter		Spring	
	Reach	N	R	N	R	N	R	N	R	N	R	N	R	N	R
Total Density (Individuals m^{-2})		1050 ±111	571 ±119	631 ±96	530 ±120	1072 ±146	1285 ±922	1082 ±173	2853 ±1323	798 ±143	444 ±260	624 ±94	368 ±121	1060 ±240	662 ±86
Total biomass (mgDM m^{-2})		1070 ±401	118 ±30	491 ±57	134 ±71	994 ±129	539 ±146	1618 ±245	1036 ±734	582 ±178	198 ±110	489 ±56	283 ±110	1122 380	376 ±88
Total Number of Taxa		51 ±8	14 ±3	42 ±2	16 ±5	50 ±4	22 ±3	48 ±4	18 ±4	49 ±4	18 ±5	43 ±2	18 ±4	52 ±4	16 ±2
Taxa Richness		7.1 ±1.1	2.1 ±0.5	6.3 ±0.5	2.4 ±0.7	7.0 ±0.6	3.0 ±0.5	6.8 ±0.6	2.1 ±0.5	7.3 ±0.6	3.0 ±0.8	6.5 ±0.4	2.9 ±0.5	7.4 ±0.5	2.3 ±0.3
Taxa Diversity		24.9 ±5.2	4.8 ±1.2	19.5 ±1.5	5.1 ±1	20.2 ±3.5	5.2 ±2.6	16.8 ±2.8	2.3 ±0.4	16.8 ±4.9	6.5 ±3.2	20.3 ±1.3	6.4 ±1.7	23.9 ±4.4	4.8 ±0.8
Evenness		0.99 ±0.002	0.97 ±0.009	0.98 ±0.002	0.96 ±0.01	0.98 ±0.002	0.96 ±0.014	0.98 ±0.002	0.93 ±0.019	0.98 ±0	0.97 ±0.01	0.99 ±0.002	0.97 ±0.008	0.98 ±0.003	0.96 ±0.006
EPT Richness		3.30 ±0.38	1.14 ±0.41	2.77 ±0.29	1.05 ±0.41	3.04 ±0.36	1.54 ±0.42	2.94 ±0.28	1.65 ±0.44	3.14 ±0.55	1.62 ±0.57	2.80 ±0.29	1.54 ±0.46	3.31 ±0.41	1.24 ±0.38
EPT Diversity		10.60 ±2.87	3.98 ±1.06	6.87 ±1.19	3.52 ±1.18	8.18 ±2.46	4.58 ±1.90	8.48 ±1.24	4.77 ±1.16	10.25 ±2	3.28 ±1.21	7.10 ±1.40	3.84 ±1.69	9.89 ±3.28	3.25 ±0.86
EPT Count%		41 ±4	7 ±3	35 ±9	8 ±2	42 ±5	12 ±6	40 ±5	2 ±1	30 ±7	15 ±5	35 ±9	22 ±6	45 ±6	7 ±3
EPT Biomass%		44 ±7	19 ±8	21 ±9	22 ±7	40 ±8	24 ±17	47 ±5	15 ±9	32 ±12	34 ±16	21 ±9	36 ±9	42 ±10	23 ±13
Chironomidae Count%		14 ±6	71 ±6	8 ±3	66 ±9	19 ±10	50 ±23	11 ±4	77 ±5	9 ±2	43 ±28	8 ±3	33 ±16	13 ±3	37 ±11
Chironomidae Biomass%		2 ±2	18 ±8	1 ±0	10 ±4	2 ±2	14 ±17	1 ±0	28 ±7	1 ±1	12 ±13	1 ±0	4 ±3	2 ±1	3 ±1

3.4.3. *Macroinvertebrate community taxonomic composition*

Before the rehabilitation process had been started, in spring 2014, both reaches differed significantly in macroinvertebrate community taxonomic composition (both Taxon Count m^{-2} and Taxon Biomass m^{-2}) (*P*=0.003 & 0.002 respectively, Appendix 3.7). Installed LWM had significant effects on the rehabilitated reach macroinvertebrate taxonomic composition. In spring 2015 the community composition was enhanced toward the natural reach, and changes were significant (Count m^{-2}, *P*=0.0002, and Biomass m^{-2}, *P*=0.0002, Appendix 3.8). Significant changes in spring 2016 compared to spring 2014 (Count m^{-2}, *P*=0.0184, Biomass m^{-2}, *P*=0.0261) were not however in the direction of the natural reach, which was the goal state of the rehabilitation. The positive changes in the macroinvertebrate community composition were not enough to make the rehabilitated reach similar to the natural reach. Thus, between reach differences in macroinvertebrate taxonomic composition remained significant after the process over the six successive sampled seasons (Appendix 3.7). The difference was demonstrated by the clear separation of seasonal samples according to the study reaches on the non-metric multidimensional scaling (nMDS) ordination plots (Figure 3.19).

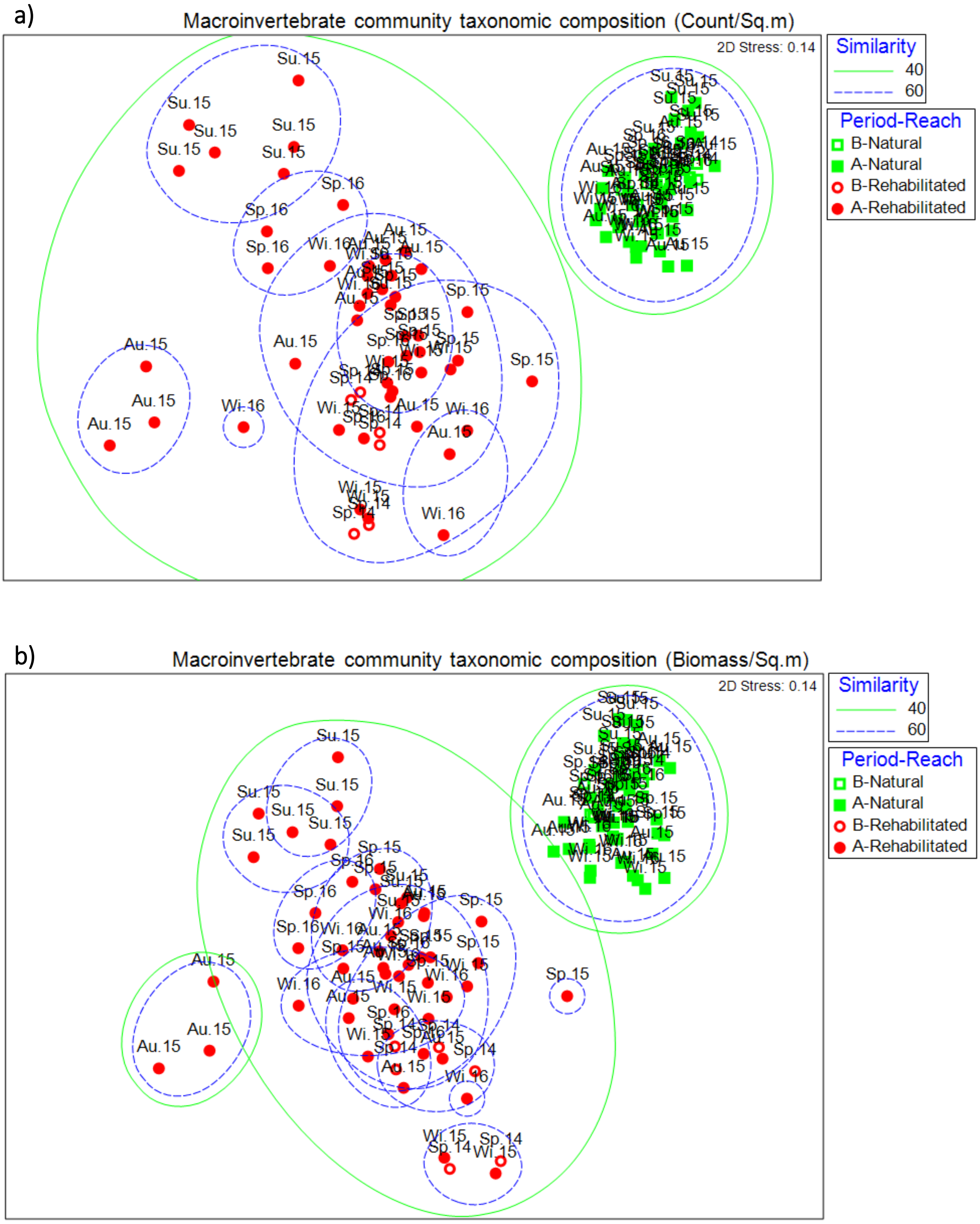


Figure 3.19. nMDS ordination plots, based on the 4th root transformed Bray-Curtis similarities of macroinvertebrate taxonomic composition, a) Counts m^{-2}; b) Biomasses m^{-2}. Clusters at 40% and 60% of similarity. Seasonal data collected before the rehabilitation process in spring 2014, then over six successive seasons after the rehabilitation process. B, before rehabilitation; A, after rehabilitation

The rehabilitation process decreased average dissimilarity in macroinvertebrate community taxonomic composition (Count m^{-2}) between the two reaches. Similarity percentages (SIMPER) analyses on the 4th root transformed data indicated that average dissimilarity between both reaches before the LWM installation process (Sp.14) was 65.42, Thirty three of the 72 observed macroinvertebrate taxa contributed up to 70% of the variability between them (Appendix 3.9). After the LWM installation, the average dissimilarity between the two reaches was decreased in Sp.15 to become 54.63. In Sp.15, Thirty four of the 78 observed taxa contributed to 70% of the variability between the two reaches (Appendix 3.9). In Sp.16, however, average dissimilarity was increased to become 62.22, and thirty four of the 77 observed taxa contributed to 70% of the between reaches variation (Appendix 3.9). Decreases in average dissimilarity between both reaches in Sp.15 are visualised in Figure 3.20. It shows that, although the differences between both reaches in community taxonomic composition were significant, the rehabilitated reach macroinvertebrate community composition was enhanced during first post-rehabilitation spring and moved toward the goal state of the rehabilitation which was the natural reach. Macroinvertebrate taxa that contributed to the between and/or within reaches dissimilarities are visualised in a shade plot (Figure 3.21), darker colours indicate higher density. List of recorded macroinvertebrate taxa is available in presence/absence form in Appendix 3.20

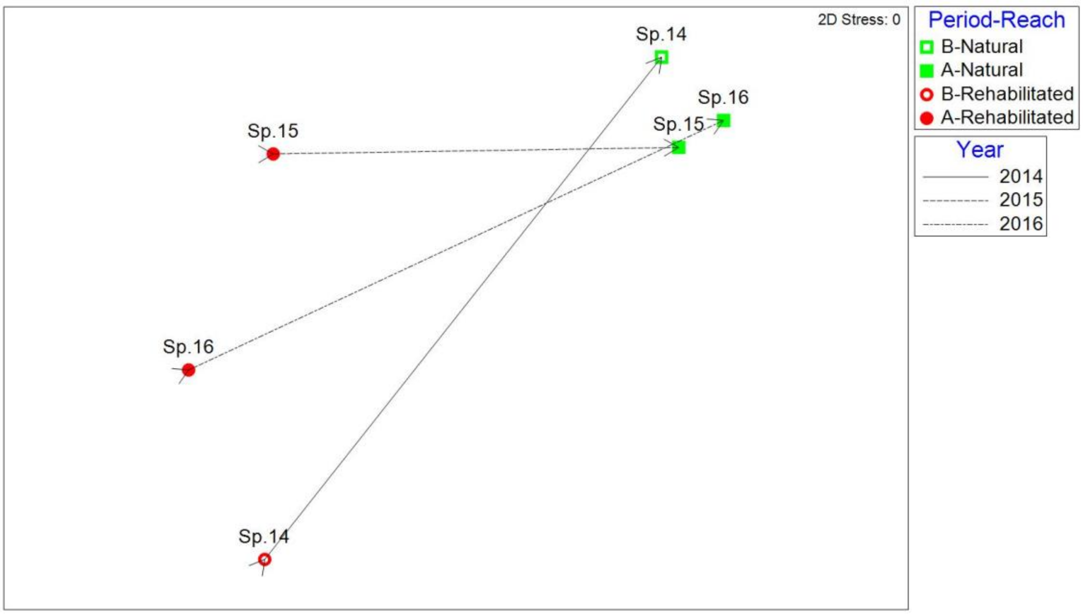


Figure 3.20. nMDS ordination plot of macroinvertebrate taxonomic composition (Count m^{-2}) showing that dissimilarity between the natural and rehabilitated reach decreased after LWM installation in spring 2015. Sp.14, spring 2014; Sp.15, spring 2015; Sp.16, Spring 2016

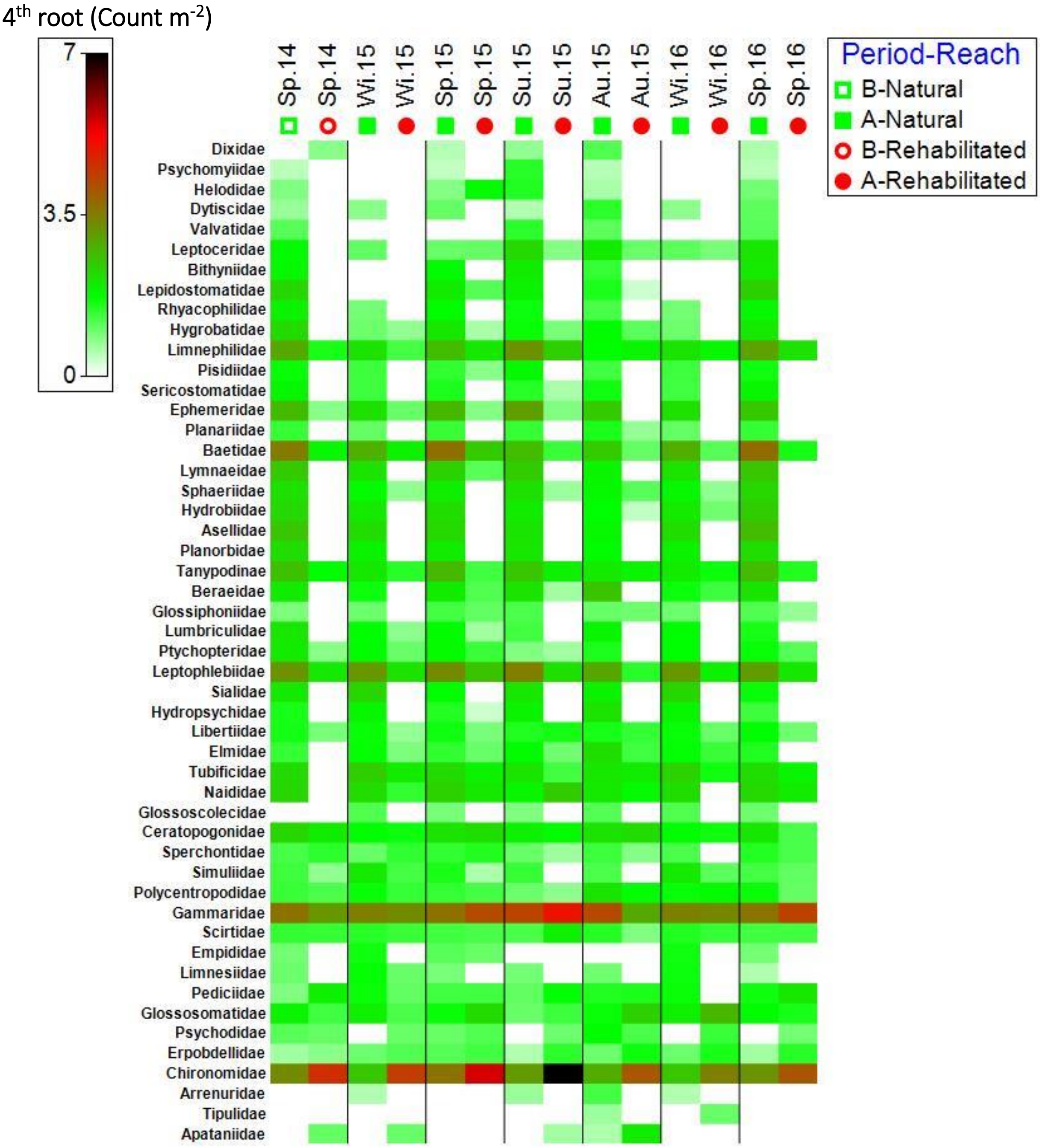


Figure 3.21. Shade plot of macroinvertebrate community taxonomic composition data matrix, showing families contribution to seasonal dissimilarities between the natural and rehabilitated reach. The depth of colour shading is linearly proportional to a 4th root transformation of the Count m^{-2}, darker colours indicate higher density. B, before the rehabilitation; A, after the rehabilitation.

Before the LWM installation, Chironomidae (non-Tanypodinae) average density contributed 26% of the dissimilarity between both reaches. They were dominant family in the degraded reach (402 individual m^{-2}) but less so in the natural reach (110 individual m^{-2}). Baetidae average density contributed 12% of the dissimilarity, with higher average density (141 individual m^{-2}) in the natural reach than the degraded reach (9 individual m^{-2}). Leptophlebiidae, Gammaridae, and Ephemeridae average densities together contributed 23% of between reaches dissimilarities. They had a high average density in the natural reach and low density in the degraded reach (Appendix 3.10). Families' average densities and dissimilarities were calculated using SIMPER analyses on non-transformed Family (Count m^{-2}).

After rehabilitation, Chironomidae (non-Tanypodinae) and Gammaridae average densities responded to the morphological changes significantly (P<0.05) (Appendix 3.12). They contributed more than 70% of the before-after changes in macroinvertebrate community composition of the rehabilitated reach (Table 3.6). In Sp.15, Chironomidae (non-Tanypodinae) average density doubled (relative to Sp.14) in the rehabilitated reach to become 820 individual m^{-2}, and contributed 54% of the pre-post rehabilitation changes (Table 3.6). Gammaridae average density tripled in Sp.15 to become 274 individual m^{-2}, while it was 89 individual m^{-2} in Sp.14. It contributed 24% of the pre-/post-rehabilitation changes. In Au.15, their average density was declined significantly. Gammaridae average density started to increase again in Wi.16, and Sp.16, but Chironomidae average density was declined significantly (P=0.0166) in Sp.16 compared with Sp.15 to become 245 individual m^{-2} (Table 3.6; Appendix 3.12).

Depending on macroinvertebrate families' biomass, before the LWM installation, the natural reach had higher biomass than the degraded reach (Appendix 3.11). The caddisfly family Limnephilidae average biomass contributed to 25% of between reaches dissimilarities, it was 259 mgDM m^{-2} in the natural reach, but only 12 mgDM m^{-2} in the degraded reach. Lymnaeidae contributed 16% of dissimilarities; it was 146 mgDM m^{-2} by 0 mgDM m^{-2} and. Baetidae contributed 8% of dissimilarities; it was 77 mgDM m^{-2} by 4 mgDM m^{-2}. Planorbidae contributed 6% of dissimilarities, it was 50 mgDM m^{-2} by 0 mgDM m^{-2}. Gammaridae contributed 6% of between reach dissimilarities; it was 101 mgDM m^{-2} by 57 mgDM m^{-2}.

After LWM installation, Gammaridae, Limnephilidae, Chironomidae (non-Tanypodinae), and Erpobdellidae average biomasses responded significantly (*P*<0.05) to the morphological changes (Table 3.7; Appendix 3.12). In Sp.15, Gammaridae average biomass increased to 218 mgDM m^{-2}, while it was 57 mgDM m^{-2} in Sp.14, and contributed in 34% of pre-/post-rehabilitation changes in community biomass (Table 3.7). Limnephilidae average biomass increased from 12 mgDM m^{-2} to 82 mgDM m^{-2} to contribute in 18% of changes. Chironomidae (non-Tanypodinae) increased from 21 mgDM m^{-2} to 93 mgDM m^{-2} and contributed in 16% of changes. Erpobdellidae average biomass increased from 7 mgDM m^{-2} to 48 mgDM m^{-2} and contributed in 10% of changes. Increasing average biomass was continued till Su.15, then was declined in Au.15. Limnephilidae and Gammaridae average biomass started to increase again in WI.16 and Sp.16, but Chironomids (non-Tanypodinae) average biomass was declined significantly (*P*=0.0169) to become 10 mgDM m^{-2} in Sp.16 compared with Sp.15 (Appendix 3.12). Family's average biomass and dissimilarities were calculated using SIMPER analyses on non-transformed Family (mg DM m^{-2}).

Table 3.6. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Count m^{-2}) data (at family-level), identifying those families most affected by morphological changes and contributing at least 70% of the temporal dissimilarity in community composition of the rehabilitated reach. Average abundances presented in Individuals m^{-2}. * indicates a significant change (P<0.05).

Spring 2014 vs Spring 2015				
Average dissimilarity = 49.42				
	Average Abundance			
Family	Sp.14	Sp.15	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	402	820*	53.71	53.71
Gammaridae	89	274***	23.68	77.39
Winter 2015 vs Winter 2016				
Average dissimilarity = 45.56				
	Average Abundance			
Family	Wi.15	Wi.16	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	340.31	129.61**	53.89	53.89
Gammaridae	106.53	117.23	10.97	64.85
Glossosomatidae	2.15	49	10.86	75.71
Spring 2014 vs Spring 2016				
Average dissimilarity = 42.17	Average Abundance			
Family	Sp.14	Sp.16	Contribution%	Cumulative%
Gammaridae	89	311**	42.94	42.94
Chironomidae (non- Tanypodinae)	401	245*	32.71	75.65
Spring 2015 vs Spring 2016				
Average dissimilarity = 37.96	Average Abundance			
Family	Sp.15	Sp.16	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	820	245*	59.97	59.97
Gammaridae	274.05	311.27	11.30	71.27

*P<0.05; **P<0.005; ***P<0.0005

Table 3.7. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Biomass m^{-2}) data (at family-level), identifying most affected families by morphological changes and contributing at least 70% of the temporal dissimilarity in community composition of the rehabilitated reach. Average biomass presented in mgDM m^{-2}. * indicates a significant change (P<0.05).

Family	Average Biomass		Contribution%	Cumulative%
Spring 2014 vs Spring 2015				
Average dissimilarity = 69.79				
Family	Sp.14	Sp.15	Contribution%	Cumulative%
Gammaridae	57	218**	34.28	34.28
Limnephilidae	12	82*	17.95	52.22
Chironomidae (non-Tanypodinae)	21	93*	15.72	67.94
Erpobdellidae	7	48*	10.00	77.94
Winter 2015 vs Winter 2016				
Average dissimilarity = 52.31				
Family	Wi.15	Wi.16	Contribution%	Cumulative%
Limnephilidae	15.13	83.31**	28.82	28.82
Gammaridae	57.87	108.37	26.44	55.26
Erpobdellidae	25.58	46.26	21.07	76.33
Spring 2014 vs Spring 2016				
Average dissimilarity = 63.42				
Family	Sp.14	Sp.16	Contribution%	Cumulative%
Gammaridae	57	194**	42.51	42.51
Erpobdellidae	7	73.35*	22.62	65.14
Limnephilidae	12	78.44*	21.79	86.93
Spring 2015 vs Spring 2016				
Average dissimilarity = 44.35				
Family	Sp.15	Sp.16	Contribution%	Cumulative%
Gammaridae	218	194	23.69	23.69
Chironomidae (non-Tanypodinae)	93	10*	17.82	41.51
Erpobdellidae	48	73.35	17.18	58.69
Limnephilidae	82	78.44	16.71	75.40

*P<0.05; **P<0.005; ***P<0.0005

3.4.5. Macroinvertebrate FFGs abandance and biomass

Before LWM installation, in spring 2014, both reaches was similar to each other only according to the average abundance of their filter-feeders (*P*>0.05) (Appendix 3.13). Shredders, scrapers, predators, and deposit-feeders feeding groups were more abundant in the natural reach than the degraded reach, while the parasite feeding group was more abundant in the degraded reach than the natural reach. Absorbers and piercers were totally absent from the degraded reach (Figure 3.22). Shredders were the most dominant group in the natural reach (410 individual m^{-2}) but less so in the degraded reach (118 individual m^{-2}). Scrapers had a higher average abundance (238 individual m^{-2}) in the natural reach than the degraded reach (178 individual m^{-2}). Predators had a higher average abundance (139 individual m^{-2}) in the natural reach than the degraded reach (49 individual m^{-2}). The parasite feeding group average abundance was higher in the degraded (57.7 individual m^{-2}) reach than the natural reach (13.9 individual m^{-2}) (Table 3.8).

After LWM installation, in spring 2015, rehabilitated reach's shredders, deposit-feeders, scrapers, and filter-feeders average abundance were increased significantly (*P*<0.05) (Table 3.8; Appendix 3.14). Shredders average abundance was increased about 4 times to become 409 individual m^{-2}. This change contributed more than 38.12% of the pre-/post-rehabilitation difference in macroinvertebrate FFG structure of the rehabilitated reach. Deposit-feeder average abundance tripled to become 266 individual/m^2. This difference contributed 17% of the pre-/post-rehabilitation differences. Filter-feeder average abundance was doubled to 160 individual m^{-2}. This increase contributed 13% of the differences. Scraper average abundance increased from 178 to 261 individual m^{-2} and contributed 14% of the overall differences. In the second post-installation spring (Sp.16), shredders, deposit-feeders, and filter-feeders average abundances were declined significantly (*P*<0.05) compared with Sp.15 (Table 3.8; Appendix 3.14) and reflected the loss of channel morphological enhancements. Most affected FFGs average abundance and pre-/post-rehabilitation dissimilarities in feeding groups structure were calculated using SIMPER analyses on non-transformed FFGs (Count m^{-2}).

The changes in FFGs average abundances caused the rehabilitated reach to become more similar to the natural reach in Sp.15, driven primarily by changes in shredders, deposit-feeders, scrapers, and the filter-feeders groups. In autumn 2015, filter-feeder, and deposit-feeder average abundances were similar between both reaches. In Sp.16, rehabilitated reach was remained similar to the natural reach according to shredders and filter-feeders average abundance. Although the rehabilitated reach average abundance of parasites feeding group was decreased significantly in Sp.16 compared with Sp.14, rehabilitated reach parasite group was remained higher than the natural reach (Table 3.10; Appendix 3.13).

Table 3.8. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate FFGs composition (Count m^{-2}), identifying feeding groups were most affected by the addition of LWM and contributing at least 70% of the temporal dissimilarity in community composition of the rehabilitated reach. Average abundances presented in Individual m^{-2}. * indicates a significant change (P<0.05).

Spring 2014 vs Spring 2015				
Average dissimilarity = 38.25				
	Average Abundance			
Feeding group	Sp.14	Sp.15	Contribution%	Cumulative%
Shredder	118	409***	38.12	38.12
Deposit-feeder	95.5	266*	17.42	55.54
Scraper	178	261*	14.11	69.66
Filter-feeder	72.6	160*	13.24	82.90
Spring 2014 vs Spring 2016				
Average dissimilarity = 26.39				
	Average Abundance			
Feeding group	Sp.14	Sp.16	Contribution%	Cumulative%
Shredder	118	284.6**	51.37	51.37
Scraper	178	181	15.31	66.68
Filter-feeder	72.6	45.4	9.06	75.74
Spring 2015 vs Spring 2016				
Average dissimilarity = 28.98				
	Average Abundance			
Feeding group	Sp.15	Sp.16	Contribution%	Cumulative%
Shredder	409	284.6*	24.49	24.49
Deposit-feeder	266	74.8*	23.62	48.11
Scraper	261	181	16.90	65.01
Filter-feeder	160	45.4*	15.20	80.21
Winter 2015 vs Winter 2016				
Average dissimilarity = 33.07				
	Average Abundance			
Feeding group	Wi.15	Wi.16	Contribution%	Cumulative%
Scraper	160.6	68.4**	31.47	31.47
Shredder	126.5	172.9	19.25	50.72
Deposit-feeder	96.1	48.1*	17.30	68.02
Filter-feeder	63.9	29.1**	12.28	80.30

*P<0.05; **P<0.005; ***P<0.0005

Regarding FFGs average biomass, in Sp.14, both reaches was differed significantly from each other according to all recorded feeding groups average biomass (Appendix 3.15). Average biomass of all FFGs was higher in the natural reach than the degraded reach (Figure 3.22; Table 3.10). Shredder, scraper, and predator average biomass all responded significantly (P<0.05) to the LWM installation (Table 3.9). In Sp.15, shredders average biomass was increased to 283 mgDM m^{-2}, while it was 60 mgDM m^{-2}. It contributed 54% of the pre-/post-rehabilitation differences in feeding groups biomass. Scraper average biomass was increased to 101 mgDM m^{-2}, while it was 27 mgDM m^{-2}, and contribute 17% of differences. Predator average biomass was increased from 17 mgDM m^{-2} to 63 mgDM m^{-2}. Rehabilitated reach become similar to the natural reach according to deposit-feeder, piercer, and predator average biomass. Predator biomass continued to increase until summer 2015. In autumn 2015 predator biomass was declined significantly, then increased again in following winter and spring seasons. In Sp.16, scraper, deposit-feeder, and parasite average biomasses were decreased significantly. In contrast, predator average biomass was remained higher than before rehabilitation significantly (P<0.05) (Table 3.9; Appendix 3.16) due to a significant increase of Erpobdellidae biomass (Appendix 3.12). Reaches was similar according to predator and parasite average biomass in Sp.16. Most affected FFGs average biomass and pre-/post-rehabilitation dissimilarities in the feeding groups' structure were calculated using SIMPER analyses on non-transformed FFGs (Biomass m^{-2}) (Appendix 3.16).

In Sp.15, Rehabilitated reach was more similar to the natural reach in according to feeding groups average abundance than average biomass. Rehabilitated reach had a higher average abundance of shredder, scraper, and filter-feeder groups. In contrast, their average biomass was less than those of the natural reach (Figure 3.22; Table 3.9; Table 3.10). Rehabilitated reach shredders average biomass mainly came from *Gammarus pulex*, while natural reach shredders biomass came from Limnephilidae and Lymnaeidae which are larger species. Rehabilitated reach scraper biomass was mostly from Chironomids which are smaller species than other scrapers were recorded in the natural reach (e.g. gastropods, coleopterans, and Ephemeropterans) which accounted for much of the biomass. Filter-feeders average biomass was very small in the rehabilitated reach compared with that of the natural reach. This less biomass made up of chironomid species, while natural reach filter-feeder biomass mostly came from larger species such as gastropods, Bivalvia, and hydropsychids (Trichoptera), which accounted for much of the biomass. Predators had a higher average abundance in the natural reach than in the rehabilitated reach, but their average biomass was similar in both reaches. Natural reach predators biomass mostly came from water spiders (Arachnids) which were smaller than Chironomids (Tanypodinae) and Hirudinea. Rehabilitated reach predator biomass was mainly came from Chironomids (Tanypodinae) and Hirudinea (Erpobdellidae), which are larger than Arachnids.

Table 3.9. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate FFG composition (Biomass m^{-2}) data, identifying feeding groups most affected by the morphological change and contributing at least70% of the temporal dissimilarity in community composition of the rehabilitated reach. Average biomass presented in mgDM m^{-2}. * Indicates a significant change (P<0.05).

Spring 2014 vs Spring 2015				
Average dissimilarity = 63.79				
	Average Biomass			
Feeding group	Sp.14	Sp.15	Contribution%	Cumulative%
Shredder	60	283***	54.18	54.18
Scraper	27	101***	17.36	71.54
Spring 2014 vs Spring 2016				
Average dissimilarity = 54.67				
	Average Biomass			
Feeding group	Sp.14	Sp.15	Contribution%	Cumulative%
Shredder	60	224**	59.07	59.07
Predator	17	79*	25.55	84.61
Spring 2015 vs Spring 2016				
Average dissimilarity = 32.22				
	Average Biomass			
Feeding group	Sp.15	Sp.16	Contribution%	Cumulative%
Shredder	283	224	35.04	35.04
Predator	63	79	24.54	59.58
Scraper	101	57*	15.57	75.15
Winter 2015 vs Winter 2016				
Average dissimilarity = 44.54				
	Average Biomass			
Feeding group	Wi.15	Wi.16	Contribution%	Cumulative%
Shredder	64	165**	55.06	55.06
Predator	32.7	62.8	27.63	82.69

*P<0.05; **P<0.005; ***P<0.0005

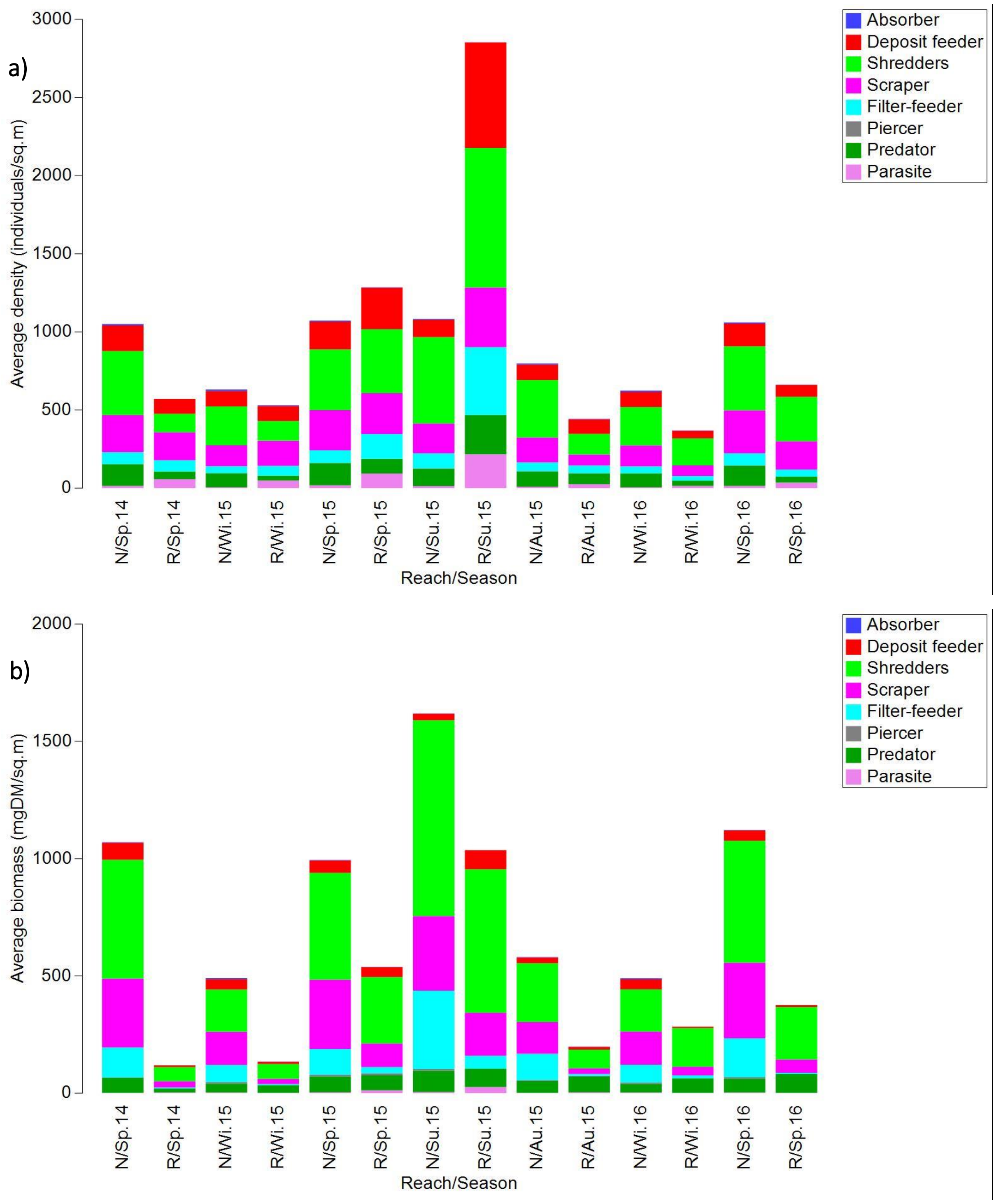


Figure 3.22. Macroinvertebrate functional feeding groups' structure based on a) average abundance (individualm^2), b) average biomass (mgDM m^{-2}). N, Natural reach; R, Rehabilitated reach.

Table 3.10. Average abundance and ±SD of functional feeding groups based on the number of individual/m^2. N, Natural reach; R, Rehabilitated reach. The grey shading means reaches become similar in the given metrics during the given season.

	Status	Before LWM installation		After LWM installation											
	Year	2014		2015								2016			
	Season	Spring		Winter		Spring		Summer		Autumn		Winter		Spring	
FFGs	Reach	N	R	N	R	N	R	N	R	N	R	N	R	N	R
Absorber		9.3 ±5.3	0.0 ±0	9.6 ±4.6	3.6 5.7	7.7 ±3.8	2.8 ±3.3	4.9 ±3.1	0.6 ±0.3	6.9 ±4	3.4 ±26	9 ±3.2	1.5 ±1.7	6.5 ±3.5	2.6 ±3
Deposit-feeder		163 ±17.2	95.5 ±19.1	98.7 ±10.7	96.1 ±20.9	177.8 ±49.2	266 ±256	110.6 ±30.2	676 ±289	99.6 ±24	92.9 ±67	96.3 ±9.7	48.1 ±27.7	145.8 ±30.7	74.8 ±13
Shredder		410 ±57	118 ±23.8	249 ±38.8	126.5 ±39.6	388.2 ±66.5	409 ±200	553.4 ±90.5	893 ±472	367.3 ±73	132.6 ±74.8	246.1 ±36.5	172.9 ±32.3	410 ±122.5	284.6 ±58
Scraper		237.6 ±25	178 ±51	133.3 ±25.6	160.6 ±36.9	257.2 ±45	261 ±119	190 ±54.9	381.7 ±175	159.3 ±30.7	70.3 ±45.3	133.1 ±27.3	68.4 ±16.7	274.4 ±44	181 ±44.3
Filter-feeder		76.6 ±24	72.6 ±17.8	44.7 ±6.7	63.9 ±17	79.8 ±31	160 ±175	96.9 ±17	434 ±201	56.6 ±23.5	49.9 ±47.2	45.5 ±7.9	29.1 ±16.4	77.4 ±32.3	45.4 ±16.9
Piercer		0.5 ±0.4	0.0 ±0	0.8 ±1.6	0.0 ±0	2.3 ±4.7	1.0 ±1.6	1.4 ±1	0.0 ±0	2.8 ±2.2	0.9 ±1.2	0.8 ±1.6	0.4 ±1.1	1.9 ±2.5	0.2 ±0.4
Predator		138.9 ±28.4	48.8 ±26.6	90.4 ±70.5	30.6 ±12.2	140.9 ±42.3	92.8 ±95.9	111.7 ±32.1	250.9 ±98.1	96.4 ±23.6	68.6 ±32.4	88.8 ±67.3	33.6 ±21.3	130 ±44.8	37.6 ±24.8
Parasite		13.9 ±4	57.7 17.1	4.8 ±1.8	48.3 ±12.5	18.6 ±10.7	93.2 ±91.1	13.2 ±4.1	217.2 ±100	9.2 ±2.6	25.5 ±24	4.8 ±1.7	14.1 ±9.4	13.7 ±3.9	35.4 ±15.5

Table 3.11. Average biomass and ±SD of functional feeding groups (FFGs) based on mgDM m^{-2}. N, Natural reach; R, Rehabilitated reach. The grey shading mean reaches become similar in the given metrics during the given season.

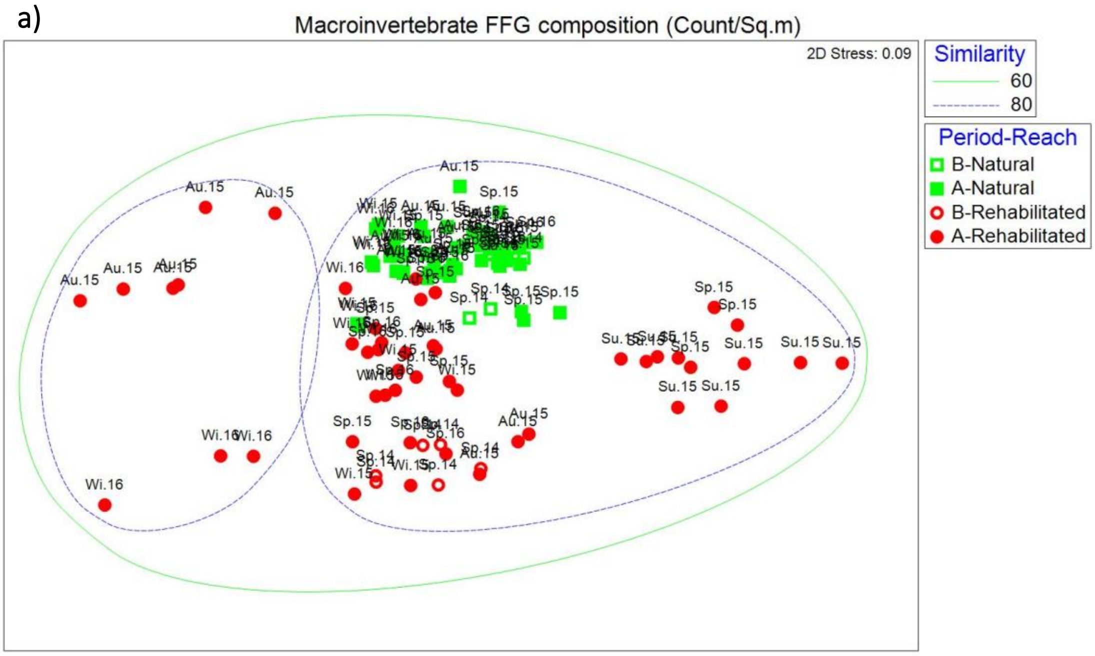
	Status	Before LWM installation		After LWM installation											
	Year	2014		2015								2016			
	Season	Spring		Winter		Spring		Summer		Autumn		Winter		Spring	
FFGs	Reach	N	R	N	R	N	R	N	R	N	R	N	R	N	R
Absorber		2.1 ±1.4	0.0 ±0	4.7 ±4	0.6 ±0.7	2.3 ±1.6	0.6 ±0.7	1.4 ±1.3	0.1 ±0.1	1.9 ±1.2	0.7 ±0.5	4.5 ±4.5	0.3 ±0.3	2.3 ±1.7	0.5 ±0.6
Deposit-feeder		72.7 ±38.6	7.1 ±2.2	44.1 ±22.8	8.9 ±4.9	52.5 ±13.8	43.1 ±31.8	27.4 ±6.9	81.3 ±37.6	24.5 ±9	11.9 ±11.9	42.8 ±21.7	4.9 ±2.7	44.2 ±20.6	7.9 ±6.1
Shredder		506.8 ±161	60 ±15	180 ±32	64 ±32.2	456.1 ±98.3	283 ±45.3	834.8 ±104	612.1 ±488.3	250.9 ±66	79.8 ±69.8	179.8 ±26.5	165 ±89.8	519.6 ±133	224 ±104
Scraper		293.3 ±64	27 ±10.2	141.6 ±50.8	22 ±8	295.2 ±83	101 ±28.3	317.6 ±71.8	183 ±142.3	135.1 ±84.9	24 ±18.7	141 ±51	37.1 ±20.3	323 ±132	57 ±24.4
Filter-feeder		128.4 ±122	4.7 ±1.1	73 ±59	4.6 ±3	110 ±52.3	26.9 ±28.2	335 ±108	55.5 ±25.2	112.4 ±81.7	8.2 ±6.6	75.5 ±62.3	11.7 ±10.1	165.5 ±93.2	5.1 ±4.2
Piercer		2 ±2.1	0 ±0	6.7 ±15.8	0 ±0	7.2 ±14.4	8.8 ±15.4	6.3 ±5.1	0 ±0	3.8 ±5.3	3.4 ±4.4	6.6 ±15.7	0 ±0	6.2 ±7.7	0.5 ±1.2
Predator		63.2 ±26.3	17 ±14	38 ±31.5	32.7 ±38.8	67.7 ±50.6	63 ±32.8	90.9 ±26.8	77.9 ±44.7	50.3 ±16	67.1 ±42.8	36.8 ±31	62.8 ±30.4	58.9 ±37.8	79 ±93
Parasite		1.4 ±0.6	3 ±1.7	2.4 ±5.3	1.4 ±0.5	3.4 ±4.3	12.2 ±17	5 ±3.1	26.2 ±12.8	1.5 ±1.7	3.1 ±3	2.4 ±5.2	1 ±0.5	2.7 ±2.3	1.6 ±0.4

3.4.6. Macroinvertebrate FFGs community composition

Before LWM installation, in spring 2014, macroinvertebrate FFGs composition (Count m^{-2}, and Biomass m^{-2}) was different between natural and degraded reach significantly (P<0.002) (Appendix 3.17). Rehabilitated reach FFGs composition responded significantly to the morphological changes (Appendix 3.18). FFGs composition (Count m^{-2}) difference was significant when comparing Sp.15 with Sp.14 (P=0.0093), Sp.16 with Sp.14 (P=0.0023), and Wi.16 with Wi.15 (P=0.0165). But, rehabilitated reach became similar to the natural reach based on FFGs composition (Count m^{-2}) only in Sp.15 (P>0.05) (Appendix 3.17). Clear tendency of the rehabilitated reach functional community to become more similar to the natural reach showed in the nMDS ordination plots (Figure 3.23).

The rehabilitated reach's FFGs composition based on Biomass m^{-2} responded to the morphological changes in the same way. Sp.15, and Sp.16 data differed significantly from Sp.14 (P=0.0003, and 0.0026 respectively), Wi.16 compositional differed significantly from Wi.15 (P=0.0423) (Appendix 3.18). Nevertheless, the post-rehabilitation changes were not enough to make the rehabilitated reach to become similar to the natural reach (Appendix 3.17).

a)



b)

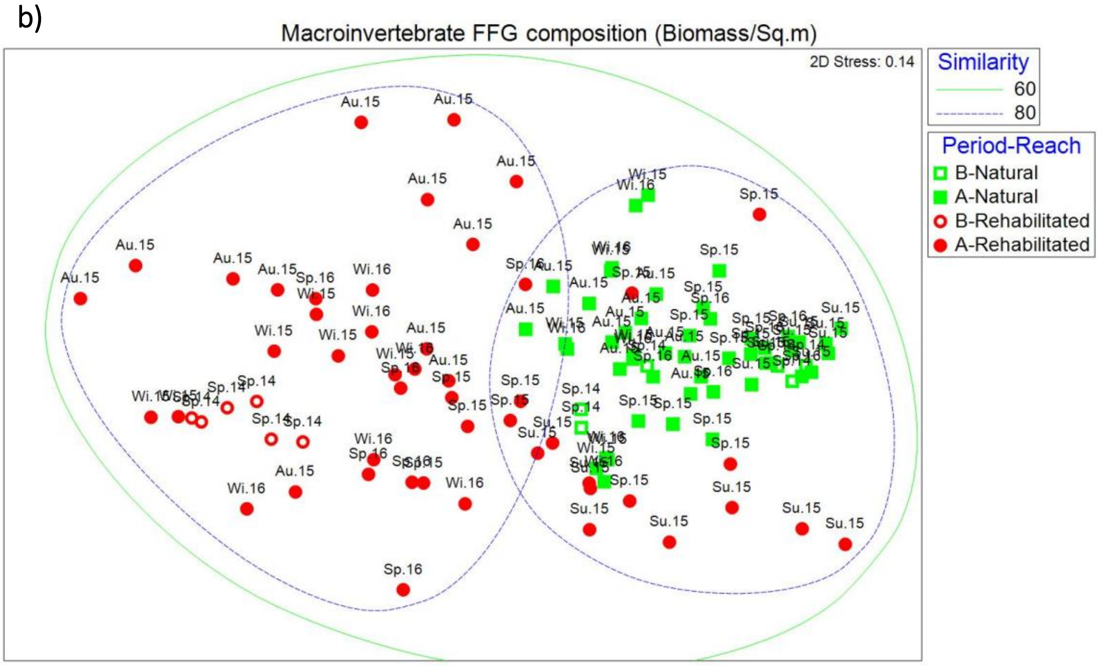


Figure 3.23. nMDS plot, based on the 4th root transformed Bray-Curtis similarities of FFGs composition showing separation of both reaches. a) Based on FFGs Count m^{-2}, b) Based on FFGs Biomass m^{-2}. Clusters at 60% and 80% of similarity. B, Before the LWM installation; A, After LWM installation.

In Sp.14, average dissimilarity in FFGs composition (Count m^{-2}) between reaches was 15.16. Absorbers contributed to 27% of dissimilarities, followed by shredders (20%), predators (14%), and parasites (13%). After the LWM installation, the average dissimilarity between reaches was decreased to 11.35 in Sp.15, and 12.42 in Sp.16. Decreases in average dissimilarity between reaches were visualised in Figure 3.24. In Sp.15, between reach dissimilarities were not dominated by one or two groups. 72% of between reach dissimilarities were based on relatively uniform contributions of predator, parasite, filter-feeder, deposit-feeder, and piercer groups. In Sp.16, predator contribution in between reaches dissimilarities was increased comparing with Sp.15, from 16% to 20%, and piercer from 13% to 17%. Although between reach dissimilarity in functional composition remained significant across periods (reaches become similar only in Sp.15), there was trend towards the goal state of the rehabilitation which was the natural reach. Between reach dissimilarity assessed using Similarity percentages (SIMPER) analysis on 4th root transformed FFGs composition (Count m^{-2}) (Appendix 3.19). FFGs contribution to between and/or within reaches dissimilarities is visualised in Figure 3.25, darker colour indicates higher abundance feeding group.

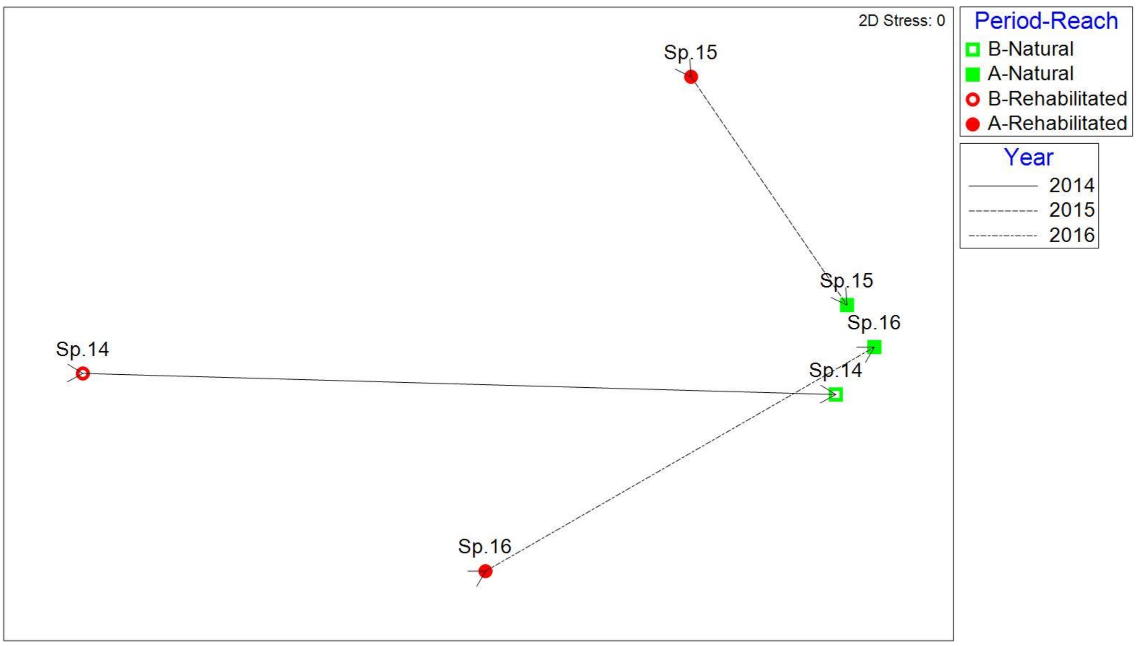


Figure 3.24. nMDS ordination plot of macroinvertebrate FFG composition (Count m^{-2}) showing that dissimilarity between both reaches has decreased after LWM installation process. Sp, spring; 14, 2014; 15, 2015; 16, 2016.

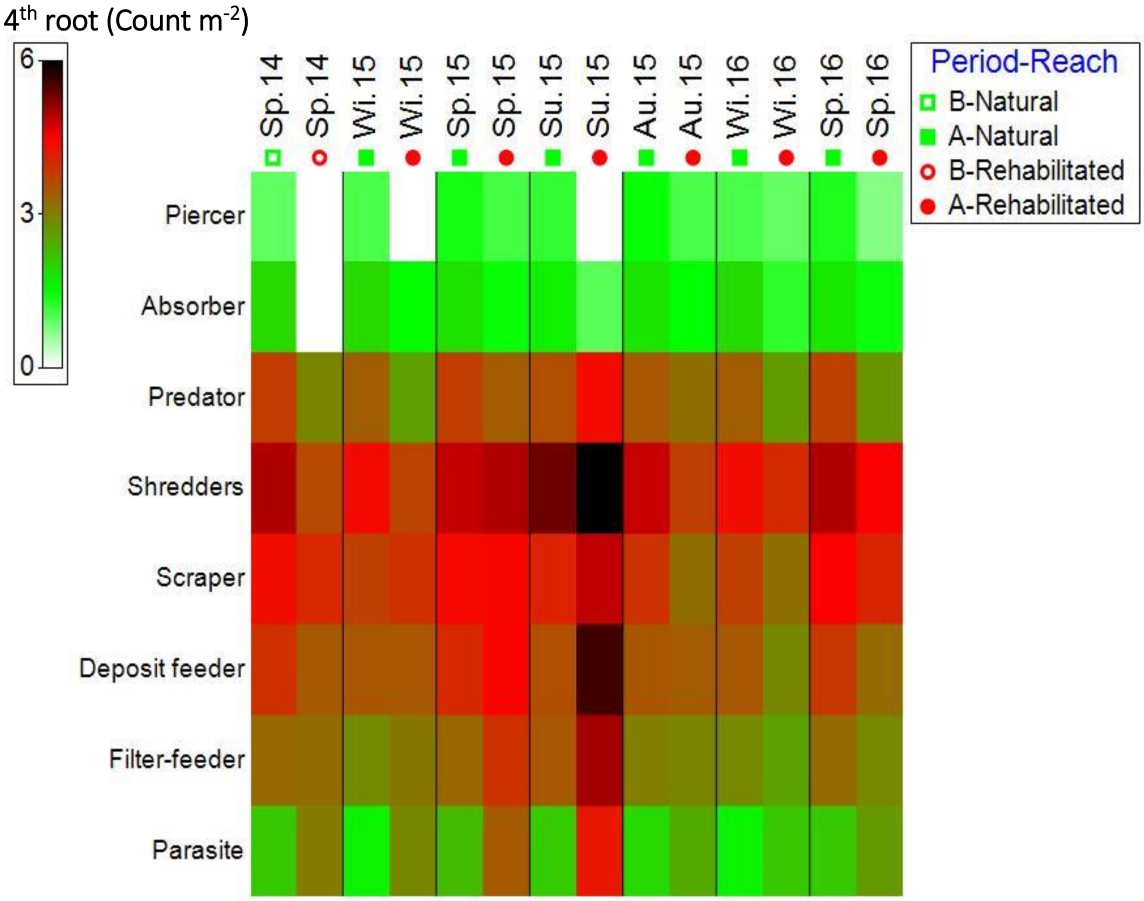


Figure 3.25. Shade plot of macroinvertebrate community Functional Feeding Groups (FFGs) composition data matrix, showing feeding groups contribution to seasonal dissimilarities between the natural and rehabilitated reach. Depth of colour shading is linearly proportional to a 4^{th} root transformation of the Count m^{-2}, darker colours indicate higher density. B, before the rehabilitation; A, after the rehabilitation.

3.4.7. Relationships between morphological variables and macroinvertebrate community structure, diversities and composition

Distance-based linear modelling (DISTLM) analysis was performed on macroinvertebrate structural and functional univariate metrics that responded significantly to the rehabilitation process. Sequential tests gave different combinations of morphological variables in the best-fit models for each macroinvertebrate metrics according to pre-/post-rehabilitation springs (Sp.14:Sp.15, & Sp.14:Sp.16), and first/second post-rehabilitation springs (Sp.15:Sp.16). In some cases, certain morphological variables improved the Akaike Information Criterion (AIC) in the model development, but their contributions to the model were not statistically significant. Therefore I chose to accept only those models that included the significant morphological variables.

Macroinvertebrate Total Density and Total Biomass were related positively to temporal variations in Leaf litter% ($\rho > 0.75$; Table 3.12). SWI_biotope, CV_width and Gravel% were also related positively to temporal variations in macroinvertebrates total density, but in a weak correlations (ρ = 0.10, 0.09, 0.08 respectively). Taxa Richness had a positive correlation with Gravels%, SWI_biotope, and Number of biotopes. Chironomidae Count% had a negative relationship with Number of biotopes ($\rho = 0.73$). Chironomidae Biomass% had a negative relationship with Gravels% ($\rho = 0.92$).

Temporal variations in macroinvertebrate FFGs abundance and biomass were explained mainly by post-rehabilitation changes in in-stream biotope percentages than measured channel morphological parameters (Table 3.13; Table 3.14). Temporal variation in Leaf litter% was related positively to Deposit-feeder ($\rho > 0.91$), Shredder ($\rho > 0.75$), and Filter-feeder ($\rho > 0.84$) abundance. They also had a positive relationship with Cobbles%, and SWI_biotope, but less strong relation. Temporal variation in Scraper abundance was related positively with Wet surface area ($\rho = 0.63$).

Temporal variation in Leaf litter% was also related positively to Absorber ($\rho = 0.42$), Deposit-feeder ($\rho > 0.81$), Shredder ($\rho > 0.67$), Scraper ($\rho > 0.47$), and Predator ($\rho = 0.57$) biomass. Temporal variations in Absorber abundance and biomass were related positively with Cobbles% ($\rho > 0.42$). Temporal variation in Parasite abundance was related negatively to variations in Gravels% ($\rho = 0.40$), while its biomass was related positively to variations in CV_width ($\rho = 0.72$).

Temporal variation in macroinvertebrate community taxonomic composition based on abundance of taxa were related to variations in Wet surface area and Leaf litter% (ρ = 0.61), while variations in taxonomic composition based on taxa biomass were related to variations in CV_depth and Leaf litter% (ρ = 0.59) (Table 3.15). Temporal variations in macroinvertebrates FFGs composition (Count/m^2, & Biomass/m^2) was best predicted by temporal variations in Wet surface area and Gravels% (ρ = 73), and Leaf litter% (ρ = 0.83) respectively.

Table 3.12. Summary of sequential tests, obtained from distance-based linear models (DISTLM), seeking relationships between temporal variations in macroinvertebrate univariate metrics and channel morphological variables. Values displayed indicate the proportion of variability explained by each channel morphological variables, and the cumulative of variability explained by the models. * indicates values significant at P <0.05. +/- indicate additions to or subtractions from the model. Correlations were obtained using Spearman's rank correlation (ρ), +/- indicate positive or negative correlations.

Macroinvertebrate community data	Morphological variables	Proportion	Cumulative	Relationship
Total Density				
Sp.14:Sp.15	+Leaf litter%	0.76867*	0.76867	+
	+CV_width	0.08079*	0.84946	+
	+Gravels%	0.09022*	0.93968	+
Sp.14:Sp.16	+Leaf litter%	0.0906	0.0906	+
Sp.15:Sp.16	+Leaf litter%	0.82764*	0.82764	+
	+SWI_biotope	0.10702*	0.93466	+
Total Biomass				
Sp.14:Sp.15	+Leaf litter%	0.9170*	0.9170	+
	+CV_width	0.0338	0.9508	+
Sp.14:Sp.16	+Leaf litter%	0.8558*	0.8558	+
Sp.15:Sp.16	+Leaf litter%	0.7525*	0.7525	+
Taxa Richness				
Sp.14:Sp.15	+Gravels%	0.6555*	0.6555	+
	+Number of biotopes	0.2251*	0.8706	+
	+Silt%	0.0831	0.9537	-
Sp.14:Sp.16	+SWI_biotope	0.0830	0.0830	+
Sp.15:Sp.16	+SWI_biotope	0.4509*	0.4509	+
Chironomidae Count%				
Sp.14:Sp.15	+Cobbles%	0.09191	0.09191	-
	+Wet surface area	0.07272	0.16463	-
	+CV_depth	0.07216	0.2368	-
Sp.14:Sp.16	+Number of biotopes	0.7330*	0.7330	-
Sp.15:Sp.16	+Leaf litter%	0.06885	0.06885	+
Chironomidae Biomass%%				
Sp.14:Sp.15	+Cobbles%	0.08729	0.08729	-
	+Gravels%	0.09083	0.17812	-
Sp.14:Sp.16	+Gravels%	0.9275*	0.9275	-
Sp.15:Sp.16	+Cobbles%	0.09024	0.09024	-

Table 3.13. Summary of sequential tests, obtained from distance-based linear models (DISTLM), seeking relationships between macroinvertebrate FFGs density and channel morphological variables. Values displayed indicate the proportion of variability explained by each variable, and the cumulative of variability explained by the models. * indicates values significant at P <0.05. +/- indicate additions to or subtractions from the model. Correlations were obtained using Spearman's rank correlation (ρ), +/- indicate positive or negative correlations.

FFGs density	Morphological variables	Proportion	Cumulative	Relationship
Absorber				
Sp.14:Sp.15	+Cobbles%	0.5836*	0.5836	+
Sp.14:Sp.16	+Number of biotopes	0.4205	0.4205	+
Sp.15:Sp.16	+Cobbles%	0.2388	0.2388	+
Deposit-feeder				
Sp.14:Sp.15	+Leaf litter%	0.9780*	0.9780	+
Sp.14:Sp.16	+Wet surface area	0.0506	0.0506	+
Sp.15:Sp.16	+Leaf litter%	0.9106*	0.9106	+
	+SWI_biotope	0.0723*	0.9829	+
Shredder				
Sp.14:Sp.15	+Leaf litter%	0.8796*	0.8796	+
	+Cobbles%	0.0868*	0.9664	+
Sp.14:Sp.16	+Leaf litter%	0.8393*	0.8393	+
	+Number of biotopes	0.0731	0.9124	+
Sp.15:Sp.16	+Leaf litter%	0.7569*	0.7569	+
	+SWI_biotope	0.1181*	0.8750	+
Scraper				
Sp.14:Sp.15	+Wet surface area	0.6381*	0.6381	+
Sp.14:Sp.16	+CV_width	0.0047	0.0047	
	-CV_width	0.0047	0	
Sp.15:Sp.16	+Boulders%	0.0155	0.0155	+
Filter-feeder				
Sp.14:Sp.15	+Cobbles%	0.5610*	0.5610	-
	+Wet surface area	0.0599	0.6209	-
	+ Leaf litter%	0.0524	0.6733	+
Sp.14:Sp.16	+Gravels%	0.1821	0.1821	-
Sp.15:Sp.16	+Leaf litter%	0.8457*	0.8457	+
	+SWI_biotope	0.1236*	0.9693	+
Parasite				
Sp.14:Sp.15	+Cobbles%	0.3522	0.3522	-
	+Leaf litter%	0.5499	0.9021	+
	+Silt%	0.0285	0.9306	-
	-Cobbles%	0.0157	0.9149	-
Sp.14:Sp.16	+Gravels%	0.4072*	0.4072	-
Sp.15:Sp.16	+Gravels%	0.0542	0.0542	+

Table 3.14. Summary of sequential tests, obtained from distance-based linear models (DISTLM), seeking relationships between macroinvertebrate FFGs biomass and channel morphological variables. Values displayed indicate the proportion of variability explained by each metrics, and the cumulative of variability explained by the models. * indicates values significant at P <0.05. +/- indicate additions to or subtractions from the model. Correlations were obtained using Spearman's rank correlation (ρ), +/- indicate positive or negative correlations.

FFGs biomass	Morphological variables	Proportion	Cumulative	Relationship
Absorber				
Sp.14:Sp.15	+Cobbles%	0.5458*	0.5458	+
Sp.14:Sp.16	+Cobbles%	0.4226*	0.4226	+
Sp.15:Sp.16	+Cobbles%	0.2273	0.2273	+
Deposit-feeder				
Sp.14:Sp.15	+Leaf litter%	0.8196*	0.8196	+
Sp.14:Sp.16	+CV_width	0.0381	0.0381	
	-CV_width	0.0381	0	
Sp.15:Sp.16	+Leaf litter%	0.9179*	0.9179	+
Shredder				
Sp.14:Sp.15	+Leaf litter%	0.8437*	0.8437	+
	+CV_width	0.0862	0.9299	+
Sp.14:Sp.16	+Leaf litter%	0.6725*	0.6725	+
Sp.15:Sp.16	+CV_width	0.1776	0.1776	+
Scraper				
Sp.14:Sp.15	+Leaf litter%	0.8179*	0.8179	+
	+Gravel%	0.0851*	0.9030	+
Sp.14:Sp.16	+Leaf litter%	0.4714*	0.4714	+
Sp.15:Sp.16	+Leaf litter%	0.6484*	0.6484	+
Predator				
Sp.14:Sp.15	+Leaf litter%	0.5715*	0.5715	+
Sp.14:Sp.16	+SWI_biotope	0.2113	0.2113	
	-SWI_biotope	0.2113	0	
Sp.15:Sp.16	+Cobbles%	0.0394	0.0394	
	-Cobbles%	0.0394	0	
Parasite				
Sp.14:Sp.15	+Leaf litter%	0.1555	0.1555	+
	+Silt%	0.0609	0.2164	-
Sp.14:Sp.16	CV_width	0.7238*	0.7238	+
Sp.15:Sp.16	+Leaf litter%	0.1336	0.1336	+
	+SWI-biotope	0.1308	0.2644	+

Table 3.15. Optimal BIOENV selected morphological variables with total Spearman's rank correlation coefficient (ρ) for temporal variations in macroinvertebrate community taxonomic and feeding groups composition.

Macroinvertebrate community data	Sp.14:Sp.15		Sp.14:Sp.16		Sp.15:Sp.16	
	Variables	(ρ)	Variables	(ρ)	Variables	(ρ)
Taxonomic composition (Count m^{-2})	Wet surface area Leaf litter%	(0.61)	Leaf litter% Silt% Gravels%	(0.31)	Leaf litter% Wet surface area	(0.39)
Taxonomic composition (Biomass m^{-2})	CV_depth Leaf litter%	(0.59)	SWI_biotope Gravel%	(0.22)	Leaf litter% Wet surface area	(0.43)
FFG composition (Count m^{-2})	Wet surface area Gravels%	(0.73)	SWI_biotope Silt%	(0.40)	Leaf litter% Cobbles% Wet surface area	(0.70)
FFG composition (Biomass m^{-2})	Leaf litter%	(0.83)	SWI_biotope	(0.33)	Leaf litter% Wet surface area	(0.60)

3.5. Discussion

In-stream habitat enhancement projects that rely on the installation of LWM are based on the hypothesis that changes enhancing substrate heterogeneity will result in increased biodiversity. This assumption has been questioned by many authors (see Table 2.3; Chapter 2)

The results of the present study partially support the first hypothesis and confirm that the Rolleston Brook LWM rehabilitation project was initially successful in enhancing reach-level channel morphology and in-stream biotope heterogeneity. Despite the positive changes, however, the rehabilitated reach channel morphology and in-stream biotope composition did not become similar to those of the natural reach. Installed wood pieces was successful in reducing downstream transport of leaf-litter, and were particularly important in increasing leaf-litter biotope proportion at the reach-level especially during leaf-fall in autumn. The biotic community is heavily dependent on detritus that enters the stream during the autumn season. LWM reduces the distance travelled by newly fallen dry leaves since much leaf litter is dry when it first enters a stream (Smock, Metzler & Gladden 1989). The amount of leaf-litter that enters the reach is not as important as the reach's ability to retain it within the fluvial system (Cummins *et al.* 1989).

Installed woody material was also successful in dissipating flow energy, enhancing the stability of the stream-bed through controlling the distribution of silt, the appearance of coarse biotopes for different species and increasing the in-stream biotope diversity. These results are in line with those of previous studies which found that installed LWM increased storage of organic matter and sediments, improved bed and bank stability, and enhanced appearance of new in-stream biotopes (Gregory *et al.* 1991; Maohua, Tarmi & Helenius 2002; Lester, Wright & Jones-Lennon 2007).

The modest effects of installed LWM could be explained by the facts that: (1) most of the wood pieces were installed above the low flow level, aiming to have most effects during peak floods; and (2) that at the beginning of spring 2016 (during the 2nd post-rehabilitation year) most, if not all the installed LWM were washed down downstream of the rehabilitated reach, they have been trapped by the concrete structures and blocked the channel during a flood, meaning that the rehabilitated reach morphological metrics and in-stream biotope composition declined.

Another important point is that silt was the key driver of changes in rehabilitated reach in-stream biotope composition. The rehabilitated stream had a high sediment load, which was not addressed by LWM installation. Therefore, LWM played a secondary role, controlling only the distribution of silt locally, as also observed in the study of lowland streams by Thompson (2015). The scale of this was demonstrated when in-stream biotope composition is compared between the first and the second post-rehabilitation spring: when LWM washed away, gravel patches became covered by silt again, which was due to catchment scale factors like erosion from agricultural land and an upstream village. This silt deposition negatively affected the in-steam biotope composition by covering coarser biotopes (cobbles and gravels).

There was good support for the hypothesis that macroinvertebrate communities were enhanced by the installed LWM at the reach-scale. Collecting samples in a BACI study design was an effective way to compare before-after ecological changes induced by installed LWM, and gauge the direction of the changes toward the natural reach, which was used as ecological baseline. Non-significant difference in the natural reach macroinvertebrate structural and functional metrics (before vs after) was a good indicator that the positive changes in the rehabilitated reach metrics were absolutely induced by the morphological effects of the installed LWM. Macroinvertebrate total density, total biomass, and taxa richness all responded to the morphological changes. The rehabilitated reach became similar to the natural reach in first post-rehabilitation winter and spring seasons according to the total density of their macroinvertebrate community. This outcome is contrary to the growing body of literature which reports only minor effects of stream rehabilitation processes on macroinvertebrates (see Table 2.3, Chapter 2), but is consistent with some studies that compared rehabilitation outcomes with nearby natural systems and/or the status before rehabilitation. Smock, Metzler and Gladden (1989) found that macroinvertebrate abundance and biomass increased with an increase in the number of woody dams that led to the collection of organic matter and increased food availability in two low-gradient, headwater streams on the Coastal Plain of Virginia, US. Entrekin *et al.* (2009) in a study of LWM installation effects in three forested headwater streams in the Upper Peninsula of Michigan, USA, found a significant increase in macroinvertebrate biomass in one rehabilitated reach, while there were no changes in two other reaches compared to values before LWM installation. Thompson (2015) also found that macroinvertebrate biomass increased significantly after LWM installation in rehabilitated reaches of five chalk streams in England. Significant increases in total density and richness were also observed in studies by Gerhard and Reich (2000), Pretty and Dobson (2004), and Lester, Wright and Jones-Lennon (2007).

EPT count and biomass were also responded to the rehabilitation process. Their proportions were significantly increased in the second post-rehabilitation winter (before the flood) compared with the first winter. The rehabilitated reach become similar to the natural reach in winter and autumn 2015 according to their EPT biomass percentage. This is consistent with Hilderbrand *et al.* (1997) who found that Ephemeroptera abundance was increased after the addition of LWM and consequent formation of pool habitats (changes in depth).

Chironomids are generally tolerant of pollution and silt so they are not a good target indicator for rehabilitation (Thompson 2015), but their relative abundance and biomass responded uniquely to in-stream biotope changes, and critically, Chironomids are a robust indicator of changes in fine sediment. Significant increases in their density and biomass proportions during the first post-rehabilitation spring samples were related to increases in organic matter on trapped sediments behind the woody dams, as the stepped channel profile created by dams reduces water velocity by dissipating the flow energy (Heede 1972; Keller & Swanson 1979). This slows suspended particles throughout the reach and thus facilitates their retention and settling behind dams (Smock, Metzler & Gladden 1989), in addition to increasing the stability of the silty patches. In the second post-rehabilitation spring, the installed LWM washed away, and Chironomid density and biomass proportion were declined significantly as retained silt patches became scattered and the silt biotope became less stable.

Shredders became the dominant group in terms of density and biomass in the rehabilitated reach. Increased gravel and leaf-litter biotopes percentages, and decreasing silt biotope percentage explain why shredders density and biomass increased significantly. Higher abundance and biomass of shredding macroinvertebrates indicate greater habitat complexity (Lester, Wright & Jones-Lennon 2007), this group is dependent on the availability of coarse particulate organic matter (Smock, Metzler & Gladden 1989), which is retained by LWM (Benke *et al.* 1985). Shredder biomass increased after LWM addition as increasing the number of woody material led to increasing collection of organic matter and thus food availability by Smock, Metzler and Gladden (1989). Shredder abundance was also related significantly to trapped leaf litter by Dobson *et al.* (1992). The significant increases in predator density and biomass after LWM installation in the present study indicates an increase in the complexity of the food web supported in the rehabilitated reach, as also observed by Lester, Wright and Jones-Lennon (2007). Deposit-feeders and filter-feeders were highly abundant in the rehabilitated reach in first post-rehabilitated winter and spring seasons, which could be related to the fact that at reach-level silt coverage area was still favourable for them.

Using macroinvertebrate community composition as a response variable was effective in gauging outcomes toward the project goals. Macroinvertebrate community taxonomic composition (depending on taxa density and biomass), and functional composition (depending on FFG density and biomass) were also effective ways (besides using total density and total biomass metrics) than only depending on taxa richness and/or diversity metrics (the most commonly used metrics in the literature) for understanding the relationship between LWM installation and macroinvertebrate community responses. Rehabilitated reach community taxonomic and functional composition changes led to greater similarity with the natural reach condition. Macroinvertebrate community composition was an effective response variable to gauge the outcome of integrated catchment management effects on macroinvertebrates in four streams of Waikato, New Zealand (Quinn *et al.* 2009), and in rehabilitation of former sewage channels in the Emscher River (right tributary of the River Rhine), Germany towards 'Good Ecological Potential' (Winking 2015). Enhanced macroinvertebrate community composition in the present study was a result of increased space (wet surface area), in-stream biotope heterogeneity (changes in biotope%, especially gravel, cobbles and silt proportion) and/or increased resources (detritus or leaf litter).

These results strengthen the call for a broader range of macroinvertebrate metrics (structural and functional) to be used to understand ecological effects of LWM installation, rather than depending only on diversity and/or richness measures. Thus, monitoring of rehabilitation outcomes must not focus solely on the structural attributes (taxa richness, diversity) of macroinvertebrate communities (Muhar *et al.* 2015); it needs to focus more on assessing natural processes and changes in their dynamic shifts toward the targeted rehabilitation endpoint through inclusion of both structural and functional measures (Palmer *et al.* 2005; Feld *et al.* 2011).

Seasonal changes in macroinvertebrate community taxonomic and functional compositions, especially of the natural reach, reveal that repeated seasonal samples are a fundamental requirement of an effective monitoring design because a stream's biotic community usually follows a cyclical pattern. If the post-rehabilitation evaluation is conducted during a peak or lull in the cycle, misleading results can be obtained (Leal 2012). Biotic samples should be collected in all 4 seasons of the year; we cannot depend on one season (e.g. spring) data to compare between both reaches.

Comparing the changes in the macroinvertebrate community of the rehabilitated reach with that of a nearby natural reach was a successful tool to gauge the direction of the change, as well as a key to determine success or failures of the project. This further supports the idea of monitoring the direction and not only the extent of change in biotic communities.

The overall changes in rehabilitated reach's morphological parameters did not explain a significant proportion of its macroinvertebrate taxonomic or functional univariate metrics changes. At the in-stream biotope-level, small increases in the number of in-stream biotopes (appearance of gravel and leaf litter), and changes in biotope proportions (decreasing silt%) were significantly related to changes in the rehabilitated reach's macroinvertebrate community metrics. This reveals that the effects on macroinvertebrates could be related to changes in the cover of those specific biotope types in the rehabilitated reach. Verdonschot *et al.* (2015) claimed that 'the effects on macroinvertebrates could be related to changes in the cover of specific substrate (here biotope) types in the rehabilitated section''. It is, therefore, necessary to sample all available in-stream biotopes to collect biotic data representative of the study reach's biotic community and to enable us to quantify the changes. Since macroinvertebrates species often have specific and changing in-stream biotope requirements throughout their life, all these habitats must be present and of sufficient quality to guarantee recolonisation and the development of sustainable populations (Verdonschot *et al.* 2015). This finding confirms that inadequate sampling could be the limitation factor behind the rare outcomes of previous studies. For example, evaluation studies often collect biotic samples in riffles, and yet these habitats are less likely to change as a result of most habitat enhancement projects (Brooks *et al.* 2002; Palmer, Menninger & Bernhardt 2010). But, when sampling is stratified by biotope type, improvements can be more evident (e.g. Nakano & Nakamura 2008; Sundermann, Stoll & Haase 2011; Winking 2015).

The present findings may be somewhat limited by catchment process outside the rehabilitation scale, and the limited temporal scale of the evaluation itself. Identification and prioritisation of the main pressures at appropriate scales are regarded as the main requirements of an effective rehabilitation of natural resources (Feld *et al.* 2011). Adverse effects of different kinds of land-use in the surrounding catchment are integrated in rivers (Palmer, Menninger & Bernhardt 2010). The upstream reach of the rehabilitated site was severely degraded, which made the rehabilitation potential very limited (depending on taxa diversity), as dispersal of stream invertebrates (e.g. to the rehabilitated reach) requires the proximity of healthy headwaters with source populations of appropriate taxa (Parkyn & Smith 2011; Sundermann, Stoll & Haase 2011), which was absent here. Dispersal of aquatic stages of benthic invertebrate species is limited. It is generally believed to be more effective downstream because of passive drift (Williams & Williamce 1993). In a case like this, reestablishment of macroinvertebrate community must primarily rely on immigration from other systems (Milner 1996; Hansen, Friberg & Baattrup-Pedersen 1999).

The scale of the rehabilitation effort also affected the project outcomes. It must correspond to that of the degrading process (Hobbs & Norton 1996). The rehabilitation process did not address the presence of concrete structures affecting longitudinal connectivity. These structures caused the total wet surface area to decrease severely in August 2015, which might have affected the recovery of the biotic community. High supply of soft sediments from the stream’s north bank also needs to be addressed, which can be reduced by changing land-use and restoring sufficiently wide and mixed riparian vegetation (Barton, Taylor & Biette 1985; Castelle, Johnson & Conolly 1994). Installed LWM played a secondary role in controlling sediment distribution which also found by Thompson (2015).

The temporal scale of this study was also short (18 months, including 16 following LWM installation), which may have limited the ability of the study to detect responses in some taxa or longer-term trends (Lester, Wright & Jones-Lennon 2007). The rehabilitation project was not properly sustained, as installed LWM washed away during monitoring. Channel morphological changes can continue over decades, along with macroinvertebrate responses to these changes (Greenwood *et al.* 1999). LWM was put into the rehabilitated reach unanchored, which simulates natural deposition and habitat creation (Brooks *et al.* 2004; Johnson *et al.* 2005), but the installed LWM were washed away and trapped by the concrete barriers. They also blocked the channel. Anchoring LWM in the stream bed by burying parts of it or otherwise anchoring it with cables could prevent this from happening. Anchoring installed LWM (e.g. Shields *et al.* 2003; Hrodey, Kalb & Sutton 2008) gives the rehabilitation team more control and may produce a better outcome (Leal 2012).

Chapter 4. Short-term ecological effects of rehabilitation of the Welland River at Welland Park, Market Harborough

4.1. Introduction

The physical habitats that English rivers provide for riverine biota have been greatly modified over many decades (Raven *et al.* 1998). Most lowland river channels in England have been changed by humans, through drainage of floodplain wetlands to use as agricultural land, use of them for navigation, or construction of barriers. They have thus been simplified, straightened, deepened and separated from their floodplains (Brooks 1995). These changes have often acted in combination to (they impose environmental stresses on aquatic communities) degrade them (Feld *et al.* 2011). Abundance and biomass of invertebrates, macrophytes and fishes has decreased (McCarthy 1985; Boon 1988).

Rehabilitating lost physical features seems to be the best way to minimise or reverse the ecological effects of stream and river morphological degradation (Mitsch & Jørgensen 2003; Ormerod 2003; Pedersen, Baattrup-Pedersen & Madsen 2006). Morphological rehabilitation of UK rivers has some history, especially after the formation of the River Restoration Project (RRP) in 1992 together with partners in Denmark, with the support of EU-Life funding, and then the formation of the River Restoration Centre (http://www.therrc.co.uk/) in the UK (Mainstone & Holmes 2010). Rehabilitation projects have thus been based on the assumption that habitat heterogeneity promotes biodiversity and enhances ecological functioning (Feld *et al.* 2011). Their success depends on whether population, community and ecological functions recover and attain the characteristics typical of non-degraded reference systems (Ormerod 2003), but this has been largely untested (Feld *et al.* 2011). Only 10% of about 40,000 reported rehabilitation projects in the United States of America contained any monitoring (Palmer *et al.* 2007) and only 30% of rehabilitation projects in Europe, including the UK, provided ecological monitoring information (Thompson 2015).

The success of a rehabilitated ecosystem is often measured by the recovery of biodiversity and other biotic features. Evaluating and comparing the functionality of the rehabilitated system can determine whether the system can sustain natural levels of biodiversity (Palmer, Ambrose & Poff 1997). Only a few hundred of the rehabilitation projects in the USA and EU, designed to rehabilitate natural flow and enhance habitat heterogeneity in streams and rivers, have been monitored to assess their effectiveness on macroinvertebrate biodiversity (see Chapter 2. Literature Review), so the influence is still unclear and probably limited. About 10% of entire-channel hydromorphological rehabilitation projects have been shown to enhance macroinvertebrate biodiversity (Table 2.1; Chapter 2). Possible explanations for these limited positive results include:

a) Failure of many rehabilitation measures to enhance physical and hydrological heterogeneity of the rehabilitated reach, or improve in-stream biotope heterogeneity after rehabilitation.
b) Lack of standardised, multi-habitat sampling (at biotope-level), or BACI study designs incorporating undisturbed reaches; and
c) A focus only on taxon richness and diversity as biotic response variables.

In some cases macroinvertebrate recovery was also limited by declining habitat quality over time due to erosion, lack of diversity (a source population) in adjacent reaches from which to recruit (e.g. Moerke *et al.* 2004), barriers to dispersal (e.g. Wallace 1990), and pollutant input which may have affected sensitive taxa and impact community recolonisation (Palmer, Menninger & Bernhardt 2010).

A more holistic view of river rehabilitation, that rehabilitates the entire channel and tackles deficient hydromorphological processes, has been gaining ground within the rehabilitation community (Ayres *et al.* 2014). An holistic approach means improving the flow regime, the channel morphology, considering the whole physical and biological potential of the rehabilitated site and the scale of implementation to shape and sustain river habitats and biota; and thus enhance the recovery of both ecosystem structure and processes (Beechie *et al.* 2010). Holistic approaches that focus on returning critical drivers such as hydrological regime and river functions (Friberg *et al.* 2016) will help to avoid common pitfalls of engineered solutions, such as creation of localised habitats that cannot be sustained by natural processes (Beechie *et al.* 2010; Palmer, Hondula & Koch 2014). Rehabilitating free water flow will restore natural erosion-sedimentation processes (Friberg *et al.* 2016).

Rehabilitation by meandering and adding coarse substrate such as artificial riffles has led to immediate rehabilitation of some features of natural stream channel morphology (Pedersen *et al.* 2007), to enhancement of the structural heterogeneity (Brookes, Knight & Shields 1996; Harrison *et al.* 2004), and to promotion of biotic recovery and biodiversity (Harper *et al.* 1997; Palmer, Hakenkamp & Nelson-Baker 1997; Gerhard & Reich 2000). The success and sustainability of such local-scale rehabilitation approaches is dependent upon on flow dynamics: there is a greater likelihood of failure when degraded flow dynamics and natural processes have not been addressed (e.g. Jähnig *et al.* 2010; Palmer, Menninger & Bernhardt 2010).

In my study, both the rehabilitation process itself and the monitoring of its outcomes were designed to address the shortcomings mentioned above. The project, entitled ''Welland for People and Wildlife'', rehabilitated reach hydromorphology through re-creation of a two-stage channel within a channel that had been considerably over-enlarged 40 years previously for flood protection. The rehabilitation used the concept of biotopes as the basis for the design (Chapter 2; (Harper, Smith & Barham 1992; Demars *et al.* 2012), with a natural upstream reach of the river as the reference and as a potential source of aquatic biota for natural recolonisation. Rehabilitation was through the creation of the natural physical conditions, such as meanders, berms and riffle-pool sequences in the appropriate distances apart predicted by mean annual discharge as a surrogate of original natural channel size (Smith, Harper & Barham 1990). These were expected to create a low-flow channel with variable width and depth and more wet area on berms for marginal plants to grow. The original high-flow channel remained to accommodate flood water.

Many projects have been previously applied in the Welland Valley to improve the river and its tributaries' chemical, physical and biological status, and to ensure that, in time, the river will reach Good Ecological Status (GES) of the European Water Framework Directive (WFD). These have included: fencing off rivers and roofing yards to reduce diffuse pollution and improve the river environment; provision of practical advice and promotion of good practice to farmers to minimise diffuse pollution; removal or cutting of weirs to provide safe fish passage; implementation of in-channel habitat improvement works; improvement of river and water side habitats; and rehabilitation of fenland (Barham 2013).

To assess this rehabilitation project's success and outcomes, I conducted a double-control BACI study in which I compared a section of the rehabilitated with both a natural (upstream) and a degraded (tributary) reach. The rehabilitated section (about 250 m of the total 1800 m rehabilitated) of the Welland River at Welland Park, Market Harborough (Figure 4.1a) was mapped, sampled and compared with an upstream natural reach of the same river at Lubbenham (Figure 4.1b) (used as the reference state and goal of the rehabilitation process), and a physically degraded (straightened and uniform) reach of the Jordan River at Market Harborough (Figure 4.1c) (used as a control or degraded). The Jordan joined the Welland downstream of the rehabilitated reach. I collected multiple samples of all available biotopes (biotopes that covered ≥1% of the study reach stream bed) and collected data over seven successive seasons (2015-2016) to partition the outcomes of rehabilitation from other confounding pressures (e.g. temporal changes). I used a broad range of macroinvertebrate metrics (not only taxa richness or diversity) as response variables to examine the relationship between the overall channel hydromorphological rehabilitation process and changes in macroinvertebrate community composition, structure and function.

Figure 4.1. A section of the control reaches, a) A reach of Welland River before rehabilitated; b) Natural reach of Welland River at Lubbenham; c) Degraded reach of Jordan River.

4.2. Aim and objectives

This study aimed to provide evidence for the effectiveness of channel hydromorphological rehabilitation treatments and their success as assessed by physical and biological outcomes.

The following methodological core hypotheses were designed to test the effects of the rehabilitation process:

a) Entire-channel hydromorphological rehabilitation will improve the rehabilitated reach hydromorphology.
b) Using a broader range of macroinvertebrate metrics (structural and functional) than has been used in previous studies will help understand and potentially explain the ecological effects of rehabilitation better than could be achieved by using only diversity and/or richness measures.
c) Using a BACI study design and collecting samples over seven successive seasons will show the direction of the rehabilitation, and partition the effects from other confounding factors.

The specific ecological hypotheses were (expected reasons for them in brackets):

1) Hydromorphological rehabilitation will enhance morphological complexity and physical heterogeneity (through increasing the depositional zone, trapping silt, increasing erosion from adjacent habitats, enhancing leaf litter retention, creating pool-riffle sequences, changing stream depth and width, and altering in-stream biotope number and diversity).
2) Macroinvertebrate Total Density (individuals m^{-2}), Total Biomass (mgDM m^{-2}), Taxon Richness, Taxa Diversity, Evenness, EPT Richness, EPT Diversity, EPT Count%, and EPT Biomass% will be enhanced in the rehabilitated reach compared with before rehabilitation.
3) The rehabilitated reach macroinvertebrate community metrics will resemble those of the natural reach.
4) Chironomidae Count% and Biomass% will decrease (due to reduction in silt biotope coverage area), while EPT Count% and EPT Biomass% will increase (due to increase in coarser biotopes area).

5) Macroinvertebrate community taxonomical composition (based on Count m^{-2}, and Biomass m^{-2}) will be enhanced by enhanced physical heterogeneity in the rehabilitated reach compared with the pre-rehabilitation situation, and will resemble that of the natural reach (as newly installed coarser biotopes and growing marginal plants will provide shelter for different macroinvertebrate assemblages).
6) Macroinvertebrate functional feeding groups' density and biomass will be changed by the rehabilitation process – shredders and scraper macroinvertebrates will increase, while deposit-feeders and filter-feeders will decrease. The rehabilitated reach FFGs composition (based on Count m^{-2}, and Biomass m^{-2}) will resemble that of the natural reach.

4.3. Materials and methods

4.3.1. Study sites

The Welland River rises in south west Leicestershire, near Market Harborough. It flows through the gently rolling countryside of Northamptonshire, Leicestershire, Rutland, and Lincolnshire for about 80 km and finally to the sea at the Wash; the main river and its tributaries together form more than 480 km of waterway. The catchment area is approximately 1554 km^2, The landscape of the valley is varied from livestock dominated rolling hilly land of the upper Welland, with 2 market towns and several villages, into the largely arable fenlands of Lincolnshire below Stamford and highly straightened channels tidal below Spalding, discharging to the Wash estuary. Over the last 100 years, the Welland River and its tributaries have greatly changed. Land use has changed, Eyebrook reservoir was created in the 1930s to provide water for industry in Corby, and Empingham reservoir (Rutland Water) was built to provide water for Peterborough, Kettering and Northampton in the 1970s. Natural meandering rivers have been straightened and deepened, especially during the 1960s and 1970s by engineering works to mitigate floods and improve land drainage. These works mainly affected all 'main river' upstream of Stamford. In Lincolnshire the Welland had been widened, straightened and deepened over many centuries, to create new agricultural land from former fens, and protect them from inundation to increase food production. Riparian habitats and water meadows in the floodplains had been lost by disuse before the 20th Century. The challenges affecting the valley are now exacerbated by high nutrient and sediment inputs, low flow at times, as well as changes in the natural path and shape of watercourses (Barham 2013).

The study was carried out on a 250 m reach of the Welland River at Welland Park, Market Harborough (52.475427 N, -0.926341 W; Figure 4.2) within a 2 km long rehabilitation programme. A 250 m undisturbed reach of the Welland (upstream at Lubbenham, 52.473637 N, -0.972636 W; Figure 4.2) was used as the goal state of the rehabilitation (and provided a potential source of macroinvertebrate population recolonisation). A straightened reach (250 m) of the Jordan River at Market Harborough (52.476865 N, -0.909979 W; Figure 4.2) was used as a control physically degraded reach. It joins the Welland River downstream of the rehabilitated reach. The positions of study reaches are shown in Figure 4.2.

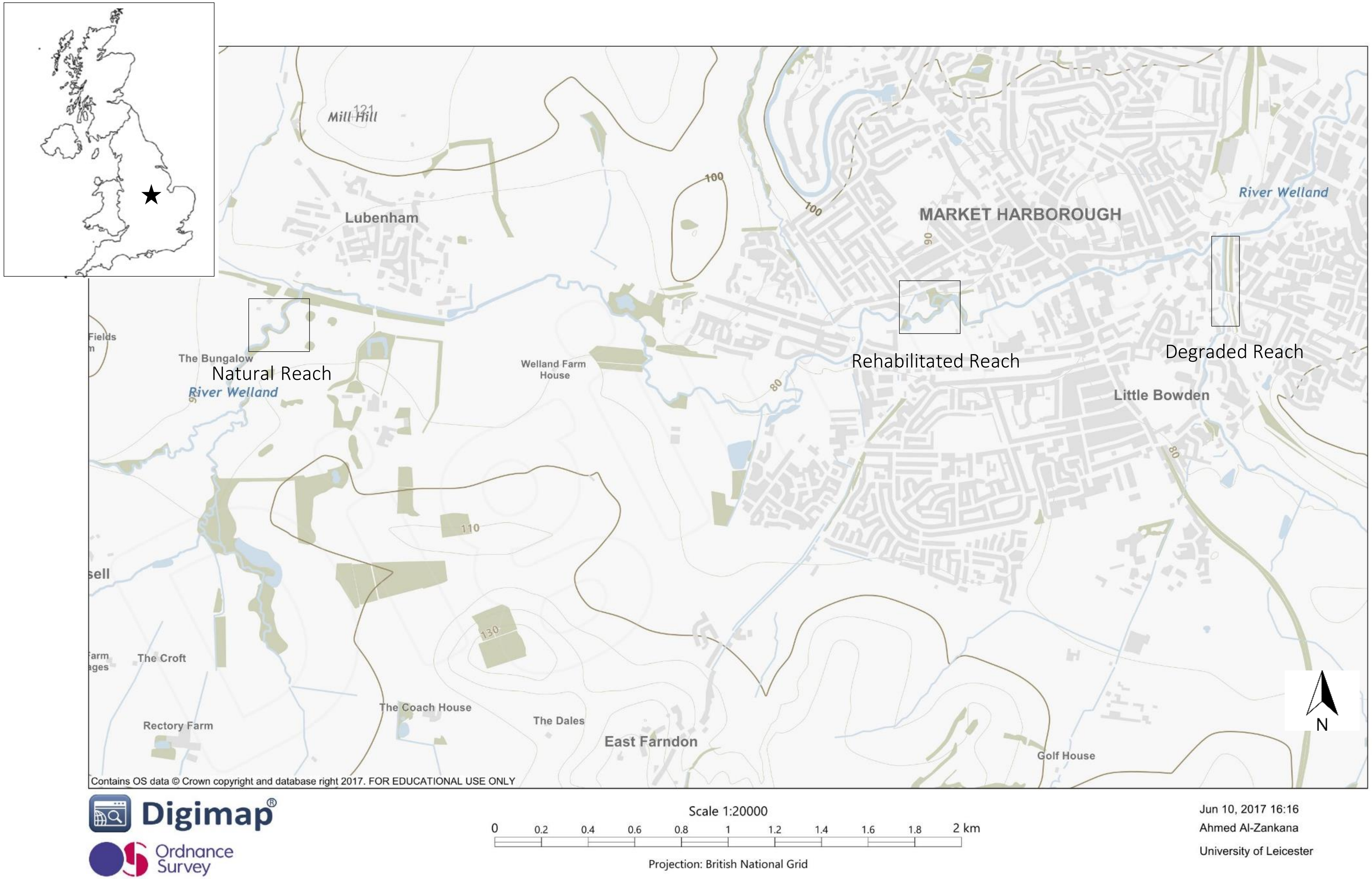


Figure 4.2. Map of study reaches of Welland River and Jordan River at Market Harborough, Leicestershire, UK.

4.3.2. Rehabilitation activities

A 1.8 km reach of the Welland River through Market Harborough (Welland Park) which had been extensively straightened, widened and deepened due to the past flood defence works, has now been actively restructured and rehabilitated by the Welland Rivers Trust and the University of Leicester as the 'Welland for People and Wildlife' project (https://restorerivers.eu/wiki/index.php?title=Case_study%3AWelland_for_People_and_Wildlife_Project) in Summer 2014 (Welland Rivers Trust 2015). Rehabilitation included removing weirs, which trapped sediments and acted as barriers to fish and eel movements. A meander running around a patch of woodland was re-opened where it had previously been bypassed by a flood channel. At the study reach (Figure 4.3), the channel was meandered and narrowed, and a low-flow channel created by building berms constructed from the spoil derived from the digging of pools. This forced the water to move downstream to prevent stagnation of the water that had previously been clogged up with vegetation. A series of riffle-pool sequences were constructed by digging pools in meander bends and depositing the material between the bends; silt was carried away by water flow. Creating a gradual gradient (by the meandering and weir removal) provided more marginal space for plants and provided safer access to the river for the community as well as reducing the risk of erosion. Large woods been added to the reach. Some native macrophytes were planted to provide allochthonous organic matter and shade (Welland Rivers Trust 2014).

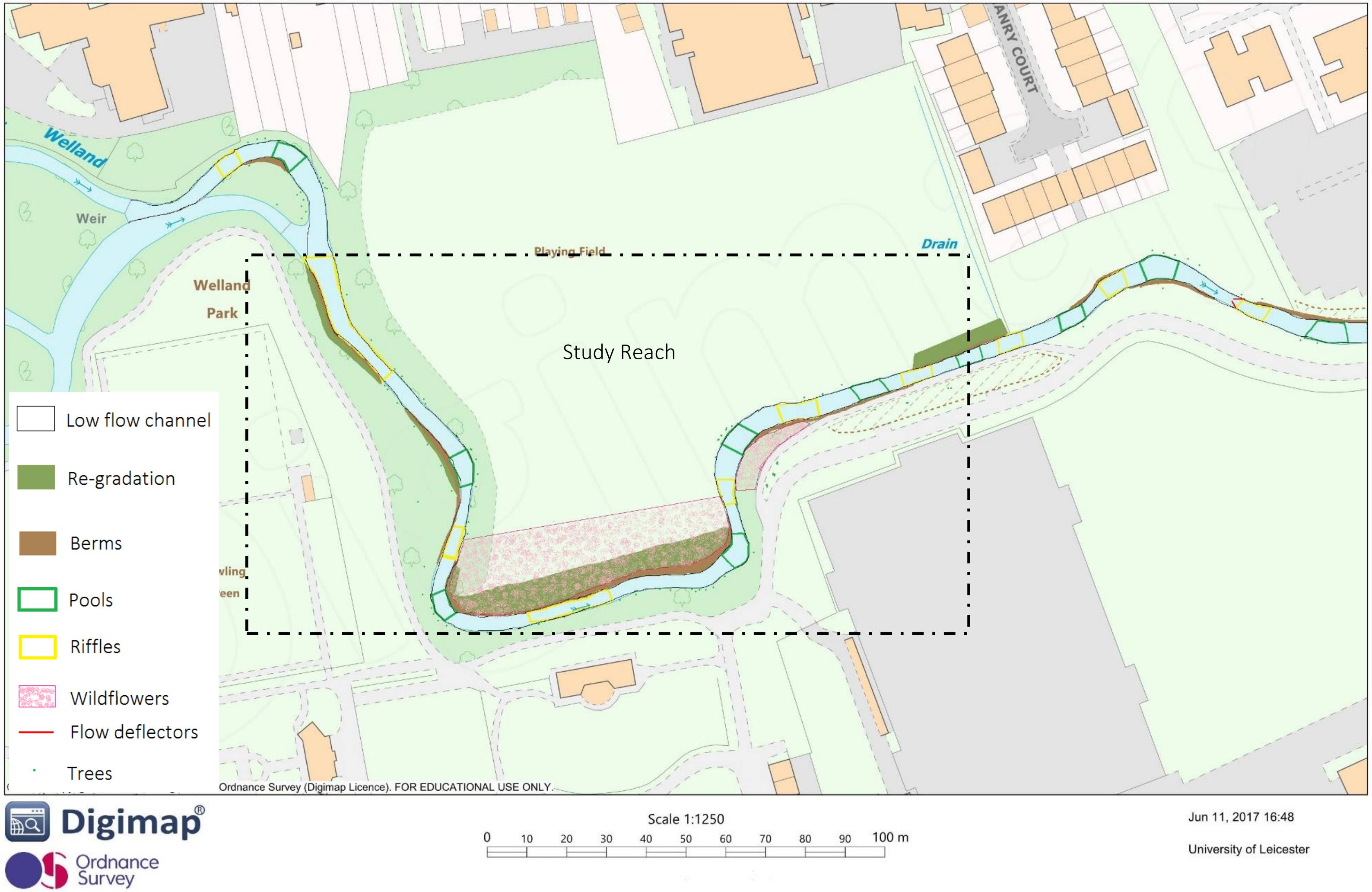


Figure 4.3. A section of the rehabilitated reach (entire study reach) shows low-flow channel design and rehabilitation measures applied.

4.3.3. Surveying channel morphological features and mapping in-stream biotopes

The three study reaches were surveyed and mapped in spring 2014 (before the rehabilitation of the Welland River had begun), and both the Degraded and Natural reach again in summer 2014 (study reach was under rehabilitation). The wetted area, percentage of biotopes, channel width and depth were recorded, every 5m; the depth was measured to the nearest cm at the centre of each 5m cross section. In-stream biotopes were visually identified and named according to Demars *et al.* (2012). Following rehabilitation in 2014, the study reaches were re-surveyed and mapped seasonally for two years (2015-2016) to record morphological changes, appearance of new biotopes, growth of macrophytes, and sustainability of the created physical habitats. A clear-plastic-bottom hydroscope (Figure 4.4) was used to facilitate underwater observations during periods of high flow and turbidity. The biotopes identified and sampled were boulders, cobbles, gravel and sand (mineral substrate), silt (soft substrate with organic matter), emergent plants, submerged fine-leaved plants, marginal plants, woody material, leaf litter and macro-algae (vegetation types). In-stream biotope diversity (SWI_biotope), and coefficient of variation of channel water depth and width (CV_depth, CV_width) were calculated from the measurements.

Figure 4.4. Hydroscope with clear plastic bottom (32 cm diameter).

4.3.4. Sampling and preservation of macroinvertebrates

Before the rehabilitation process started (in 2014), spring and summer samples were collected from all reaches (except summer samples were not collected from the rehabilitation reach, due to the work). After the rehabilitation, macroinvertebrate samples were collected from all study reaches for 7 successive seasons (Table 4.1). Three samples from all existing biotopes (those covering ≥1% area of the river bed within a given reach) were collected in each sampling visit. Samples were collected using a Surber sampler (500 µm mesh size and 0.09 m^2). In-stream macrophyte stems and leaves within the sampler frame were enclosed in the net and then cut off from the plant as close to the substratum as possible. Further details about sampling procedures and preservation are available in Chapter 3.

Table 4.1. Macroinvertebrate sampling visit dates for each study reach.

Year	**Season**	**Abbreviation**	**Rehabilitated reach**	**Degraded reach**	**Natural reach**
2014	Spring	Sp.14	17th March	17th March	19th March
			19th May	19th May	22nd May
	Summer	Su.14	-	18th Jun	20th Jun
			-	23th July	25th July
2015	Winter	Wi.15	19th January	20th January	20th January
			16th February	17th February	17th February
	Spring	Sp.15	16th March	17th March	17th March
			13th April	14th April	14th April
			11th May	12th May	12th May
	Summer	Su.15	7th Jun	9th Jun	10th Jun
			4th July	5th July	6th July
			2nd August	4nd August	5nd August
	Autumn	Au.15	1st September	2nd September	3rd September
			28th September	28th September	30th September
			26th October	26th October	28th October
			23rd November	23rd November	25th November
	Winter	Wi.16	21st December	21st December	23rd December
2016			19th January	20th January	20th January
	Spring	Sp.16	14th March	14th March	16th March
			17th May	19th May	21st May
	Summer	Su.16	22nd Jun	24th Jun	24th Jun
			25th July	27th July	29th July

4.3.5. *Identification and counting of macroinvertebrate specimens*

Macroinvertebrate specimens collected from each sampled biotope were identified and counted in the laboratory. Specimens were identified to the lowest possible taxonomic level, either species or genus, with the exception of Oligochaeta, Coleoptera, and Diptera, which were identified to family and Chironomidae, which were identified to sub-family. Specimens were morphologically identified using the following standard UK lotic invertebrate taxonomic keys and guidance books – (Soar & Williamson 1925; Soar & Williamson 1927; Soar & Williamson 1929; Mann & Watson 1954; Hynes, Macan & Williams 1960; Brinkhurst 1971; Gledhill, Sutcliffe & Williams 1976; Hynes 1977; Macan & Cooper 1977; Elliott & Mann 1979; Cranston 1982; Croft 1986; Elliott, Humpesch & Macan 1988; Wallace, Wallace & Philipson 1990; Edington & Hildrew 1995; Killeen, Aldridge & Oliver 2004; Wallace 2006; Greenhalgh & Ovenden 2007; Elliott 2009; Elliott & Humpesch 2010; Dobson *et al.* 2012; Waringer & Graf 2013).

4.3.6. *Assessing biomass*

Macroinvertebrate population biomass (mgDM m^{-2}) was estimated according to the published size-specific mass regressions in the literature (Appendix 1), in addition to direct estimation for worms and some insect larva. Further details of biomass assessment and the size-specific mass regressions are available in Chapter 3.

4.3.7. *Feeding strategy assignment*

Macroinvertebrate abundance and biomass data for each biotope were assigned to eight feeding strategies (Table 4.2) (hereafter called Functional Feeding Groups, FFGs) according to Tachet *et al.* (2010) (Appendix 2). More details are available in Chapter 3.

Table 4.2. Macroinvertebrate strategies, adopted from Chevene, Doleadec and Chessel (1994).

No.	Group descriptor
1	Absorber
2	Deposit feeder
3	Shredder
4	Scraper
5	Filter feeder
6	Piercer (plant or animals)
7	Predator (carver/engulfer/swallower)
8	Parasite

4.3.8. Calculating reach-level macroinvertebrate community composition

Reach-level values of taxon count sample^{-1} (T_{count}), taxon biomass sample^{-1} ($T_{biomass}$), FFG count sample^{-1} (FFG_{count}), and FFG biomass sample^{-1} ($FFG_{biomass}$) were calculated according to the relative coverage area of each sampled biotope in the given reach. The given reach-level variable lists were created by summing biotope-specific list values that were weighted by their availability percentage (following Huryn & Wallace 1987; Lugthart & Wallace 1992; Kedzierski & Smock 2001; Pedersen *et al.* 2007; Jähnig *et al.* 2010). More details are available in Chapter 3.

4.3.9. Calculating reach-level macroinvertebrate univariate metrics

Total Density (N), Taxa Richness (d), Pielou's Evenness (J´), Shannon-Wiener diversity (H´), EPT Richness, EPT Count%, EPT Diversity, and Chironomidae Count% univariate metrics were calculated from the reach-level T_{count} data lists. Total Biomass (mgDM/sample), EPT Biomass%, and Chironomidae Biomass% were calculated from reach-level $T_{biomass}$ data lists. The reach-level FFG_{count} and $FFG_{biomass}$ data lists were used to calculate the percentage of density and biomass contributed by each FFG (following Tullos *et al.* 2009). More details are available in Chapter 3.

4.3.10. Data analysis

Channel morphological metrics and in-stream biotope composition (biotope coverage area relative percentages) were normalised, Euclidean distance matrices were then calculated and used in one-way ANOSIM (Analysis of Similarity) (Clarke *et al.* 2014). This tested for differences in morphological variables and substrate composition among the study reaches in a control-impact (C-I) design, depending on reach-level data collected over seven successive seasons (winter, spring, summer, autumn 2015, and winter, spring, summer 2016) within the first and second years after rehabilitation. Greater global R values in ANOSIM indicate greater separation in ordination space. R values >0.5 illustrate clear differences among reaches with some degree of overlap (Clarke & Gorley 2015), values ≥0.6 indicate significant differences. Values of $P<0.05$ were considered significant. Principal component analysis (PCA) was conducted to visualise which metrics or variables separated the study reaches. PCA results were ordinated by reaches, and variables contributing >0.5 Spearman's rank correlation (ρ) were included as vectors (following Clark 2011).

Macroinvertebrate univariate metrics (Total Density and Total Biomass) and community composition data were pooled to show values per square metre before the data analysis. Permutational multivariate ANOVA (PERMANOVA) (Anderson, Gorley & Clarke 2008) was used to perform both univariate and multivariate analyses (following Eddy & Roman 2016).

Reaches were compared seasonally before and after rehabilitation. A Euclidean distance matrix was first used to calculate distances between samples for each univariate metric separately. Metrics were ln(x), ln(x+1), Sqrt(x), or Asin(x) transformed (Table 4.3) prior to the analysis to improve the normality of the data distribution and satisfy the PerANOVA test requirements, where applicable. Two-way PERMANOVA with *Reach type* (fixed factor, three levels: degraded, natural, rehabilitated) and *Seasons* (fixed factor, nine levels: Sp.14, Su.14, Wi.15, Sp.15, Su.15, Au.15, Wi.16, Sp.16, Su.16) was used to run a BACI design test on collected data, running all possible pair-wise tests. Since the design was unbalanced, a Type III test for sum of squares (SS) was used. All PerANOVA tests used 9999 random permutations under a reduced model. When there were too few possible permutations (<100) to obtain a reasonable test, a P value was calculated using 9999 Monte Carlo draws from the appropriate asymptotic permutation distribution (Anderson & Robinson 2003). Spatial and temporal differences were visualised using box plots.

Macroinvertebrate community composition differences were tested by using the same PERMANOVA designs, depending on the reach-level T_{count}, $T_{biomass}$, FFG_{count}, and $FFG_{biomass}$ data matrices (pooled to show values per square metre). All matrices were fourth-root transformed prior to the analysis to normalise the data distributions. This down-weighted the influence of numerically dominant taxa, and prevented masking of less abundant taxa. 2D non-metric multidimensional scaling (nMDS) ordination plots with Bray-Curtis dissimilarity coefficients were used to visualise significant differences. Bray-Curtis distance was chosen because it is not biased by joint absence (coincident occurrence of null values in the samples being compared). In nMDS analysis, a stress ≤0.2 indicates that the analysis gives a potentially useful picture of the data structure, while a stress ≤0.1

corresponds to a good ordination with no prospect of misleading interpretation (Clarke *et al.* 2014).

A similarity percentage procedure (SIMPER) was used to determine which taxa or FFGs accounted for the dissimilarities in any significant spatial or temporal measures, with exclusion of taxa or FFGs that contributed less than 30% of the dissimilarity (following Johnson *et al.* 2010; Gosch *et al.* 2014). These analyses were visualised using shade plots.

The relationships between channel morphological variables and macroinvertebrate univariate metrics were analysed using distance-based linear modelling (DISTLM) (following Eddy & Roman 2016; Heerhartz *et al.* 2016). These analyses were performed after standardisation and normalisation of morphological variables. Euclidean distance matrices of all univariate metrics used for the previously described PERMANOVA analyses were used separately. Sequential tests were used to determine which combinations of morphological parameters best explained variability in the response variable. Each sequential test was performed with a step-wise selection procedure using Akaike's information criteria (AIC). This analysis partitions the variability of the macroinvertebrate community composition and metrics along best-fit axes and then tests the morphological variables that are most closely related to these axes. The relationship between morphological variables and biological metrics were determined using Spearman's rank correlation (ρ).

BIOENV analysis (Clarke & Ainsworth 1993) was used to investigate relationships between patterns in macroinvertebrate community composition and morphological variables. The test selected a maximum of five morphological variables from Euclidian distance resemblance matrices that contribute the best Spearman's rank correlation (ρ) with the each of T_{count}, $T_{biomass}$, FFG_{count}, and $FFG_{biomass}$ data of the Bray-Curtis similarity matrices.

All analyses were carried out using PRIMER v.7 software (Clarke & Gorley 2015) and the PERMANOVA+ add-on package (Anderson, Gorley & Clarke 2008).

Table 4.3. Transformations applied to Univariate macroinvertebrate community metrics.

Univariate metrics	Transformation
Total Density (N)	Sqrt(N)
Taxa Richness (d)	None
Evenness (J´)	Asin(J´)
Taxa Diversity (H´)	Sqrt(H´)
EPT Richness	Sqrt(EPTR)
EPT Count%	Sqrt(EPTC)
EPT Diversity	Sqrt(EPTD)
Chironomidae Count%	Sqrt(CC%)
Total Biomass	Sqrt(TB)
EPT Biomass%	Sqrt(EPTB)
Chironomidae Biomass%	In(CB%)
FFGs Count	Sqrt(C)
FFGs Biomass	Sqrt(B)

4.4. Results

4.4.1. Channel morphological metrics and in-stream biotope structure

Rehabilitated reach morphological complexity was enhanced by creating a low-flow meandered channel with riffle-pool sequences, thus changing stream depth and width. Water flow was enhanced. This led to increases in in-stream biotope number, and diversity. Cobbles and gravel coverage area were increased. Macroalgae grew on the installed coarse biotopes. Marginal plants grew and covered berms. Floating-leaved macrophytes grew in the shallow areas. Leaf-litter and soft-sediment retention were increased (Figure 4.5).

Figure 4.5. Changes in the rehabilitated reach channel morphology and appearance of new in-stream biotopes after the rehabilitation process. a) low-flow channel meandered, and riffle-pool sequences installed; b) Macroalgae grew on installed coarse biotopes; c) Marginal plants grew on berms; d) Floating-leaved macrophytes grew in the shallow area; e) installed woody materials; f) Leaf-litter and soft-sediments trapped by installed woody materials.

The rehabilitated reach had a higher variance of river depth and width (CV_depth, and CV_width) than the degraded reach (Figure 4.6a; b). Wetted surface area was also higher than in the degraded reach (Figure 4.7a). It is evident from the pre-rehabilitation biotope mapping that the creation of a low-flow channel has provided more area for marginal macrophytes to grow. Rehabilitation had increased number of organic and mineral biotopes. Thus rehabilitated reach had a higher number of in-stream biotopes (Figure 4.7b) and biotope diversity (SWI_biotope) (Figure 4.7c) than both the degraded reach and the natural reach. Installed coarse biotopes had a very low embeddedness compared to that in the pre-rehabilitation condition and in the degraded reach (I.e. less of the surface area of the riffles was covered by silt).

Statistically, the rehabilitated reach channel morphology was enhanced and became similar to the natural reach. Analysis of Similarities (ANOSIM) revealed significant differences between degraded versus natural, and degraded versus rehabilitated reaches (R=0.96 and 0.71 respectively, P=0.0006). The rehabilitated reach became more similar to the natural reach (R=0.37, P=0.052) (Appendix 4.1). PCA showed that rehabilitated and natural reaches separated from the degraded reach along the first two axes (Figure 4.8a), PC1 and PC2 described 90.6% of the differences between the degraded reach on one side and the natural and rehabilitated reaches on the other side. Clear separation between the degraded reach and natural and rehabilitated reaches was explained by higher CV_depth, CV_width, wet surface area, number of in-stream biotopes and SWI_biotope in the natural and rehabilitated reaches than in the degraded reach. PC1 captured 53.2% of the variation. Both the SWI_biotope and number of in-stream biotopes (ρ=0.61) were highly related to PC1. PC2 captured 37.4% of the variance. Wet surface area (ρ=0.68), and CV depth (ρ=0.58) were highly related to PC2 (Appendix 4.2).

In-stream biotope composition ANOSIM revealed significant differences between degraded and natural reach (R=0.89, P=0.006), degraded and rehabilitated reach (R=0.85, P=0.006), while the rehabilitated reach become similar to the natural reach (R=0.04, P=0.20) (Appendix 4.3). PCA showed that the rehabilitated and natural reaches separated from the degraded reach along the first two axes. PC1 and PC2 described 67.4% of between-reach variations (Figure 4.8b). The degraded reach had higher coverage of silt than the natural and rehabilitated reaches (Appendix 4.4). A summary of channel morphological metrics measured at the reach-level and in-stream biotope composition is included in Appendix 4.5 and Appendix 4.6 respectively.

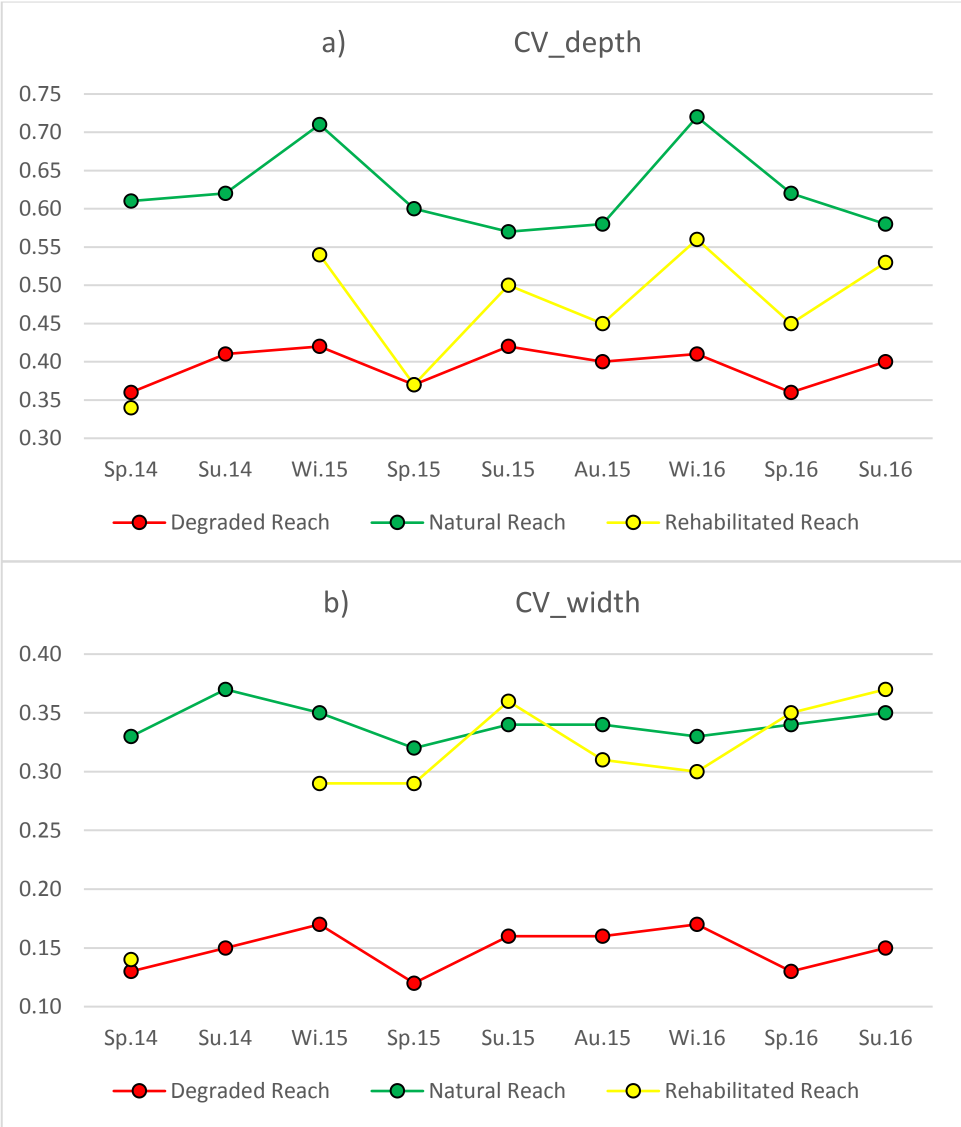


Figure 4.6. Seasonal variations in morphological metrics. a) Coefficient of variation of water depth. b) Coefficient of variation of water width. Sp.14, spring 2014 and Su.14, summer 2014 (before rehabilitation); Wi.15, winter 2015; Sp.15, spring 2015; Su.15, summer 2015; Au.15, autumn 2015; Wi.16, winter 2016; Sp.16, spring 2016; Su.16, summer 2016 (after rehabilitation).

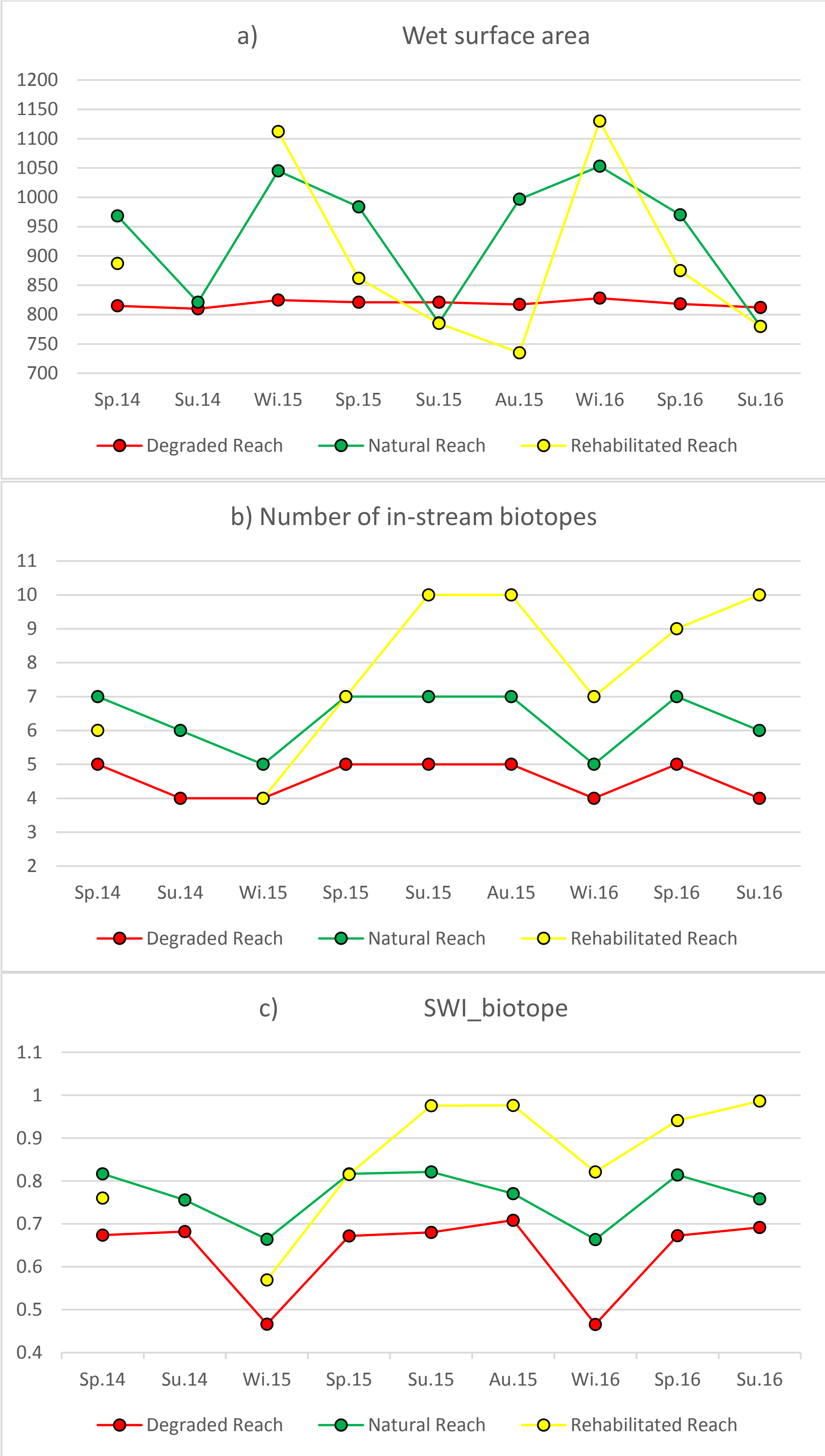


Figure 4.7. Seasonal variations in morphological metrics. a) Wet surface area. b) Number of in-stream biotopes. c) Shannon-Wiener diversity index of in-stream biotopes. Sp.14, spring 2014 and Su.14, summer 2014 (before rehabilitation); Wi.15, winter 2015; Sp.15, spring 2015; Su.15, summer 2015; Au.15, autumn 2015; Wi.16, winter 2016; Sp.16, spring 2016; Su.16, summer 2016 (after rehabilitation).

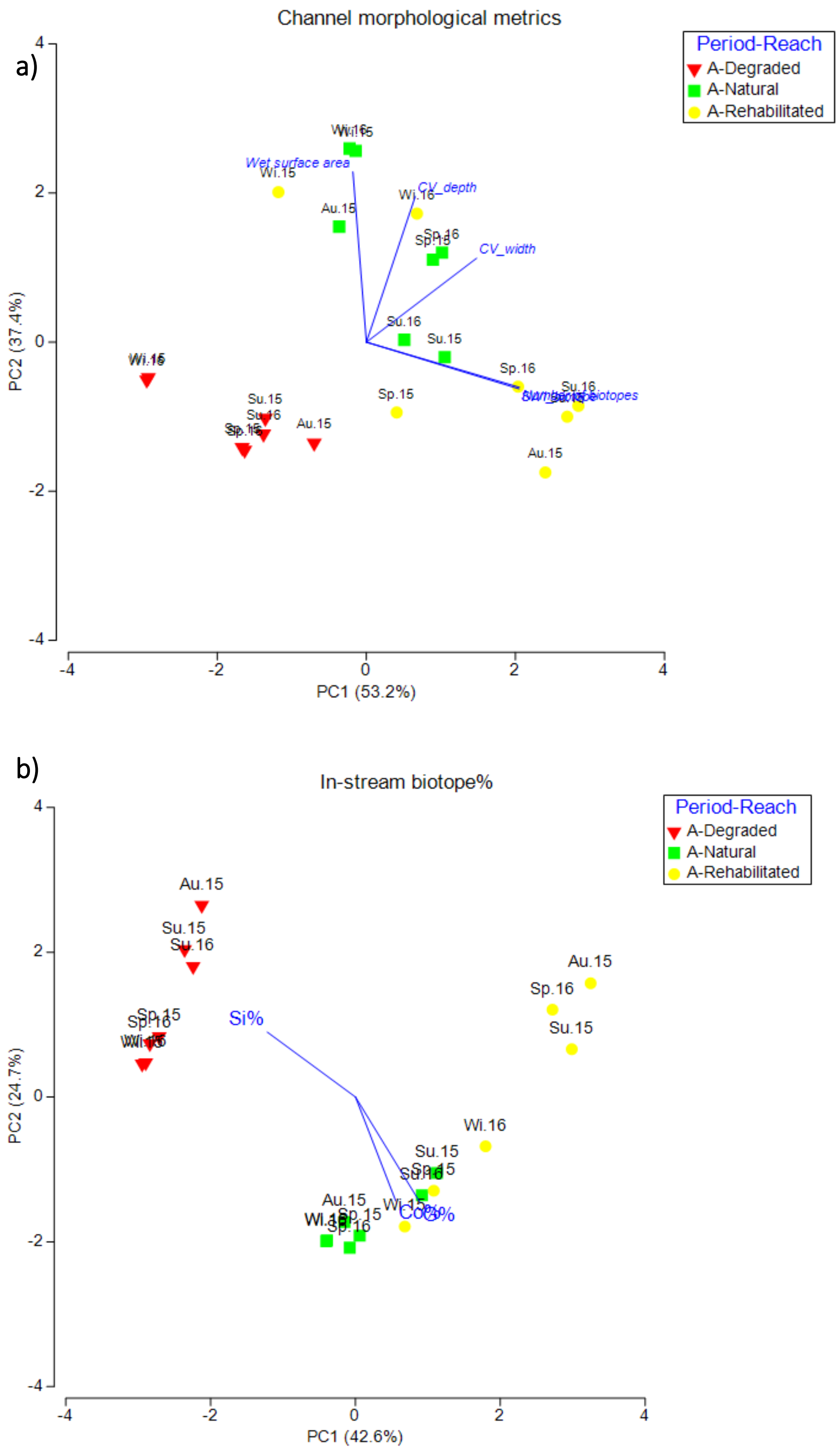


Figure 4.8. PCA ordination plots showing seasonal trends of a) channel morphological metrics, and b) in-stream biotope composition, depending on reach-level data measured over seven successive seasons during the first and second years after rehabilitation in degraded, natural and rehabilitated reaches. Wi.15, winter 2015; Sp.15, spring 2015; Su.15, summer 2015; Au.15, autumn 2015; and Wi.16, winter 2016; Sp.16, spring 2016; Su.16, summer 2016. Vectors indicate variables correlated at ρ>0.5.

4.4.2. Macroinvertebrate community structural and functional metrics

In spring, and summer 2014 (Sp.14 & Su.14), the natural reach had a higher Total Density (individuals m^{-2}), Total Biomass (mgDM m^{-2}), Taxon Richness, Taxon Diversity, Evenness, EPT Richness, EPT Diversity, EPT Count%, and EPT Biomass%. The degraded reach and before-rehabilitated (B-Rehabilitated) reach had a higher Chironomidae Count% and Chironomidae Biomass% (Figure 4.9; Figure 4.10; Figure 4.11;

Figure 4.12; Appendix 4.9. The natural reach differed significantly (P<0.05) from both the degraded and B-Rehabilitated reaches in all measured macroinvertebrate community structural metrics (natural and B-Rehabilitated reaches were not compared during Su.14, as the rehabilitation activities had been started). While degraded and B-Rehabilitated reaches were similar (P>0.05) in their measured community structural metrics (except that the degraded reach had higher Total Density than the B-Rehabilitated reach) (Appendix 4.8).

During the first post-rehabilitation year, in Sp.15, the rehabilitated reach's macroinvertebrate Total Density (individuals m^{-2}), Taxa Richness, Taxa Diversity, Evenness, EPT Richness, EPT Diversity, EPT Count%, and EPT Biomass% all increased significantly (P<0.05) compared with Sp.14. Chironomidae Count% decreased significantly (P<0.05) while Total Biomass (mgDM m^{-2}) and Chironomidae Biomass% responses were not significant (Appendix 4.7; 4.9).

The above positive influences of the rehabilitation continued during the second post-rehabilitation year. In Sp.16, all measured metrics were enhanced significantly compared with Sp.15 . The rehabilitated reach had a higher EPT Diversity than even the natural reach (P<0.05). In Sp.16 the rehabilitated reach's Total Biomass increased significantly (P<0.05) in comparison with before rehabilitation (Sp.14), while Chironomidae Biomass% decreased significantly (P<0.05). In Su.16, a significant enhancement in all of the Total Biomass, Taxa Richness, Taxa Diversity, Evenness, and EPT Diversity measures was recorded by comparison with Su.15, and the significant decrease in Chironomidae Biomass% also continued (Appendix 4.7; 4.9).

The rehabilitation was successful in enhancing the rehabilitated reach's macroinvertebrate community metrics towards those of the natural reach. During the first post-rehabilitation year, in Sp.15, the rehabilitated reach became similar to the natural reach as assessed by their Evenness, EPT Richness, and EPT Biomass% measures. In Su.15 they also became similar in terms of Taxa Diversity, Evenness, EPT Count%, EPT Biomass%, Chironomidae Count% and Chironomidae Biomass% (Appendix 4.8).

In the second post-rehabilitation year, the rehabilitated reach differed significantly from the degraded reach in terms of all measured metrics, and moved toward the natural reach in terms of Total Biomass, Taxa Richness, EPT Richness, EPT Diversity, EPT Biomass%, and Chironomidae Count%. The rehabilitated reach had a higher Taxa Diversity and Evenness than even the natural reach in Su.16 ($P<0.05$) (Appendix 4.8).

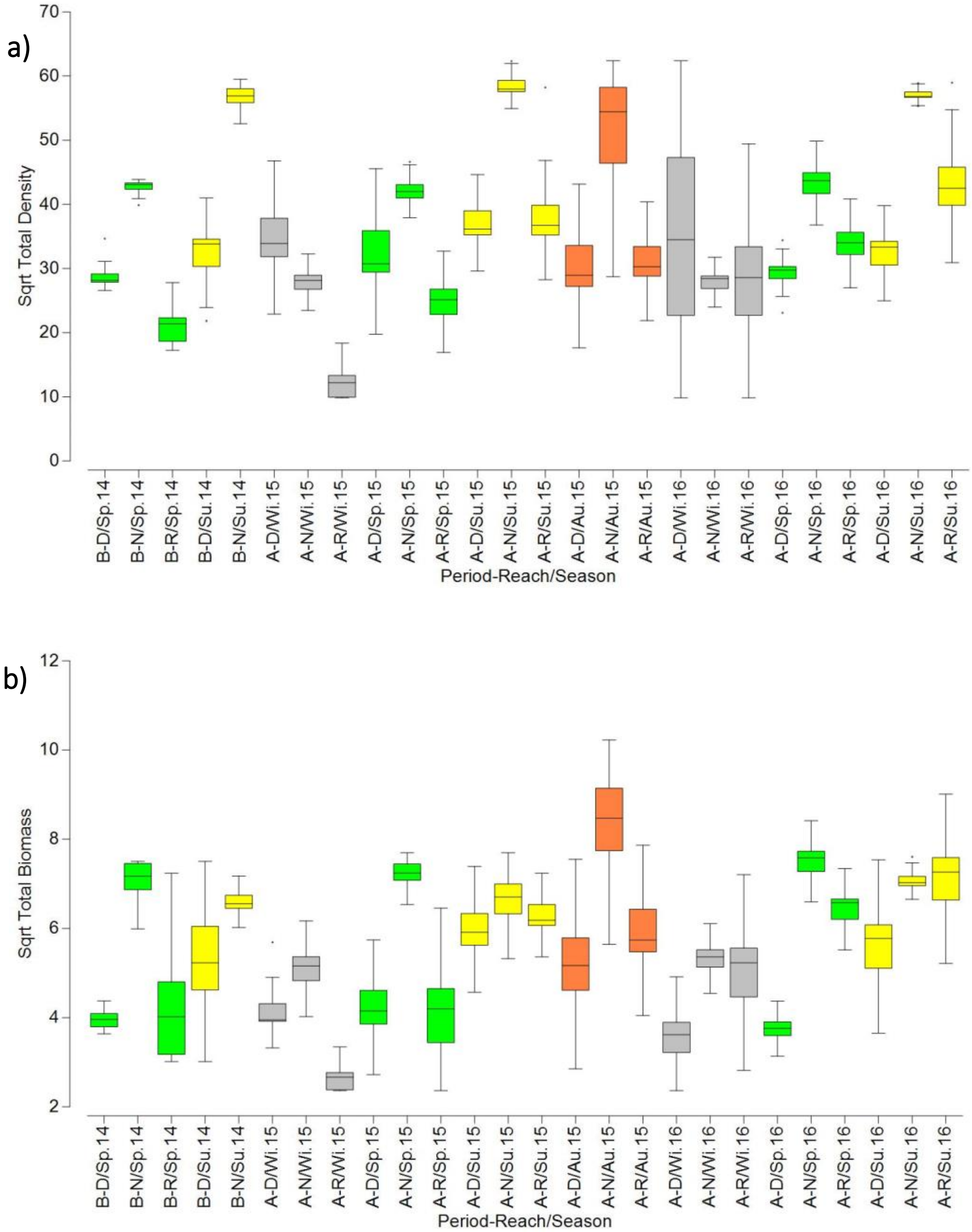


Figure 4.9. Seasonal variations in macroinvertebrate community structure according to the study reaches. a) Total Density; b) Total Biomass. D, Degraded reach; N, Natural reach; R, Rehabilitated reach. B, Before rehabilitation period; A, After rehabilitation period.

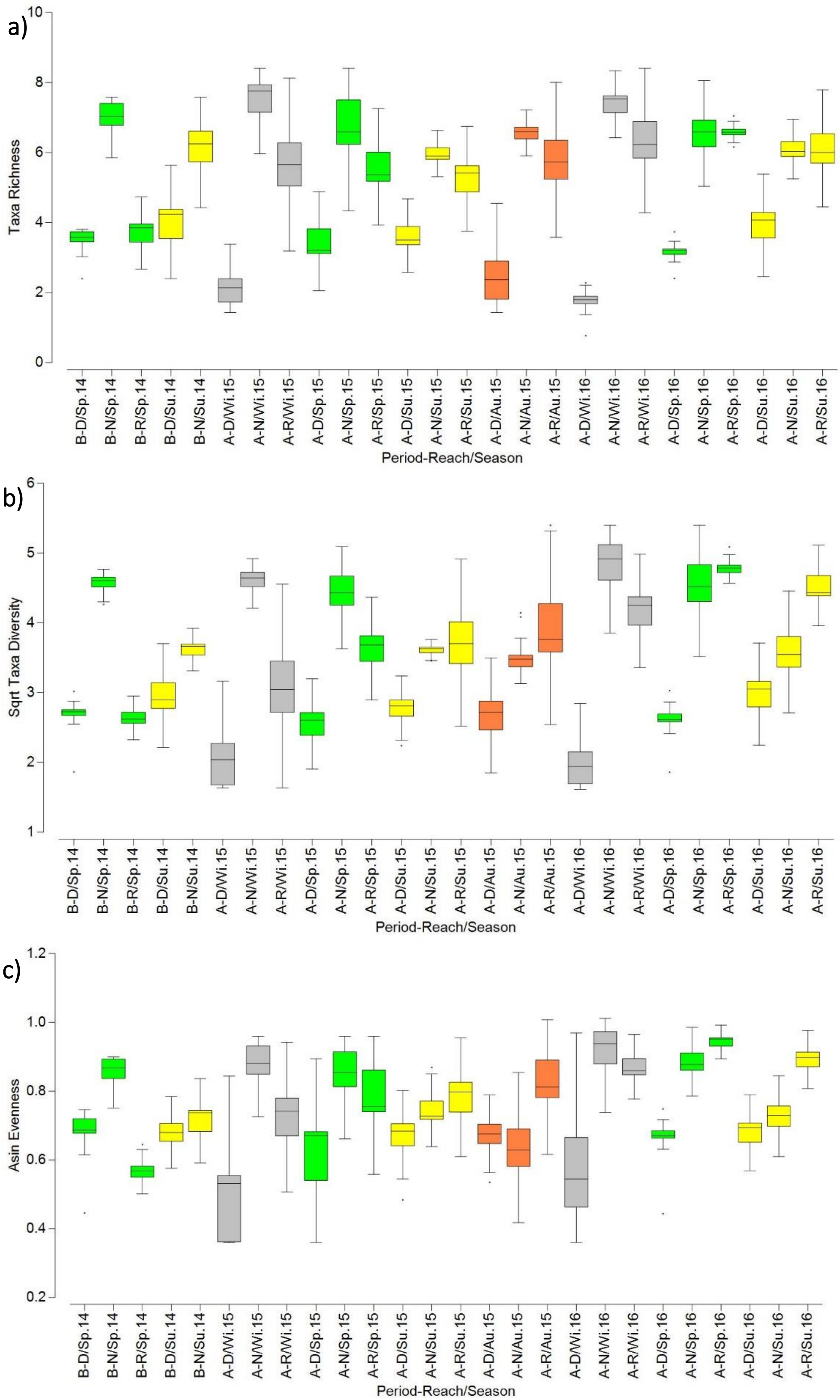
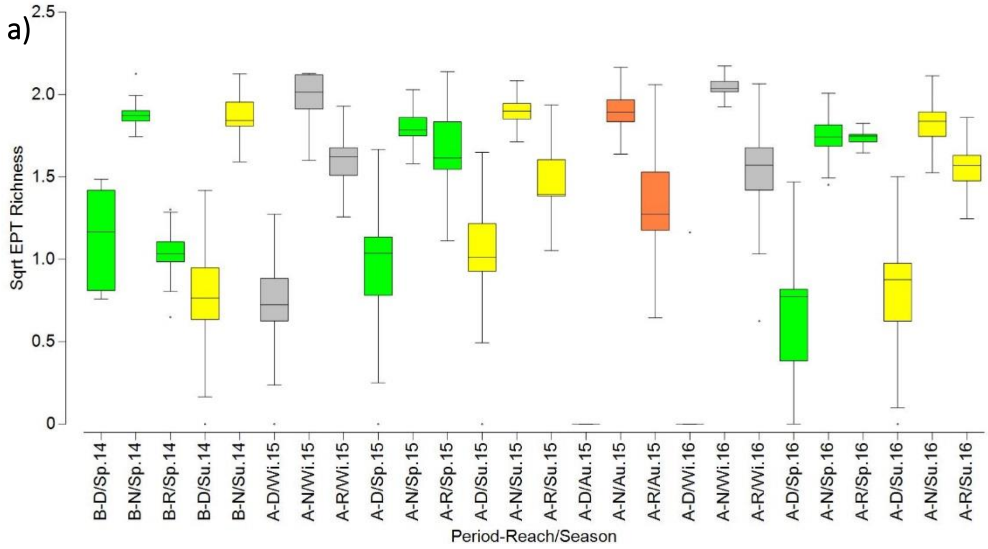


Figure 4.10. Seasonal variations in macroinvertebrate community structure according to the study reaches. a) Taxa Richness; b) Taxa Diversity; c) Evenness. D, Degraded reach; N, Natural reach; R, Rehabilitated reach; B, Before rehabilitation period; A, After rehabilitation period.



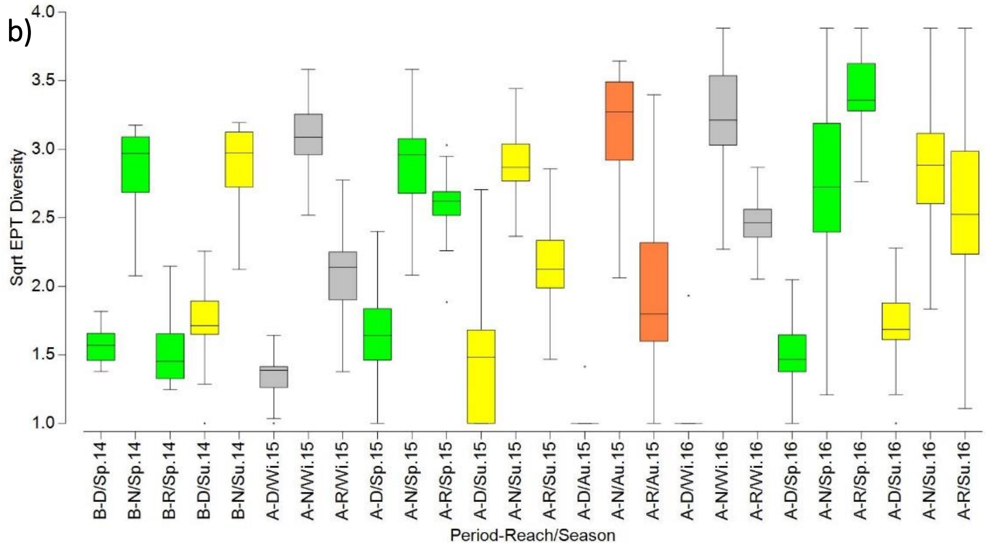


Figure 4.11. Seasonal variations in macroinvertebrate community structure according to the study reaches. a) EPT Richness; b) EPT Diversity. D, Degraded reach; N, Natural reach; R, Rehabilitated reach; B, Before rehabilitation period; A, After rehabilitation period.

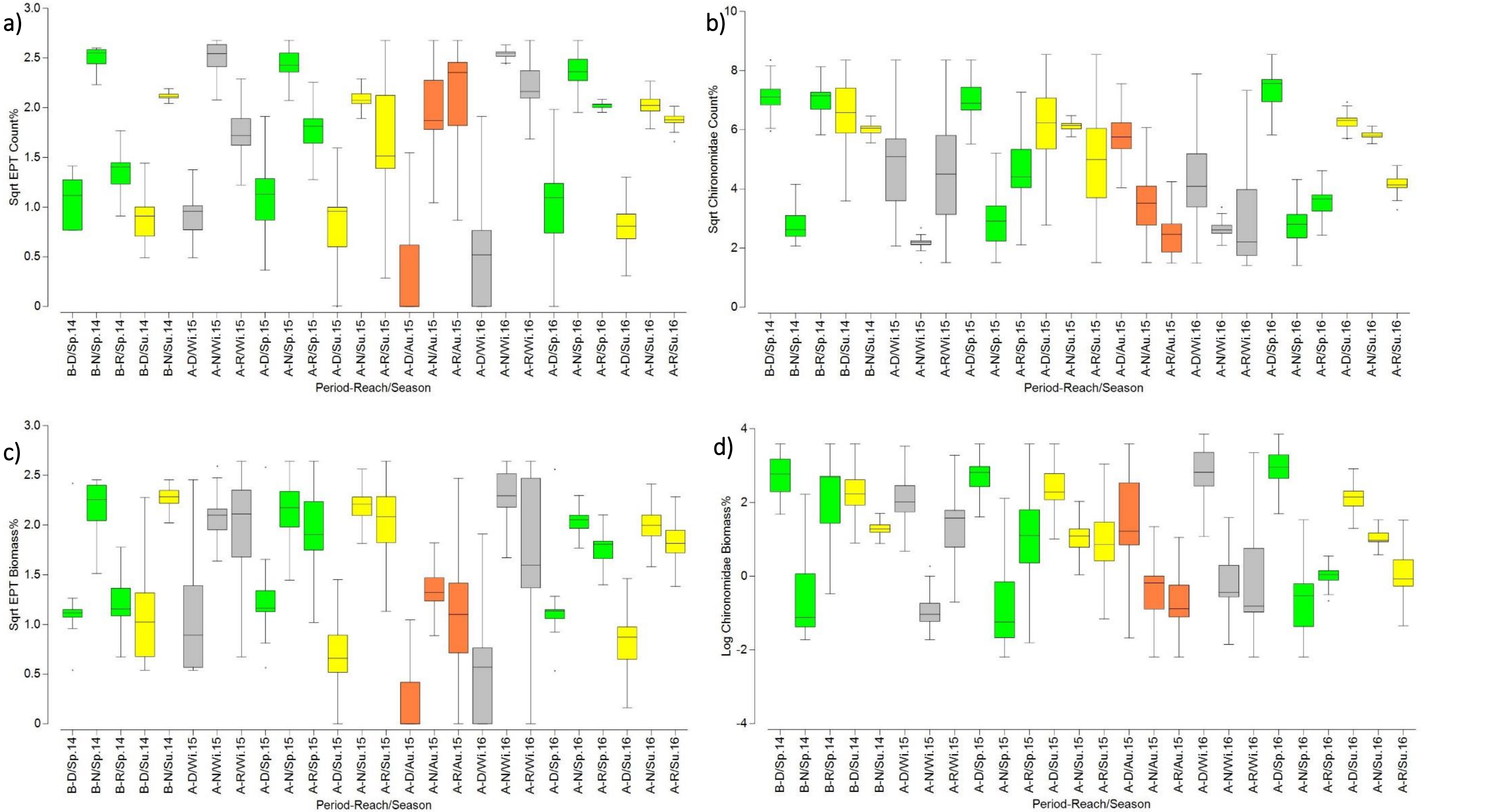


Figure 4.12. Seasonal variations in macroinvertebrate community structure according to the study reaches. a) EPT Count%; b) Chironomidae Count%; c) EPT Biomass%; d) Chironomidae Biomass%. D, Degraded reach; N, Natural reach; R, Rehabilitated reach; B, Before rehabilitation period; A, After rehabilitation period.

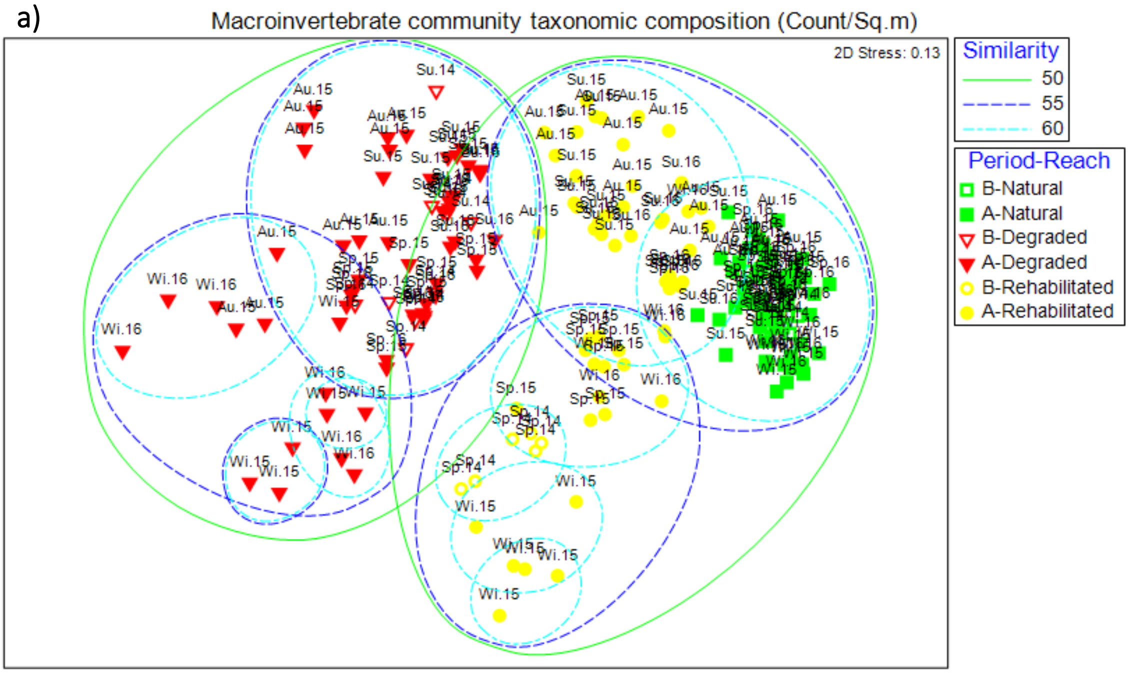
4.4.3. Macroinvertebrate community taxonomic composition

Before the rehabilitation process started, in spring 2014, the three study reaches differed significantly from each other in terms of their macroinvertebrate community taxonomic composition (both Taxa Count m^{-2} and Taxa Biomass m^{-2}) (P<0.005, Appendix 4.10). Rehabilitation had significant positive effects on the rehabilitated reach's macroinvertebrate taxonomic composition. During the first post-rehabilitation year, in spring 2015, the community composition of the rehabilitated reach was significantly enhanced toward that of the natural reach (Count m^{-2}, P=0.0005, and Biomass m^{-2}, P=0.0001, Appendix 4.11). Significant enhancements continued during the second post-rehabilitation year, especially when comparing Sp.16 with Sp.15 (P<0.0005) and Sp.14 (P<0.005). In Su.16, community composition density and biomass measures continued towards those of the natural reach in comparison with Su.15 (P<0.005).

The positive changes in the macroinvertebrate community composition were not sufficiently pronounced to make the rehabilitated reach significantly indistinguishable from the natural reach. Thus, between-reach differences in macroinvertebrate taxonomic composition remained significant after the rehabilitation process over the seven successive sampled seasons (Appendix 4.10). The increases in between-reach similarity are demonstrated by the clear separation of seasonal samples between the degraded reach on one side and the rehabilitated and natural reaches on the other side of the non-metric multidimensional scaling (nMDS) ordination plots (Figure 4.13).

The rehabilitation process decreased the average dissimilarity in macroinvertebrate community taxonomic composition (Count m^{-2}) between the rehabilitated and natural reaches. The rehabilitated reach became more similar to the natural reach than to the degraded reach. Similarity percentages (SIMPER) analyses on the 4th root transformed data indicated that, before rehabilitation, B-Rehabilitated reach was more similar to the degraded reach than the natural reach. The average dissimilarity between the B-Rehabilitated reach and the degraded reach was 45%, between the B-Rehabilitated and natural reaches was 54%, and between the degraded and the natural reaches was 59% (Appendix 4.12).

a)



b)

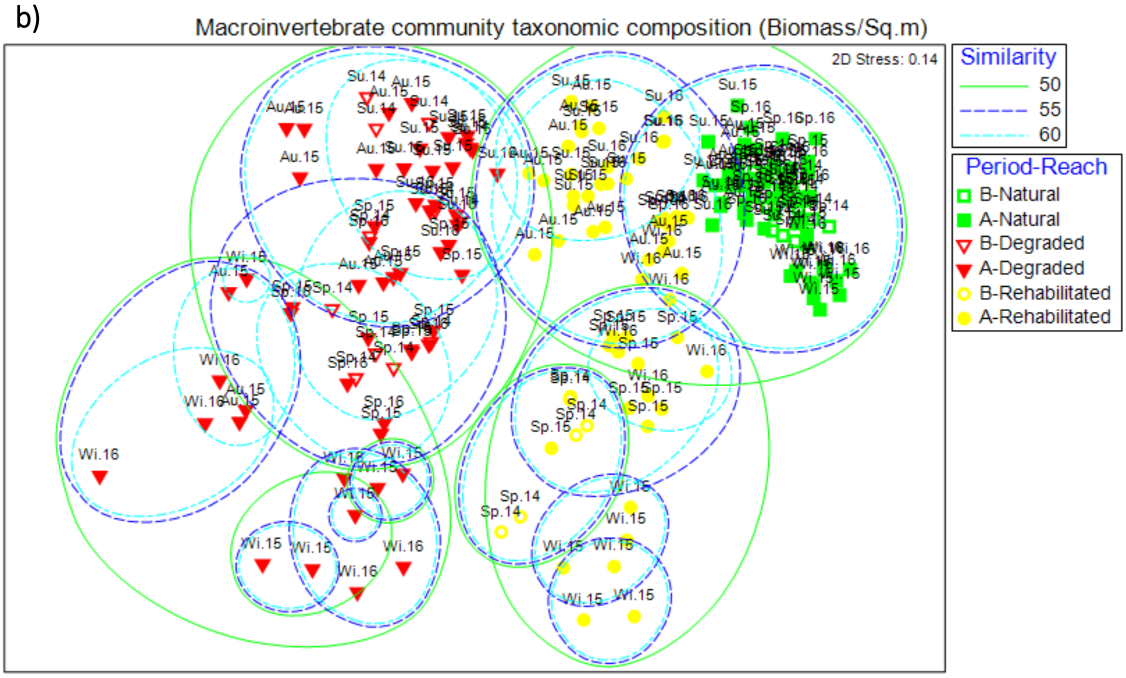


Figure 4.13. nMDS ordination plots, based on the 4th root transformed Bray-Curtis similarities of macroinvertebrate taxonomic composition, a) Counts m^{-2}; b) Biomasses m^{-2}. Clusters at 50%, 55% and 60% of similarity. Seasonal data collected before the rehabilitation process in spring 2014, then over seven successive seasons after the rehabilitation process. B, before rehabilitation; A, after rehabilitation.

After the rehabilitation process, in Sp.15, the average dissimilarity between the rehabilitated and natural reaches decreased to 44.09 in Sp.15. Thirty six of the 85 observed taxa contributed to 70% of the variability between the two reaches (Appendix 4.12). In Sp.16, the rehabilitated reach community composition continued to become similar to the natural reach, and between-reaches average dissimilarity was decreased to become 32.44. Thirty five of the 75 observed taxa contributed to 70% of the between-reaches variation (Appendix 4.12). The change of the rehabilitated reach's community composition toward the goal of the rehabilitation, and decreases in between-reach average dissimilarities are visualised in Figure 4.14. Although the differences between the rehabilitated and natural reaches in community taxonomic composition were significant, the rehabilitated reach's macroinvertebrate community composition was enhanced and moved towards that of the natural reach. Macroinvertebrate taxa that contributed to the between- and/or within-reaches dissimilarities are visualised in a shade plot (Figure 4.15): darker colours indicate higher density. A list of recorded macroinvertebrate taxa is available in presence/absence form in Appendix 4.29.

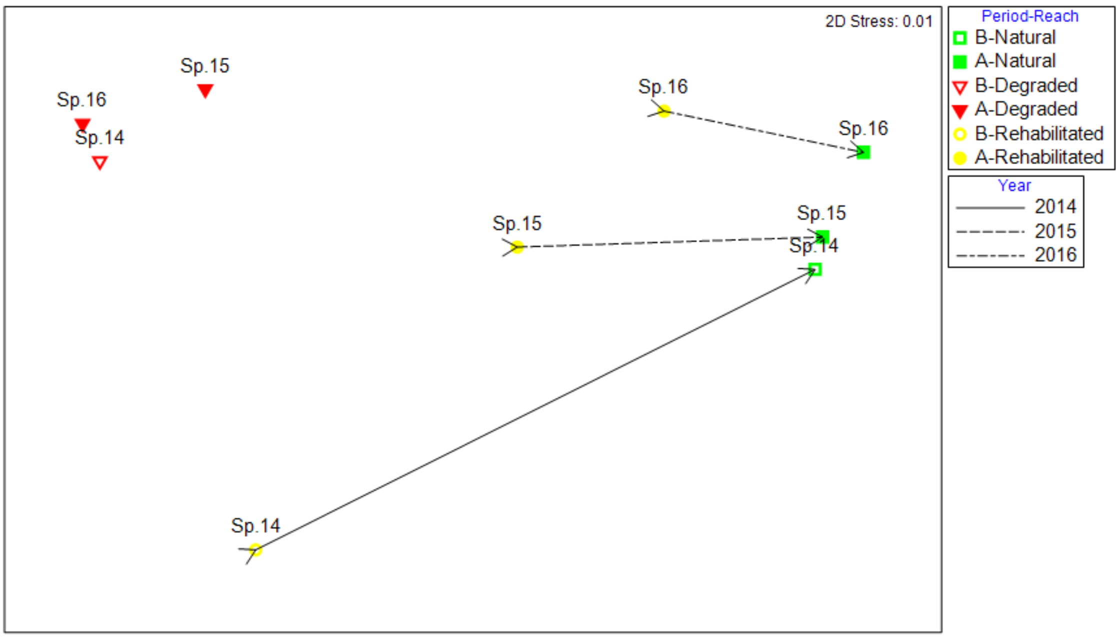


Figure 4.14. nMDS ordination plot of macroinvertebrate taxonomic composition (Count m^{-2}) showing that dissimilarity between the rehabilitated and natural reaches was decreased after rehabilitation. Sp.14, spring 2014; Sp.15, spring 2015; Sp.16, Spring 2016. The arrows indicate the direction of the changes in the rehabilitated reach's macroinvertebrate community composition towards the natural reach.

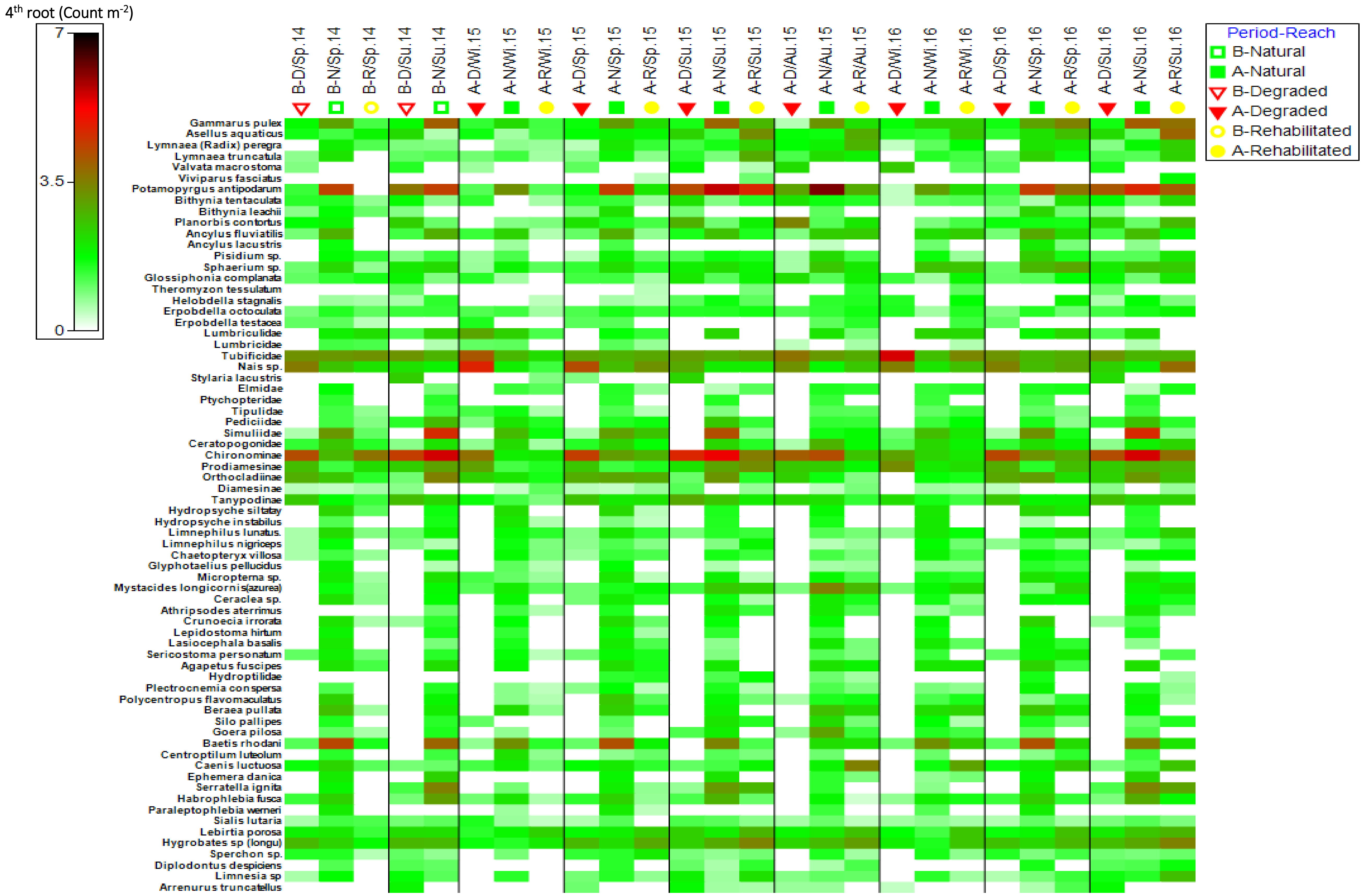


Figure 4.15. Shade plot of macroinvertebrate community taxonomic composition data matrix, showing taxa contribution to seasonal dissimilarities between the study reaches. The depth of colour shading is linearly proportional to a 4th root transformation of the Count m-2. Darker colours indicate higher density. B, before rehabilitation; A, after rehabilitation.

Macroinvertebrate family density Before the rehabilitation process started (Sp.14), both the degraded and B-Rehabilitated reaches had a higher density of Chironomidae (non-Tanypodinae) than did the natural reach. Chironomidae (non-Tanypodinae) average density contributed 15% of the dissimilarity between the degraded and natural reach, and 6.5% of the dissimilarity between the natural and B-Rehabilitated reaches. It was the most dominant family in the degraded reach (415 individual m^{-2}) and the B-Rehabilitated reach (206 individual m^{-2}), but was less dominant in the natural reach (93 individual m^{-2}) (Appendix 4.13).

Hydrobiidae and Baetidae were dominant families in the natural reach, while they were rarely recorded in the degraded or B-Rehabilitated reaches. Hydrobiidae average density contributed 17% of the dissimilarity between the degraded and natural reaches, and 20% of that between the natural and B-Rehabilitated reaches. Hydrobiidae average density was 347 individual m^{-2} in the natural reach, 3 individual m^{-2} in the degraded reach, and the family was absent in the B-Rehabilitated reach. Baetidae average density contributed 16% of the dissimilarity between the degraded and natural reaches, and 19% of that between the natural and B-Rehabilitated reaches. The natural reach had a higher average density (335 individual m^{-2}) than the degraded (2 individual m^{-2}) or B-Rehabilitated (6 individual m^{-2}) reaches (Appendix 4.13). Simuliidae, Planorbidae, Gammaridae, Limnephilidae, Lepidostomatidae, Leptophlebiidae, and Beraeidae families' average densities contributed to 70% of between-reach dissimilarities. They each had a high average density in the natural reach and were rare or absent in the degraded and B-Rehabilitated reaches (Appendix 4.13). Average densities and dissimilarities were calculated using SIMPER analyses on a non-transformed Family (Count m^{-2}) data matrix.

The rehabilitation process had significant effects on many macroinvertebrate families' average densities. In Sp.15 Chironomidae (non-Tanypodinae), and Lumbriculidae average densities decreased significantly (P<0.05) in comparison with those of the pre-rehabilitation spring (Sp.14). They contributed 20% of the pre-/post changes in macroinvertebrate community composition of the rehabilitated reach. Naididae, Hygrobatidae, Simuliidae, Libertiidae, and Gammaridae families' average density increased significantly (P<0.05) (Table 4.4; Appendix 4.14). They responded significantly to rehabilitation, but their contribution to dissimilarities between the natural and rehabilitated reaches remained nearly the same as before the rehabilitation (Appendix

4.13). In Sp.16, the average densities of many families continued to increase significantly. Hydrobiidae contribution to dissimilarity between natural and rehabilitated reaches was decreased to 14% from 20% in Sp.14. Chironomidae contribution to dissimilarity between natural and rehabilitated reaches decreased to 3.2% from 6.5% in Sp.14. In Su.16, rehabilitated reach Chironomidae average density was nearly a quarter of that recorded in the natural reach. This family was the dominant contributor of between-reach dissimilarities (27%) (Appendix 4.13). Tubificidae density decreased significantly (P<0.05) in comparison to that before rehabilitation (Sp.14).

Macroinvertebrate family biomass Before the rehabilitation process started (Sp.14), the natural reach had higher biomass than the degraded or B-Rehabilitated reaches. Hydrobiidae family average biomass contributed 33% of the dissimilarity between the degraded and natural reaches, and 34% of the dissimilarity between the natural and B-Rehabilitated reaches. It was 873 mgDM m^{-2} in the natural reach, but only 15 mgDM m^{-2} in the degraded reach, while it was absent in the B-Rehabilitated reach. Lymnaeidae contributed 13% of the dissimilarity between the degraded and natural reaches, and 12% between the natural and B-Rehabilitated reaches. It was 350 mgDM m^{-2} in the natural reach, 0.13 mgDM m^{-2} in the degraded reach, and 10 mgDM m^{-2} in the B-Rehabilitated reach. Limnephilidae, Pisidiidae, Planorbidae, and Erpobdellidae families' average biomass also contributed to the between-reaches average dissimilarities. They were dominant in the natural reach, but rare or absent in the other two reaches (Appendix 4.15).

In Sp.15, the rehabilitated reach's Lymnaeidae and Hydrobiidae families average biomass both increased significantly (*P*<0.05) in comparison with Sp.14. Increases in Lymnaeidae average biomass contributed 20%, and Hydrobiidae 5% of the pre-/post-rehabilitation changes in macroinvertebrate community composition biomass of the rehabilitated reach. Pisidiidae average biomass decreased significantly (*P*<0.05) to a fifth of that recorded in Sp.14, and contributed in 18% of pre-/post-dissimilarities in the rehabilitated reach average biomass. Glossiphoniidae and Chironomidae (non-Tanypodinae) families' average biomasses also decreased significantly and contributed to the temporal dissimilarities (Table 4.5; Appendix 4.16). They responded significantly, but their contributions to between natural and rehabilitated reach dissimilarities remained nearly same as before the rehabilitation (Appendix 4.15).

In Sp.16, Hydrobiidae average biomass contribution to dissimilarity between natural and rehabilitated reaches became 17%. Lymnaeidae contribution became 9%, Limnephilidae contribution became 5%. Pisidiidae contribution to between-reach dissimilarities, however, was increased to 27% (Appendix 4.15). Families' average biomass and dissimilarities contributions were calculated using SIMPER analyses on non-transformed Family (mg DM m^{-2}).

Table 4.4. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Count m^{-2}) data (at family-level), identifying those families most affected by morphological changes and contributing at least 70% of the temporal dissimilarity in community composition of the rehabilitated reach. Average abundances presented in Individuals m^{-2}. * indicates a significant change (P<0.05).

Spring 2014 vs Spring 2015				
Average dissimilarity = 55.07				
	Average Abundance			
Family	Sp.14	Sp.15	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	206	132*	18.28	18.28
Naididae	20	108**	15.04	33.32
Hygrobatidae	10	69**	10.09	43.40
Tubificidae	107	75	9.12	52.53
Simuliidae	1	42*	6.53	59.06
Libertiidae	3	34**	5.27	64.33
Gammaridae	3	21***	3.19	67.52
Lumbriculidae	22	4	3.14	70.66
Winter 2015 vs Winter 2016				
Average dissimilarity = 74.13				
	Average Abundance			
Family	Wi.15	Wi.16	Contribution%	Cumulative%
Tubificidae	23	130	13.67	13.67
Caenidae	1	77.51	10.12	23.79
Sphaeriidae	1.64	40.61	5.80	29.59
Hygrobatidae	15.62	40	5.63	35.22
Naididae	4	46	5.25	40.46
Lumbriculidae	2.39	25	5.23	45.70
Chironomidae (non- Tanypodinae)	29	47	4.86	50.56
Libertiidae	30.98	40	4.70	55.26
Asellidae	2.46	36.26	4.29	59.55
Gammaridae	2.67	32	4.24	63.79
Planorbidae	0.65	35.66	3.94	67.73
Baetidae	4.67	33.70	3.68	71.41
Spring 2014 vs Spring 2016				
Average dissimilarity = 63.43				
	Average Abundance			
Family	Sp.14	Sp.16	Contribution%	Cumulative%
Hydrobiidae	0	180**	17.43	17.43
Gammaridae	3	141**	13.54	30.96
Chironomidae (non- Tanypodinae)	206	137*	7.67	38.63
Sphaeriidae	0.31	75**	7.28	45.91
Tubificidae	107	65*	4.68	50.59
Naididae	20	69**	4.41	55.01
Hygrobatidae	10	54**	4.35	59.35
Libertiidae	3	45**	4.01	63.37
Limnephilidae	1.38	41**	3.87	67.24
Leptoceridae	1	34**	3.34	70.58
Spring 2015 vs Spring 2016				
Average dissimilarity = 54.61				
	Average Abundance			
Family	Sp.15	Sp.16	Contribution%	Cumulative%
Hydrobiidae	18	180***	16.09	16.09
Gammaridae	21	141***	12.00	28.09
Sphaeriidae	5	75***	7.02	35.11
Chironomidae (non- Tanypodinae)	132	137	6.76	41.87
Naididae	108	69	6.12	47.99
Simuliidae	42	6	3.80	51.79

Asellidae	11	46***	3.56	55.35
Limnephilidae	7	40.64***	3.43	58.78
Tubificidae	74.61	64.64	3.22	62.01
Hygrobatidae	69	53.92	3.15	65.15
Caenidae	4.18	32.87	2.85	68.00
Planorbidae	2.81	30.41**	2.72	70.71
Summer 15 vs Summer 16				
Average dissimilarity = 44.20				
	Average Abundance			
Family	Su.15	Su.16	Contribution%	Cumulative%
Hydrobiidae	492	244	17.69	17.69
Chironomidae (non- Tanypodinae)	275	288	14.11	31.81
Naididae	15	201***	12.04	43.85
Gammaridae	53	188**	7.83	51.67
Asellidae	116	220	6.93	58.60
Lymnaeidae	101.48	65	5.19	63.79
Ephemerellidae	54	80	4.82	68.60
Hygrobatidae	135	142	4.63	73.23

*P<0.05; **P<0.005; ***P<0.0005

Table 4.5. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Biomass m^{-2}) data (at family-level), identifying most affected families by morphological changes and contributing at least 70% of the temporal dissimilarity in community composition of the rehabilitated reach. Average biomass presented in mgDM m^{-2}. * indicates a significant change (P<0.05).

Spring 2014 vs Spring 2015				
Average dissimilarity = 75.52				
	Average Biomass			
Family	Sp.14	Sp.15	Contribution%	Cumulative%
Lymnaeidae	10	108*	20.03	20.03
Pisidiidae	98	17*	17.47	37.50
Glossiphoniidae	49	1***	9.30	46.80
Erpobdellidae	29	33	8.43	55.24
Hydrobiidae	0	26**	5.18	60.42
Chironomidae (non-Tanypodinae)	21.24	9*	3.68	64.10
Sericostomatidae	4.30	16	3.51	67.61
Limnephilidae	2	12**	2.93	70.54
Winter 2015 vs Winter 2016				
Average dissimilarity = 87.11				
	Average Biomass			
Family	Wi.15	Wi.16	Contribution%	Cumulative%
Lymnaeidae	8	209	26.35	26.35
Glossiphoniidae	0.04	157	14.19	40.54
Limnephilidae	8.87	49	12.14	52.68
Planorbidae	0.24	97	10.89	63.57
Hydrobiidae	3	68	7.47	71.04
Spring 2014 vs Spring 2016				
Average dissimilarity = 84.31				
	Average Biomass			
Family	Sp.14	Sp.16	Contribution%	Cumulative%
Lymnaeidae	10	444**	22.80	22.80
Hydrobiidae	0	403**	22.38	45.18
Bithyniidae	6	203**	11.41	56.59
Gammaridae	1	134**	7.61	64.20
Pisidiidae	98	105	6.53	70.73
Spring 2015 vs Spring 2016				
Average dissimilarity = 79.00				
	Average Biomass			
Family	Sp.15	Sp.16	Contribution%	Cumulative%
Hydrobiidae	26	403***	22.16	22.16
Lymnaeidae	108	444*	19.87	42.03
Bithyniidae	1	203***	12.33	54.36
Gammaridae	7	134***	7.65	62.02
Glossiphoniidae	1	121***	7.22	69.23
Sphaeriidae	4	114	6.60	75.83
Summer 15 vs Summer 16				
Average dissimilarity = 51.70				
	Average Biomass			
Family	Su.15	Su.16	Contribution%	Cumulative%
Hydrobiidae	1890	502	30.37	30.37
Lymnaeidae	448	761	18.34	48.71
Erpobdellidae	210	380	11.49	60.20
Pisidiidae	107	279*	6.88	67.08
Gammaridae	17.61	190***	6.31	73.38

*P<0.05; **P<0.005; ***P<0.0005

4.4.4. Macroinvertebrate FFGs community composition

In spring and summer 2014, macroinvertebrate FFGs community composition (Count m^{-2}) differed significantly between degraded, natural and B-Rehabilitated reaches ($P<0.005$). The degraded and natural reaches also differed significantly in terms of FFGs biomass composition ($P<0.005$). The B-Rehabilitated reach differed significantly from the natural reach ($P<0.005$), but was similar to the degraded reach ($P>0.05$) (Appendix 4.17).

The rehabilitated reach's FFGs composition (both Count m^{-2} and Biomass m^{-2}) difference was significantly positive when comparing first and second post-rehabilitation spring compositions with that of the pre-rehabilitation (Appendix 4.18). The rehabilitation was successful in enhancing the rehabilitated reach's feeding composition toward the natural reach and away from the degraded reach's composition. In Sp.15, the rehabilitated reach FFGs composition (Biomass m^{-2}) differed significantly from the degraded reach's composition, while they were similar to each other before the rehabilitation, and become similar to the natural reach's composition (Appendix 4.17). The study reach's FFGs compositions are shown in the nMDS ordination plots (Figure 4.16).

Before the rehabilitation process started, in Sp.14, FFGs composition of the B-Rehabilitated reach was more similar to the degraded reach than the natural reach. Average dissimilarity in FFGs composition (Count m^{-2}) between the degraded and B-Rehabilitated reaches was 10.62, while that between the natural and B-Rehabilitated reaches was 17.39. Scraper, shredder, filter-feeder, and predator feeding groups' densities contributed 80% of dissimilarity between natural and B-Rehabilitated reaches. The scraper contribution was 31%, shredders 25%, filter-feeders 14%, and predators 12% (Appendix 4.19).

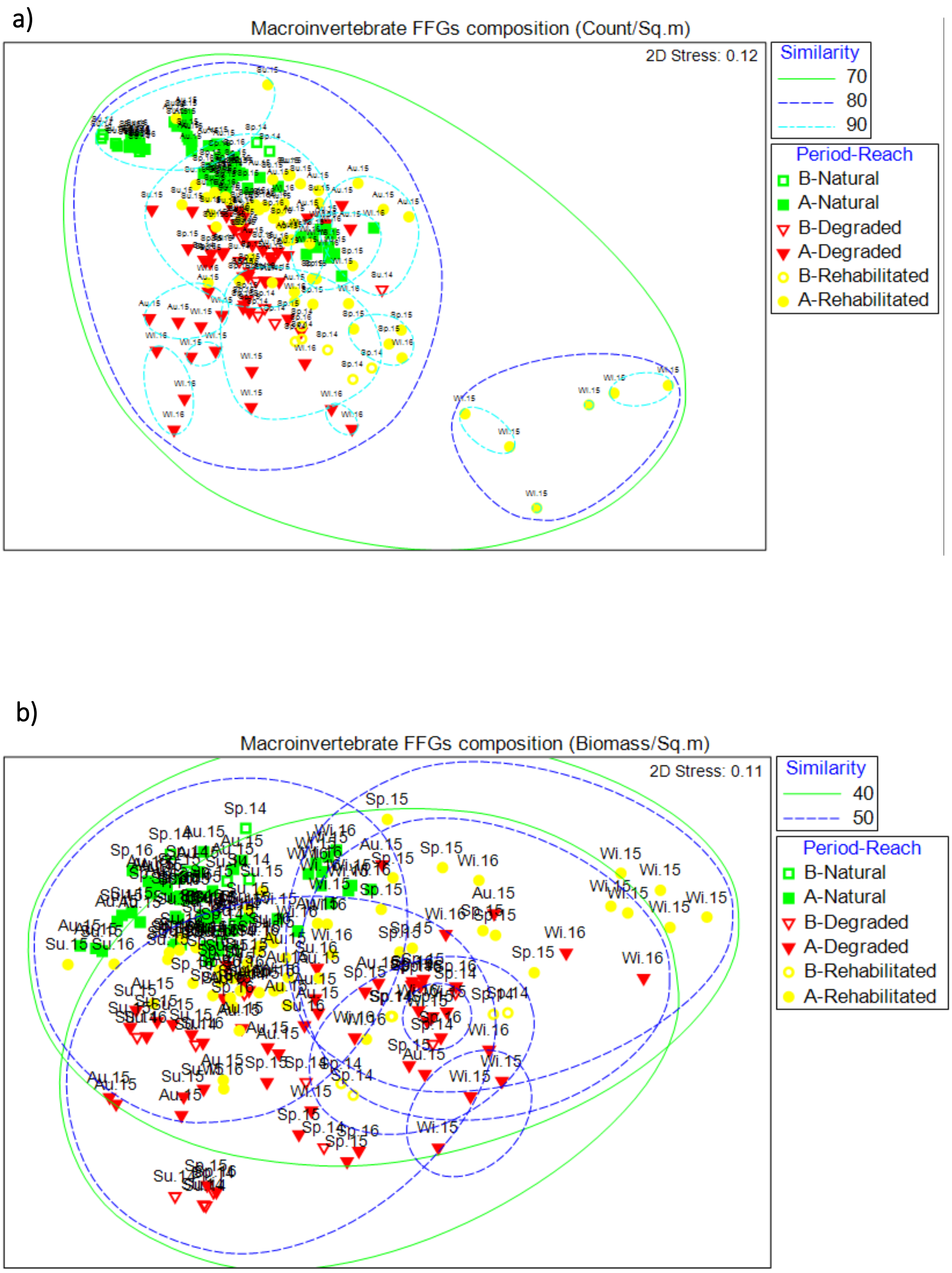


Figure 4.16. nMDS plot, based on the 4^{th} root transformed Bray-Curtis similarities of FFGs composition. a) Based on FFGs Count m^{-2}, b) Based on FFGs Biomass m^{-2}. Clusters at 70%, 80%, and 90% of similarity. B, Before the rehabilitation; A, After the rehabilitation.

The rehabilitation was successful in enhancing the rehabilitated reach's feeding groups' composition toward that of the natural reach. In Sp.15 the average dissimilarity between the rehabilitated and natural reaches was decreased to become 14.07. In Sp.16 the enhancement continued toward the natural reach, and average dissimilarity was decreased to become 6.80 while it was 17.39 in Sp.14. Shredders count contribution to between-reach dissimilarities decreased to a half (from 25% in Sp.14, to 12% in Sp.16), while scraper count contribution remained dominant. Although between-reach dissimilarity in functional composition remained significant across periods, there was a trend towards the goal of the rehabilitation, which was the natural reach (Figure 4.17; Appendix 4.19). FFGs' contribution to between- and/or within-reaches dissimilarities is visualised in Figure 4.18: darker colour indicates higher abundance feeding group.

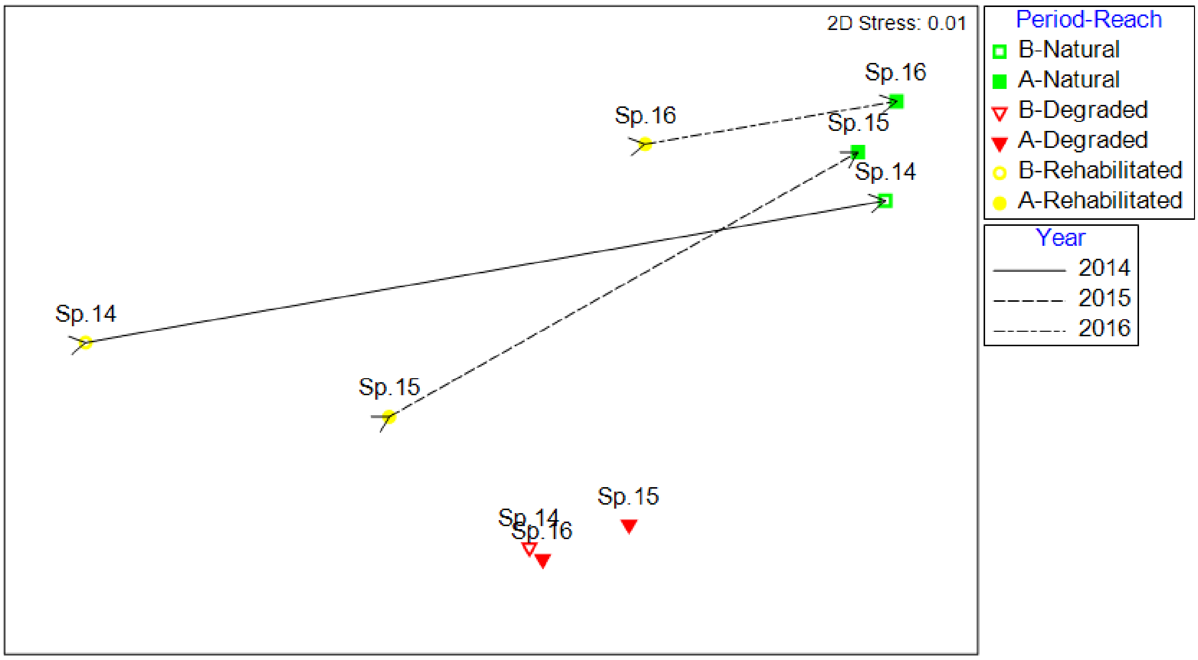


Figure 4.17. nMDS ordination plot of macroinvertebrate FFG composition (Count m^{-2}) showing that dissimilarity between the rehabilitated and natural reach compositions was decreased after the rehabilitation process. Sp, spring; 14, 2014; 15, 2015; 16, 2016. The arrows indicate the direction of the changes in the rehabilitated reach's macroinvertebrate community composition towards the natural reach.

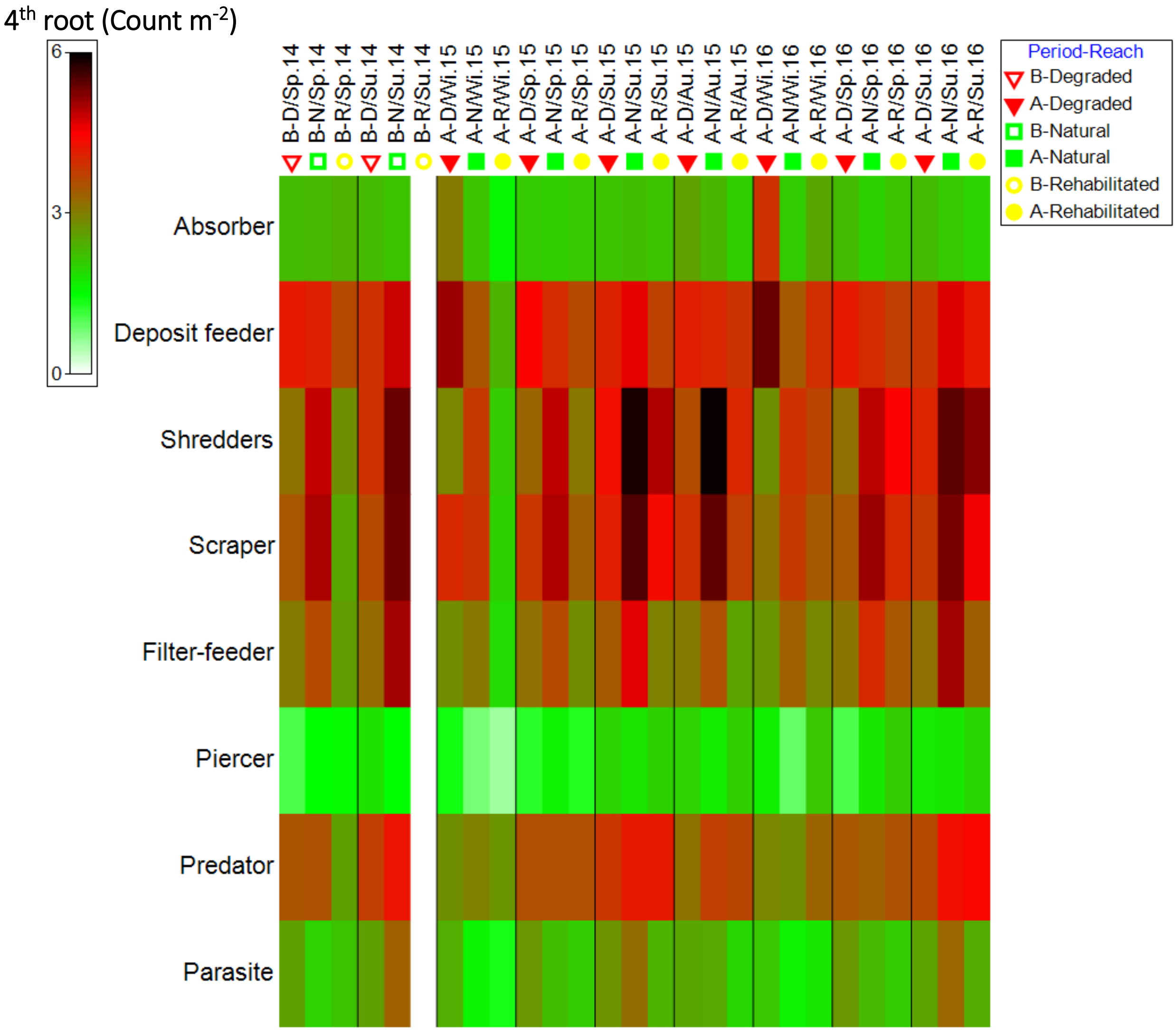


Figure 4.18. Shade plot of macroinvertebrate Functional Feeding Groups (FFGs) community composition data matrix, showing feeding groups' contribution to seasonal dissimilarities between the study reaches. The depth of colour shading is linearly proportional to a 4th root transformation of the Count m^{-2}. The darker colours indicate higher density. B, before the rehabilitation; A, after the rehabilitation.

4.4.5. Macroinvertebrate FFGs abundance and biomass

In spring 2014, before the rehabilitation process started, the natural reach had a higher average abundance (*P*<0.005) of deposit-feeder, shredder, scraper, filter-feeder, and predator macroinvertebrates than did the B-Rehabilitated reach. The natural reach also had a higher average abundance of shredder, scraper, and filter-feeder groups than the degraded reach (*P*<0.005). Parasite feeding group average abundance was higher (*P*<0.005) in the degraded reach than the natural and B-Rehabilitated reaches. In Su.14, the natural reach had a higher average abundance (*P*<0.005) of all feeding groups, except absorber and piercer feeding groups, which were similar in both reaches in terms of average abundance (Figure 4.19; Appendix 4.20; 4.21).

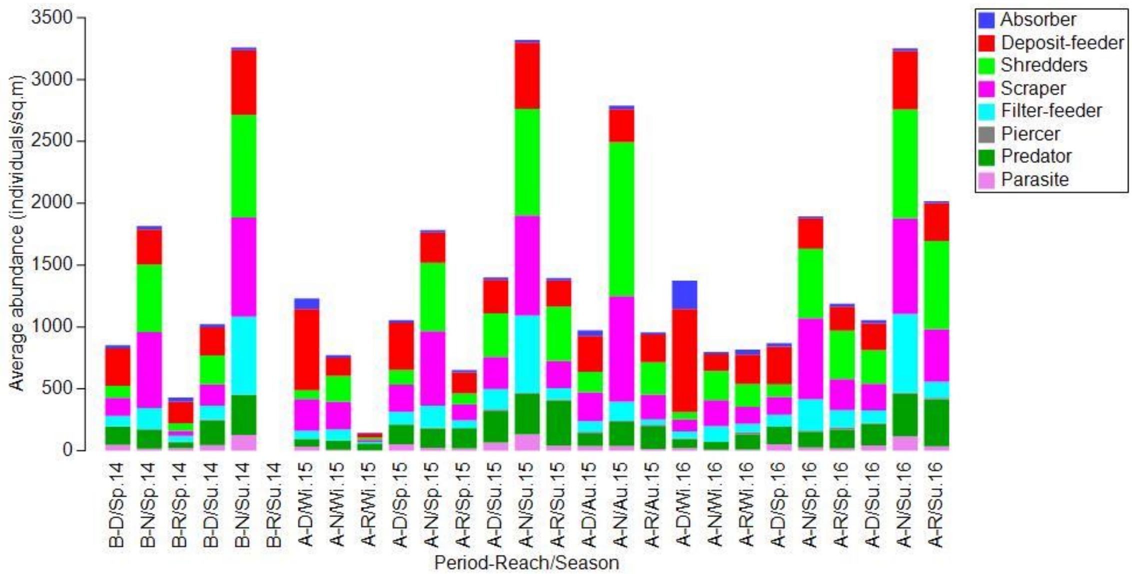


Figure 4.19. Macroinvertebrate feeding groups average abundance (individual m^{-2}). B, Before rehabilitation; A, After rehabilitation. D, Degraded reach; N, Natural reach; R, Rehabilitated reach.

The rehabilitation process affected positively the average abundance of all feeding groups (except the parasite group) (*P*<0.05) (Appendix 4.22). Deposit-feeder, shredder, scraper, filter-feeder, and predator feeding groups were the most affected groups, and contributed 70% of the pre-/post-rehabilitation differences (Table 4.6). In spring 2015, the rehabilitated reach's predator and scraper feeding groups average abundance were significantly higher (*P*<0.0005) than in Sp.14. Predator average abundance increased from 46 individual m^{-2} in Sp.14 to 163 individual m^{-2} in Sp.15. This change contributed 32% of the pre-/post-rehabilitation difference in macroinvertebrate FFG composition of the rehabilitated reach. Scraper average abundance increased from 39 individual m^{-2} in Sp.14 to 129 individual m^{-2} in Sp.15. This change contributed 24% of the pre-/post-rehabilitation differences (Table 4.6; Appendix 4.22).

In Sp.16, shredder average abundance increased significantly ($P<0.005$) to became 392 individual m^{-2}, whereas it was 61 individual m^{-2} in Sp.14. This change contributed 41% of the pre-/post-rehabilitation differences. Filter-feeder average abundance increased to 141 individuals m^{-2} from 48 individuals m^{-2} in Sp.14. Significant increases in scraper average abundance continued: it rose to 249 individuals m^{-2} in Sp.16. In Su.16, the rehabilitated reach had a higher average abundance ($P<0.05$) of each of shredders, scrapers, deposit-feeders, and filter-feeders compared with Su.15. The rehabilitation enhanced the rehabilitated reach's deposit-feeder average abundance to become similar to that of the natural reach in Sp.16.In Su.16, rehabilitated reach's shredder, and predator average abundance become similar to those of the natural reach (Appendix 4.21).

Table 4.6. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate FFGs composition (Count m^{-2}) data, identifying the most affected feeding groups that contributed 70% of the temporal dissimilarity in community composition of the rehabilitated reach. Average abundance presented in Individuals m^{-2}. Asterisks indicate the degree of significance: * = P<0.05; ** = P<0.005; *** = P<0.0005.

Spring 2014 vs Spring 2015				
Average dissimilarity = 33.82				
	Average Abundance			
Feeding group	Sp.14	Sp.15	Contribution%	Cumulative%
Predator	46	163***	32.41	32.41
Scraper	39	129***	23.74	56.15
Deposit feeder	176	168	13.97	70.12
Winter 2015 vs Winter 2016				
Average dissimilarity = 67.47				
	Average Abundance			
Feeding group	Wi.15	Wi.16	Contribution%	Cumulative%
Deposit feeder	31	240**	30.88	30.88
Shredders	19	184**	24.01	54.88
Scraper	16	136*	15.45	70.33
Spring 2014 vs Spring 2016				
Average dissimilarity = 50.52				
	Average Abundance			
Feeding group	Sp.14	Sp.16	Contribution%	Cumulative%
Shredders	61	392**	40.52	40.52
Scraper	39	249**	25.42	65.94
Predator	46	151**	13.08	79.02
Spring 2015 vs Spring 2016				
Average dissimilarity = 35.36				
	Average Abundance			
Feeding group	Sp.15	Sp.16	Contribution%	Cumulative%
Shredders	88	392***	47.18	47.18
Scraper	129	249**	18.87	66.05
Filter-feeder	63	141*	12.47	78.52
Summer 15 vs Summer 16				
Average dissimilarity = 24.40				
	Average Abundance			
Feeding group	Su.15	Su.16	Contribution%	Cumulative%
Shredders	438	714*	33.50	33.50
Scraper	220	425*	26.40	59.90
Deposit feeder	213	306*	16.71	76.61

In Sp.14, deposit-feeder, shredder, scraper, predator, and parasite FFGs average biomass differed (*P*<0.05) most between the reaches. The natural reach had higher average biomasses of deposit-feeder, shredder, scraper, and predator FFGs than the degraded and B-Rehabilitated reaches. Parasite average biomass was higher in the degraded reach than the natural and B-Rehabilitated reaches. In Su.14, the natural reach differed significantly (*P*<0.05) from the degraded reach. The natural reach had higher average biomasses of deposit-feeder, shredder, and scraper FFGs, while the degraded reach had higher average biomasses of filter-feeder, piercer, and parasite FFGs (Figure 4.20; Appendix 4.23; 4.24).

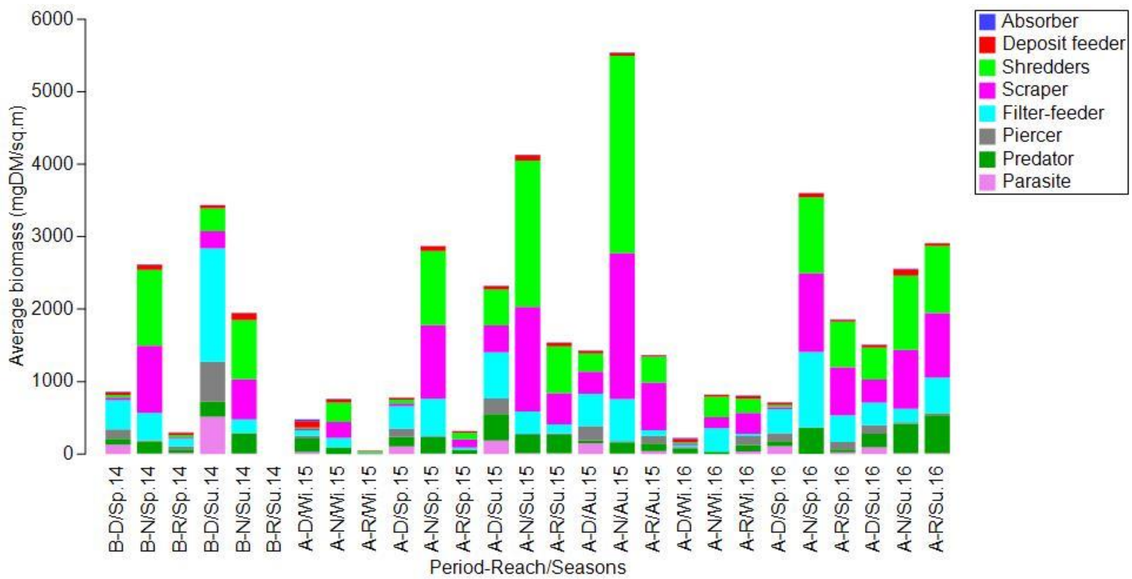


Figure 4.20. Functional feeding groups based on average biomass (mgDM m^{-2}). B, Before rehabilitation; A, After rehabilitation. D, Degraded reach; N, Natural reach; R, Rehabilitated reach.

Shredder, scraper, filter-feeder, piercer, and predator feeding groups contributed 70% of the pre-/post-rehabilitation differences (Table 4.7; Appendix 4.25). In Sp.15, scraper average biomass increased from 18 mgDM m^{-2} in Sp.14 to 111 mgDM m^{-2}, and contributed 25% of pre-/post-rehabilitation differences (*P*<0.05). Shredder average biomass increased from 29 mgDM m$^{2-2}$ to 88 mgDM m^{-2} and contributed 18% of differences (*P*<0.05). Filter-feeder average biomass decreased significantly from 107 mgDM m^{-2} in Sp.14 to 30 mgDM m^{-2}, and contributed 24% of pre-/post-rehabilitation differences (*P*<0.05).

In Wi.16, average biomass of all feeding groups increased significantly (P<0.05) compared with Wi.15. In Sp.16, shredder, scraper, filter-feeder, piercer, and parasite average biomasses increased significantly compared with Sp.15 and Sp.14. Scraper, shredder, and filter-feeder group average biomass contributed 89% of differences between Sp.16 and Sp.15. In Su.16, scraper, shredder, and predator group average biomasses contributed 77% of differences between Su.16 and Su.15. The rehabilitation was successful in enhancing the rehabilitated reach's shredder, scraper, predator, and parasite average biomasses to become similar to those of the natural reach in Su.16 (Appendix 4.24).

Table 4.7. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate FFGs composition (Biomass m^{-2}) data, identifying the most affected feeding groups that contributed in 70% of the temporal dissimilarity in community composition of the rehabilitated reach. Average biomass presented in mgDM/m^{2}. Asterisks indicate the degree of significance: * = P<0.05; ** = P<0.005; *** = P<0.0005.

Spring 2014 vs Spring 2015				
Average dissimilarity = 57.42				
	Average Biomass			
Feeding group	Sp.14	Sp.15	Contribution%	Cumulative%
Scraper	18	111*	25.01	25.01
Filter-feeder	107	30*	23.93	48.95
Shredders	29	88*	17.79	66.74
Predator	51	58	14.23	80.96
Winter 2015 vs Winter 2016				
Average dissimilarity = 83.83				
	Average Biomass			
Feeding group	Wi.15	Wi.16	Contribution%	Cumulative%
Scraper	9.40	288**	35.83	35.83
Shredders	17.82	196.35**	31.13	66.96
Piercer	0.13	122.44*	11.53	78.50
Spring 2014 vs Spring 2016				
Average dissimilarity = 76.25				
	Average Biomass			
Feeding group	Sp.14	Sp.15	Contribution%	Cumulative%
Scraper	18	661**	38.44	38.44
Shredders	29	630**	36.93	75.37
Spring 2015 vs Spring 2016				
Average dissimilarity = 74.03				
	Average Biomass			
Feeding group	Sp.15	Sp.16	Contribution%	Cumulative%
Shredders	88	630***	33.99	33.99
Scraper	111	661**	33.69	67.68
Filter-feeder	30	371***	21.32	89.00
Summer 15 vs Summer 16				
Average dissimilarity = 42.25				
	Average Biomass			
Feeding group	Su.15	Su.16	Contribution%	Cumulative%
Scraper	430	891*	27.28	27.28
Shredders	645	924*	25.76	53.04
Predator	253	522*	24.22	77.26

3.4.6. Relationships between morphological variables and macroinvertebrate community structure, diversities and composition

Distance-based linear modelling (DISTLM) analysis was carried out on macroinvertebrate structural and functional univariate metrics that responded significantly to the rehabilitation process. Sequential tests gave a different combination of morphological variables or biotope% in the best-fit models for each macroinvertebrate metric according to each of both pre-/post-rehabilitation springs (Sp.14:Sp.15, & Sp.14:Sp.16), and first/second post-rehabilitation summers (Su.15:Su.16). In some cases, certain morphological variables improved the Akaike Information Criterion (AIC) in the model development, but their contributions to the model were not statistically significant. Therefore I chose to accept only those models that included the significant morphological variables.

At the reach-level, post-rehabilitation increases in in-stream biotope diversity (SWI_biotope), the covariance of channel depth (CV_depth), and covariance of channel width (CV_width) explained significant variations in some of the measured macroinvertebrate community univariate metrics (Appendix 4.26). SWI_biotope was related positively to increases in Taxa Richness, Evenness, and EPT Diversity, but negatively related to Chironomidae Count%. Increases in CV_depth were related positively to increases in Evenness and EPT Richness. Increases in CV_width were related positively to increases in Evenness, but were related negatively to Chironomidae Biomass%.

At biotope-level, increases in Gravel%, Marginal plant%, Woody debris%, and Leaf-litter% were related positively to significant increases in most of the measured macroinvertebrate community univariate metrics (Appendix 4.26). They were related positively to post-rehabilitation increases of Total Density, Total Biomass, Taxa Richness, Taxa Diversity, EPT Richness, EPT Diversity, and EPT Biomass%. However, Gravel% was related negatively to variations in Chironomidae Count% and Chironomidae Biomass%. Silt% was related negatively to Total Biomass and EPT Count%.

Temporal variations in macroinvertebrate FFGs abundance and biomass were explained mainly by post-rehabilitation changes in in-stream biotope percentages rather than by measured channel morphological parameters (Appendix 4.27 & 4.28). Significant increases in shredder macroinvertebrates abundance and biomass were related positively to post-rehabilitation increases in Gravel%, Marginal plant%, Leaf-litter%, and CV_depth. Increases in Scraper abundance and biomass were related positively to increases in CV_width, Gravel%, and Macroalgae%, but were related negatively to Sand%.

Filter-feeder and Piercer biomasses decreased in the first post-rehabilitation spring along with decreased Silt%. Filter-feeder macroinvertebrate abundance and biomass recovered during the second post-rehabilitation spring and summer. They increased significantly in a positive relationship to post-rehabilitation increases in SWI_biotope, Gravel%, Leaf-litter%, and Marginal plant%. Piercer macroinvertebrates abundance and biomass were also increased in Sp.16. They were related positively to post-rehabilitation increases in CV_width and Gravel%. Predator abundance and biomass were related positively to increases of Gravel%, and Marginal plant%. Absorber biomass decreased with decreasing Silt% in Sp.15.

Temporal variation in macroinvertebrate community taxonomic composition was related strongly to post-rehabilitation increases in channel morphological parameters, while FFGs community variation had a weaker correlation with both channel morphological parameters and in-stream biotope percentages. BIOENV identified those channel morphological parameters and in-stream biotopes that best explained temporal variations in macroinvertebrate community taxonomic and functional feeding group composition (Table 4.8). Measured channel morphological parameters (CV_depth, CV_width, SWI_biotope, and Wet surface area) were the best predictors of pre-/post-rehabilitation [Sp.14:Sp.15 & Sp.14:Sp.16 comparison] variations in macroinvertebrate community taxonomic composition (Count m^{-2}, Biomass m^{-2}) ($\rho \geq 0.81$). A combination of the same morphological parameters and Marginal plant% were the best predictors of first/second year post-rehabilitation [Su.15:Su.16 comparison] variations in community taxonomic composition, but with a weaker correlation ($\rho = 0.42$).

Temporal variations in macroinvertebrate FFGs composition (Count m^{-2}, Biomass m^{-2}) were best predicted by a combination of channel morphological parameters and in-stream biotope percentages [CV_depth, CV_width, SWI_biotope, Number of biotopes, Gravel%, Cobbles%, Silt%, and Marginal plant%], but with a weaker correlation compared with variations in community taxonomic composition.

Table 4.8. Optimal BIOENV selected morphological variables with total Spearman's rank correlation coefficient (ρ) for temporal variations in macroinvertebrate community taxonomic and feeding groups composition.

Macroinvertebrate community data	Sp.14:Sp.15		Sp.14:Sp.16		Su.15:Su.16	
	Variables	(ρ)	Variables	(ρ)	Variables	(ρ)
Taxonomic composition (Count m^{-2})	CV_depth SWI_biotope	(0.84)	CV_depth CV_width Wet surface area	(0.86)	SWI_biotope CV_depth CV_width	(0.42)
Taxonomic composition (Biomass m^{-2})	CV_width Wet surface area CV_depth	(0.81)	Wet surface area CV_depth SWI_biotope CV_width	(0.81)	CV_depth Wet surface area CV_width Marginal plant%	(0.42)
FFG composition (Count m^{-2})	CV_width CV_depth Number of biotopes Gravels%	(0.54)	Number of biotopes CV_width CV_depth Leaf-litter%	(0.79)	CV_depth Cobbles% Gravels%	(0.18)
FFG composition (Biomass m^{-2})	Silt%	(0.41)	Number of biotopes Marginal plant% SWI_biotope CV_width	(0.77)	Wet surface area Cobbles% CV_width	(0.32)

4.5. Discussion

This study examined the ecological effects of a rehabilitation project on a reach of the Welland River, UK, using biotopes as the target unit of the rehabilitation. As such, it is novel within the UK, as rehabilitation projects have previously focused at a larger scale; on, for example, installing large woody materials as flow deflectors, or installing riffle areas, or widening a reach to reinstate a multichannel planform (e.g. Biggs *et al.* 1998; Harrison *et al.* 2004; Pretty & Dobson 2004; Smith & Chadwick 2014; Thompson 2015; White *et al.* 2017).

Rehabilitation of the Welland increased the variability in channel depth, width, in-stream biotope and hydraulics. Rehabilitated reach morphological complexity was enhanced by creating a low-flow meandered channel with riffle-pool sequences, thus changing stream depth and width. This led to alterations in in-stream biotope number, and diversity. Water flow was enhanced because the low-flow channel had less width as berms were installed in the river banks. These increased the hydraulic roughness of the rehabilitated reach. At the in-stream biotope level, the number of in-stream biotopes was increased. Cobbles and gravel were increased due to the installation of riffle areas. Macroalgae grew on the installed coarse biotopes. Marginal plants grew and covered berms. Floating-leaved macrophytes grew in the shallow areas. Enhanced channel longitudinal connectivity and installed LWM increased the rehabilitated reach's amount of leaf-litter and small woody materials through retention. Longitudinal fluvial processes appear to be functioning, allowing sediment transport processes to distribute silty sediment in accordance with changes in the reach hydraulics. These consequences for the hydromorphological variability are similar to results from other rehabilitation projects in lowland rivers (Friberg *et al.* 1998; Pedersen *et al.* 2007; Lorenz, Jahnig & Hering 2009; Jähnig *et al.* 2010).

The hydromorphological improvements brought on by the rehabilitation process was evidenced by significant enhancements in the rehabilitated reach's macroinvertebrate community. The rapid re-colonisation of the rehabilitated reach by macroinvertebrates in this short-term study was similar to results from other river rehabilitation studies (Friberg *et al.* 1994; Biggs *et al.* 1998; Laasonen, Muotka & Kivijärvi 1998; Pedersen *et al.*

2007). The primary source was the downstream drift from an available natural reach (Matthaei, Werthmüller & Frutiger 1997).

The significant relationship between increases in macroinvertebrates structural and functional metrics with changes in biotope percentages rather than changes in measured channel morphological parameters indicates the importance of in-stream biotopes as structural and function units in stream ecology and the role that they could have in monitoring the outcomes of stream rehabilitation projects. The significant post-rehabilitation increases in macroinvertebrate taxa richness, taxa diversity, total density and total biomass recorded in the rehabilitated reach indicate that rehabilitation increased the stability of coarse mineral biotopes and resource availability of organic biotopes for macroinvertebrates. Reduced embeddedness of coarse biotopes has improved the suitability of this substrate for many taxa because of increased substrate stability, reduced deposition of fine sediments, and increased availability of food in epilithic biofilms (Wood & Armitage 1997). Organic biotopes were also known to support higher taxon richness and diversity elsewhere (Friberg *et al.* 1994; Friberg *et al.* 1998; Harrison *et al.* 2004; Friberg *et al.* 2013; Verdonschot *et al.* 2015).

Significantly higher estimates of EPT richness, EPT diversity, EPT count%, and EPT biomass also suggest that environmental conditions, particularly oxygen concentrations, were improved by rehabilitation. EPT taxa are considered sensitive to a wide array of environmental stressors (Downes *et al.* 1998).

A significant increase in abundance and biomass of shredders indicates greater in-stream complexity, as these taxa are dependent on the availability of coarse particulate organic matter (Smock, Metzler & Gladden 1989; Fenoglio *et al.* 2005). The higher water velocities and larger, more stable substratum particles of riffles offer more profitable foraging areas for scrapers (algal grazers) and attachment sites for filter-feeders (Williams & Moore 1986; Allan 1995). Larger interstitial pore sizes increase retention of particulate organic food and act as refugia from diverse flow conditions and/or predators (Gee 1982; Culp, Walde & Davies 1983). The significant increases in predator density and biomass in the present study indicate an increase in the complexity of the food web supported in the rehabilitated reach.

Deposit-feeders dominated the degraded reach samples indicating the negative effects that siltation of the stream-bed can have on macroinvertebrate community composition. Degraded reaches are often characterised by monotonous habitat conditions (e.g. reduced flow diversity) and limited biotope availability (e.g. loss of coarse biotopes by siltation). Siltation can shift the macroinvertebrate composition toward taxa with low dissolved oxygen requirements (Angradi 1999; Zweig & Rabeni 2001), or cause a reduction of taxa vulnerable to fine sediments (due to damage of filter-feeding apparatus or delicate gills) (Wood & Armitage 1997; Larsen, Vaughan & Ormerod 2009). Low abundance and biomass of scrapers and filter-feeders in the degraded reach compared to the other two reaches are more evidence of the negative effects of silty sediment on macroinvertebrate functional composition. Deposition of fine sediment is associated with reduced food quality or impaired access to food resources for scraper and filter-feeder invertebrates (Kreutzweiser, Capell & Good 2005; Rabení, Doisy & Zweig 2005).

The observed shift in macroinvertebrate community taxonomic and functional composition of the rehabilitated reach toward that of the natural reach, and the increased between-reach similarity, provide further evidence that rehabilitation was successful. Macroinvertebrate community FFGs composition responded to rehabilitation more slowly than did taxonomic composition. Temporal variations in macroinvertebrate community taxonomic composition had a strong correlation with channel morphological parameters, while FFGs composition had less strong correlations with a combination of channel morphological parameters and in-stream biotope percentages. The relatively slow response of FFGs composition to the rehabilitation process was related to slower increases in number of in-stream biotopes and biotope diversity [due to establishment of new in-stream biotopes, such as marginal plants, leaf-litter, and accumulation of silts] than actively increased channel morphological parameters.

Collecting samples in a BACI study design was the best way of comparing ecological changes induced by the rehabilitation process, and gauging the direction of the changes toward the natural reach, which was used as an ecological baseline. The lack of any difference in the natural reach's macroinvertebrate structural and functional metrics (before vs after) was a good indicator that the positive changes in the rehabilitated reach metrics were induced by the morphological effects of the rehabilitation applied to that reach only. Thus, enhanced community composition and diversity in the rehabilitated reach of the Welland River will possibly be sustained and even increase in the future as colonisation from upstream reaches will continue, and biotope heterogeneity will increase due to enhanced hydromorphological variability.

The rehabilitated reach attained conditions of the natural reach by the second post-rehabilitation spring and summer. This shows signs of structural and functional recovery of macroinvertebrate populations/communities in the rehabilitated reach, which have not been shown by all other rehabilitation studies. Some of these have indicated that hydromorphological rehabilitation did not generally promote macroinvertebrate biodiversity, even if habitat changes were considerable (Lepori *et al.* 2005; Jähnig *et al.* 2010; Friberg *et al.* 2013; Haase *et al.* 2013; Pedersen, Kristensen & Friberg 2014), whilst others reported only moderate level of improvement (Purcell, Friedrich & Resh 2002; Harrison *et al.* 2004; Schiff, Benoit & Macbroom 2011). The possible reason that these studies could not capture positive effects of the rehabilitation projects on macroinvertebrate biodiversity could be related to the applied 1) study design or 2) the ways of sampling macroinvertebrates. The most comprehensive study design "BACI" which is able to separate the outcomes of rehabilitation activities from other confounding factors was not depended in any of these post-rehabilitation monitoring studies. The dearth of pre-rehabilitation data has pushed researchers to use a surrogate – a Control-Impact (CI) study design, which can be misleading (Miller, Budy & Schmidt 2010) and "render [supposed] impacts on macroinvertebrates questionable" (Feld *et al.* 2011). This approach might confound responses to rehabilitation activities with differences between macroinvertebrate communities (Laasonen, Muotka & Kivijärvi 1998; Negishi & Richardson 2003) because macroinvertebrate community metrics vary naturally at small spatial scales for reasons unrelated to rehabilitation activities (Negishi & Richardson 2003; Miller, Budy & Schmidt 2010).

Most of the above evaluation studies sampled only riffle or riffle-pool habitats, thus did not cover all available in-stream biotopes. These habitats are also less likely to change as a result of habitat enhancement projects (Brooks *et al.* 2002; Palmer, Menninger & Bernhardt 2010). Multi-habitat sampling protocol, of the official EU WFD, which reflect the proportion of the microhabitat types (in-stream biotopes) that are present with ≥5% cover was applied rarely (Jähnig *et al.* 2010; Haase *et al.* 2013; Verdonschot *et al.* 2015), but partitioning the effects of rehabilitation outcomes from other sources of variance - especially seasonal and inter-annual variation - was also not possible as these projects evaluated by sampling only once (either during spring or summer) and without incorporating undisturbed control reaches. Significant seasonal changes in macroinvertebrate community taxonomic and functional compositions, especially of the natural reach, reveal that repeated seasonal samples are a fundamental requirement of an effective monitoring design because a stream's biotic community usually follows a cyclical pattern. If the post-rehabilitation evaluation is conducted during a peak or lull in the cycle, misleading results can be obtained (Leal 2012). Monitoring of rehabilitation outcomes also needs to consider the direction - not only the change - of biotic communities towards undisturbed reference reach (Downes *et al.* 2002), which was absent in these studies.

The failure of some rehabilitation projects to have an effect on biotope composition and diversity perhaps explains the consequent lack of positive response by macroinvertebrates (e.g. Jähnig & Lorenz 2008; Verdonschot *et al.* 2015). Macroinvertebrate species often have different specific biotope requirements at different stages of their life, requiring that all these biotopes must be present and of sufficient quality to guarantee re-colonisation and development of sustainable populations (Verdonschot *et al.* 2015). Organic biotopes are key biotopes in rivers, limited availability of theses biotopes in rehabilitated rivers can hinder colonisation by additional species (Lorenz, Jahnig & Hering 2009).

This case-study highlights the importance of rehabilitating in-stream biotope conditions, which are ecologically relevant for diverse species of macroinvertebrates. It also highlights the importance of using a monitoring design that can measure both structural and functional outcomes. In-stream biotopes represent the building blocks of river rehabilitation and should become the prime focus of river managers (Harper, Smith & Barham 1992; Harper & Everard 1998; Newson *et al.* 1998). Stratified random sampling (at in-stream biotope) of macroinvertebrate community is better than random sampling to appreciate hydromorphological rehabilitation outcomes. Both structural and functional aspects of ecological integrity in macroinvertebrate communities need to be assessed because maintaining functional redundancy through taxonomic biodiversity is the main rehabilitation target (Palmer, Ambrose & Poff 1997).

Chapter 5. Secondary production of macroinvertebrates as a tool to assess the success of a stream rehabilitation process

5.1. Introduction

Natural streams are physically diverse because of the hydrological and geomorphological forces that structure them (Vannote *et al.* 1980). Higher levels of physical heterogeneity in freshwater ecosystems are usually accompanied by more diverse biotic communities (Pilotto *et al.* 2016). Physical habitat degradation is therefore regarded as a serious threat to biodiversity (Vitousek *et al.* 1997; Wilcove *et al.* 1998); and aquatic ecosystems are generally more heavily affected than terrestrial ecosystems (Allan & Flecker 1993; Sala *et al.* 2000). Many rehabilitation projects have been based on the assumption that habitat heterogeneity promotes biodiversity and enhances ecological functioning (Feld *et al.* 2011): therefore, restoring lost physical features may be the best way to reverse the ecological effects of morphological degradation (Mitsch & Jørgensen 2003; Ormerod 2003; Pedersen, Baattrup-Pedersen & Madsen 2006).

Many hundreds of projects in the USA and EU, designed to rehabilitate natural flow and enhance habitat heterogeneity in streams and rivers, have been monitored to assess their effects on macroinvertebrate biodiversity, but their influence is still unclear and probably limited (see Chapter 2. Literature Review). Returning biodiversity to approximately historical levels may not be a sufficient criterion by which to gauge the ecological recovery or enhancement of rehabilitated streams (Dolph *et al.* 2015). It is thus possible that ecosystem function may be enhanced more readily than biodiversity in degraded streams, because different species may have similar functional roles (Palmer, Ambrose & Poff 1997; Hilderbrand, Watts & Randle 2005). Measures of ecosystem function may thus provide a more comprehensive understanding of biotic condition than biodiversity alone (Bunn & Davies 2000). Secondary production, for example, integrates several measures of biological success beyond species richness, including changes in population density, biomass and growth rate over time (Benke & Huryn 2006). Secondary production is the formation of heterotrophic biomass (Dry Mass (DM)) through time (Benke 1993). Assessing the secondary production of macroinvertebrates is especially useful in the context of stream rehabilitation because it assesses the produced heterotrophic biomass over a given period, and comprises energy transferred to higher trophic levels (Waters 1979; Huryn & Wallace 2000).

In-stream hydromorphological rehabilitation, either through active installation of coarse biotopes (through riffle installation) or of large woody material (LWM) alone, can enhance channel stability, in-stream biotope availability, and hence food availability for macroinvertebrates (Smock, Metzler & Gladden 1989; Benke & Wallace 2003). The installation of LWM (formerly LWD) can control in-stream biotope sorting through exposing gravels in the main channel and depositing sediments along the banks of the stream channel (Kail 2003), and can increase retention of terrestrially derived (allochthonous) organic matter (Johnson, Breneman & Richards 2003; Lepori *et al.* 2005). Morphological changes can thus alter organic matter retention and consequently macroinvertebrate secondary production.

Dolbeth *et al.* (2012) review many published examples of different applications of secondary production studies in aquatic ecosystems, but little is known about how stream rehabilitation activities influence stream ecosystem function generally, and macroinvertebrate secondary production in particular. Secondary production has been used to gauge the recovery of stream ecosystem structure and function after reach-scale LWM installation in low-order, forested systems (Wallace, Webster & Meyer 1995; Entrekin *et al.* 2009), and of stream rehabilitation activities (riparian re-vegetation, installation of boulder weirs and of LWM) in highly modified agricultural regions (Dolph *et al.* 2015). But to my knowledge, no response of macroinvertebrate secondary production to reach-scale channel hydromorphological rehabilitation in urban areas has yet been evaluated. In this study, I have assessed changes in macroinvertebrate secondary production following entire-channel hydromorphological rehabilitation of an urbanised reach of the Upper Welland in Market Harborough, in Leicestershire, UK.

5.2. Aim and Objectives

My aim was to assess changes in macroinvertebrate secondary production following hydromorphological rehabilitation of a reach of the Upper Welland in Market Harborough, in Leicestershire, UK. This chapter extends the biotic evaluation (Chapter 4) by calculating macroinvertebrate secondary production as a variable metric, which is a novel approach to address the current knowledge gap in the field of river rehabilitation.

The specific objectives were:

1. To determine whether active enhancement of in-stream biotope numbers and diversity would increase macroinvertebrate secondary production in the rehabilitated reach of the Welland River through increased availability and percentages of different biotopes.

2. To determine whether macroinvertebrate secondary production in rehabilitated reach would come to resemble those of the natural reach.

5.3. Methods

5.3.1. Study sites

This study was carried out on a reach of the Upper Welland in Market Harborough, in Leicestershire, UK. A 250 m reach of the rehabilitated River Welland at Welland Park, Market Harborough was compared with a 250 m undisturbed reach of the Welland (upstream at Lubbenham) as a reference reach, and a 250 m of straightened reach of the Jordan River at Market Harborough as a control physically degraded reach. Full information about the study sites and rehabilitation measures are given in Chapter 4.

5.3.2. Macroinvertebrate sampling and data processing

After the rehabilitation process, macroinvertebrate samples were collected from all study reaches on an approximate 28 day schedule for one year (2015), then seasonally during spring (March and May) and summer (Jun and July) 2016 (see Chapter 4, Table 4.1 for sampling dates). In parallel to the invertebrate sampling, water temperature was also recorded for each study reach. Three replicate samples were collected from each biotope (all those covering ≥ 1% area of the river bed within a given reach) at each sampling visit. Samples were collected using a Surber sampler (500 µm mesh size and 0.09 m^2). They were then placed in 2.5 litre plastic buckets, labelled, and returned to the laboratory. They were stored in a cold room at 4°C and sorted into major groups within 48 h. Invertebrate specimens were placed in 50 ml sealable plastic sample tubes containing 75% ethanol and kept for later taxonomic identification and counting in the laboratory.

Specimens were identified to the lowest possible taxonomic level using standard UK lotic invertebrate taxonomic keys and guide books. Macroinvertebrate specimens' dry masses (mg DM $sample^{-1}$) were estimated according to published size-specific mass regressions, or by direct estimation for worms and some insect larva. The list of regressions and length parameters that were used and relevant references are given in Appendix 1. Macroinvertebrate species were also assigned to eight functional feeding groups (FFGs) according to Tachet *et al.* (2010) (Appendix 2).

Reach-level density and biomass were calculated according to the relative coverage area of each sampled in-stream biotope in each reach (see Chapter 3, Figure 3.9). Thus, all measurements necessary for the estimation of secondary production (i.e. density, biomass and temperature) were acquired independently for each study reach at each sampling visit.

5.3.3. Estimation of macroinvertebrates secondary production

Secondary production (mgDM m^{-2} $time^{-1}$) of macroinvertebrate taxa and FFGs in each study reach were estimated using the empirical models of Morin and Bourassa (1992) and Benke (1993). Taxa or FFG production values were then summed for each reach to obtain total secondary production (TP). TP values were assessed during two post-rehabilitation years (2015 and 2016). The first post-rehabilitation year covered winter-spring-summer 2015, the second year covered winter-spring-summer 2016 (Table 5.1). The use of empirical models provides reliable estimates of macroinvertebrate community secondary production when applied to multispecies communities using monthly body mass and density data (Morin & Dumont 1994; Morin 1997). The results of this study were therefore robust for the purposes of relative comparison between the study reaches.

Table 5.1. Macroinvertebrate sampling visit dates used for calculation of secondary production for each study reach.

Year	Season	Rehabilitated reach	Degraded reach	Natural reach
2015	Winter	19th January	20th January	20th January
		16th February	17th February	17th February
	Spring	16th March	17th March	17th March
		13th April	14th April	14th April
		11th May	12th May	12th May
	Summer	7th Jun	9th Jun	10th Jun
		4th July	5th July	6th July
		2nd August	4nd August	5nd August
Number of days		**195 days**	**196 days**	**197 days**
2016	Winter	19th January	20th January	20th January
	Spring	14th March	14th March	16th March
		17th May	19th May	21st May
	Summer	22nd Jun	24th Jun	24th Jun
		25th July	27th July	29th July
Number of days		**188 days**	**189 days**	**191 days**

5.3.4. Data analysis

Differences in secondary production between the degraded, natural and rehabilitated reaches were analysed using Permutational ANOVA. Reaches were compared according to 1st and 2nd post-rehabilitation years. A Euclidean distance matrix was used to calculate distances between production values according to the study reaches. One-way Permutational ANOVA with *Reach Year* (fixed factor, six levels: Degraded 1st, Natural 1st, Rehabilitated 1st, Degraded 2nd, Natural 2nd, Rehabilitated 2nd) was used to run all possible pair-wise tests.

5.4. Results

During the 1st post-rehabilitation year, the natural reach had approximately three times higher total production (TP) (11,337 mgDM m^{-2}) than either the rehabilitated reach (4,541 mgDM m^{-2}) or the degraded reach (3,591 mgDM m^{-2}) (Figure 5.1 and Table 5.2). The differences between the natural reach TP and that of the other two reaches were statistically significant ($p < 0.05$), while the rehabilitated reach TP was similar to that of the degraded reach ($p > 0.05$) (Appendix 5). Gastropoda, Bivalvia, Diptera, and EPT production was many times higher in the natural reach than the other two reaches ($p < 0.05$) (Table 5.2 and Appendix 5.1). Gastropoda were the largest relative contributor to TP in all three reaches (49% to 60%), with the highest proportion in the rehabilitated reach and the lowest proportion in the degraded reach (Figure 5.2 and Table 5.4). Ephemeroptera, Plecoptera and Trichoptera (EPT) production was the second largest relative contributor to TP in the natural and rehabilitated reach (20.4% and 11.6%, respectively), while it contributed to only 1.5% of the degraded reach's TP. In the degraded reach, Chironomidae and Hirudinea were the second- and third-highest relative contributors to the reach's TP (20.3% and 16.6%, respectively), but they were less dominant in the other two reaches. In the natural reach, each of them was relatively contributed in about 3% of the reach's TP. In the rehabilitated reach, Hirudinea contributed 5.6% and Chironomidae 3.7% of its TP (Figure 5.2 and Table 5.4).

Functionally, shredder, scraper and filter-feeder production was many times higher in the natural reach than in the other two reaches ($p < 0.05$) (Table 5.3 and Appendix 5.1). Shredder and scraper feeding groups' relative contributions to the natural and rehabilitated reach's TP were similar, however. They contributed about 43% and 33% of each reach's TP respectively (Figure 5.3 and Table 5.5). In the degraded reach, shredder relative contribution was about 24%, and scraper was about 19% of its TP. Deposit-feeder relative contribution to the degraded reach's TP was about two times higher than to the other two reaches (7.4% and 3.6%, respectively).

During the 2nd post-rehabilitation year, the rehabilitated reach's TP was enhanced over that of the natural reach. The rehabilitated reach's TP value had doubled compared to the 1st post-rehabilitation year ($p < 0.05$); up to 9,098 mgDM m^{-2}. Thus, TP was about 3 times higher in the rehabilitated than in the degraded reach significantly different ($p <$

0.05), while they had been similar to each other during the 1st post-rehabilitation year (Figure 5.1). Rehabilitated reach's TP remained significantly different from that of the natural reach ($p < 0.05$), however. Malacostraca, Gastropoda, Bivalvia, and EPT production was each positively affected ($p < 0.05$), with significantly higher production in the rehabilitated reach than the degraded reach ($p < 0.05$) (Figure 5.2, Table 5.2 and Appendix 5.1). All functional feeding groups' production were positively affected. Shredder, scraper, filter-feeder, and predator production became significantly higher in the rehabilitated reach than the degraded reach ($p < 0.05$) (Figure 5.3, Table 5.3, and Appendix 5.1). The rehabilitated reach was similar to the natural reach according to Gastropoda, Bivalvia, shredder, scraper, and filter-feeder's production ($p > 0.05$) (Appendix 5.1).

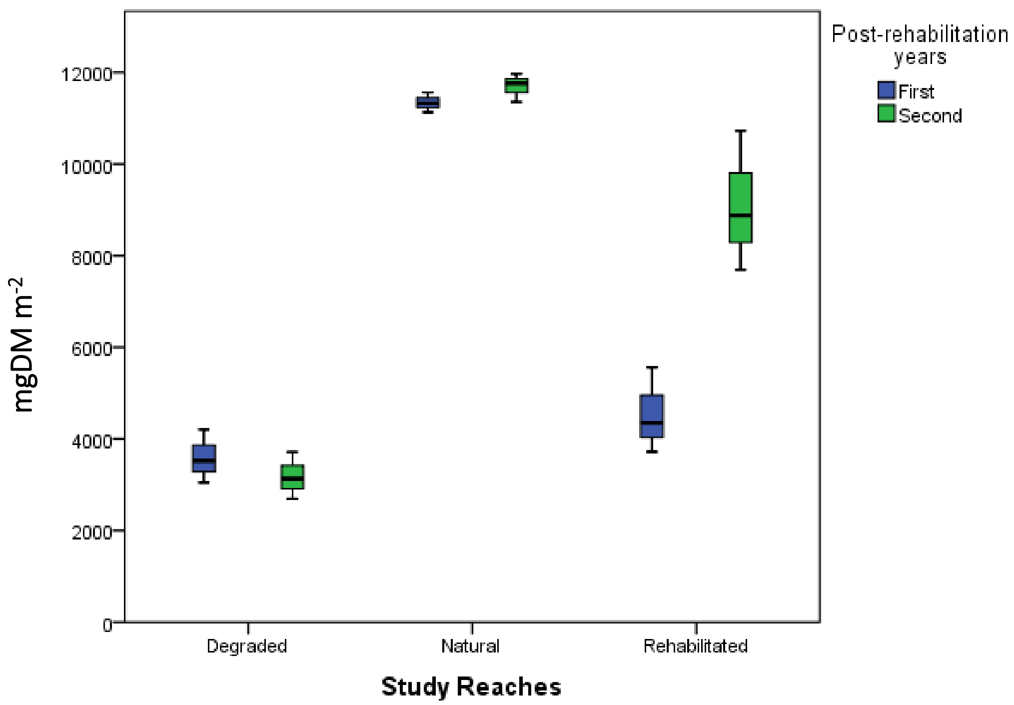


Figure 5.1. Total production of macroinvertebrate community in each study reach for the 1st and 2nd post-rehabilitation years.

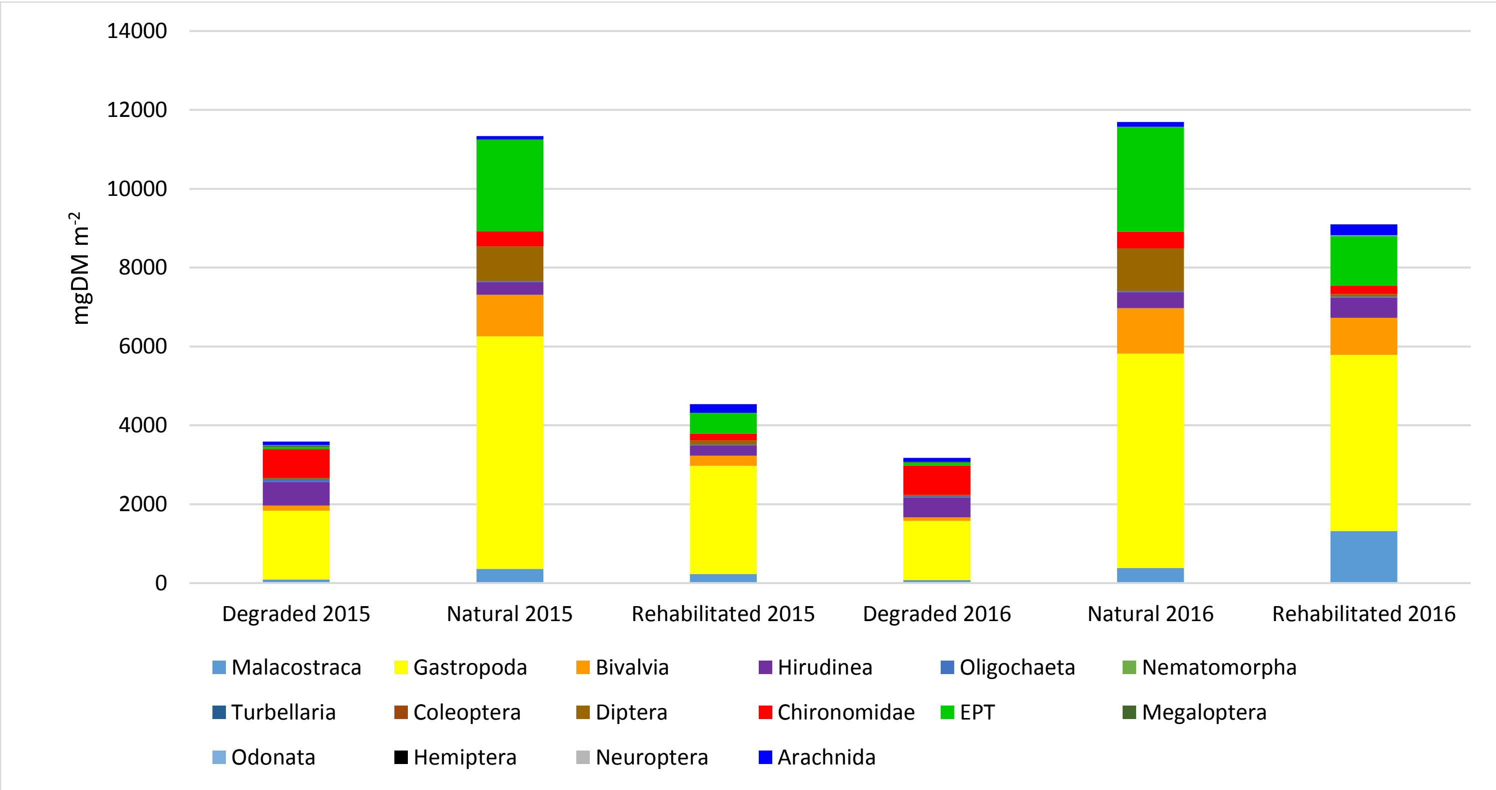


Figure 5.2. Secondary production contributed by each macroinvertebrate taxonomic group to the study reaches total production for the 1st and 2nd post-rehabilitation years. EPT: Ephemeroptera, Plecoptera, Trichoptera.

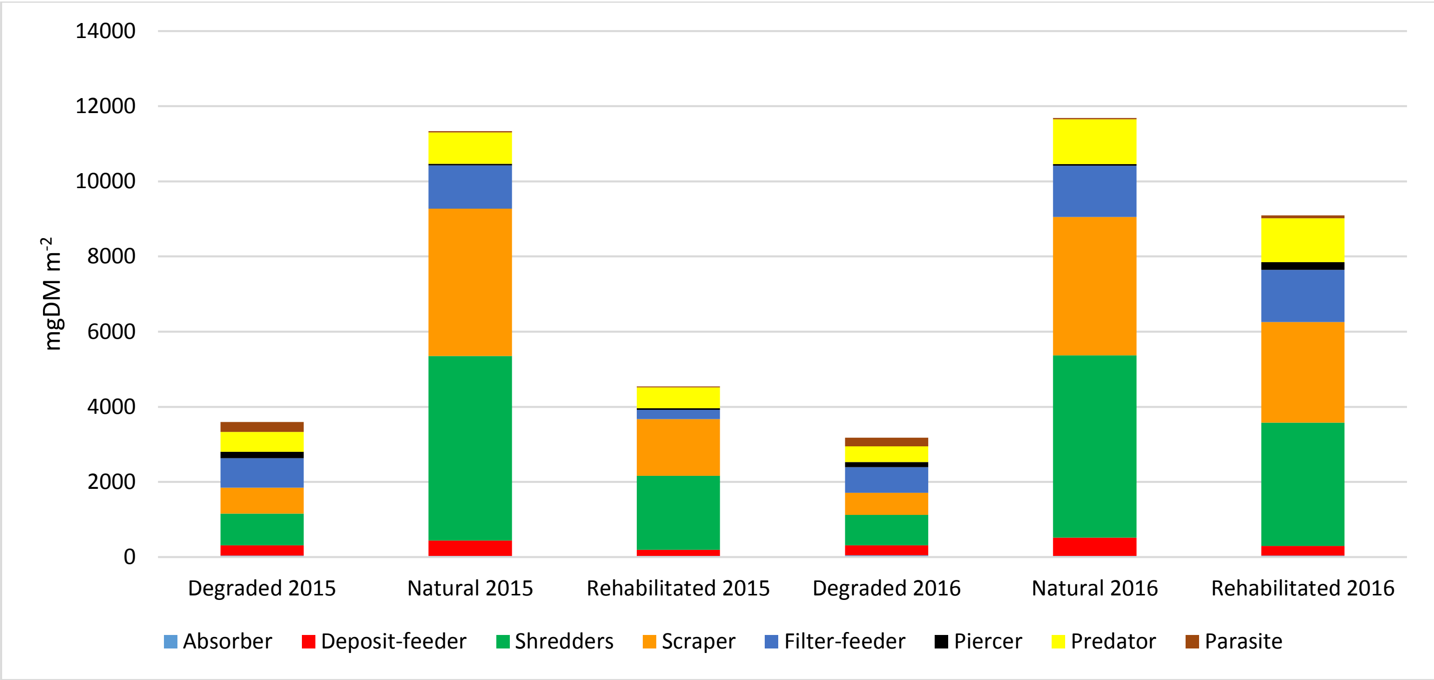


Figure 5.3. Secondary production contributed by each macroinvertebrate feeding group to the study reaches total production for the 1st and 2nd post-rehabilitation years.

Table 5.2. Mean (SD) secondary production (mgDM m^{-2}) for each macroinvertebrate taxonomic group in each study reach for the 1st and 2nd post-rehabilitation years.

	Degraded 2015		Natural 2015		Rehabilitated 2015		Degraded 2016		Natural 2016		Rehabilitated 2016	
Taxonomic groups	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Malacostraca	88.6	18.2	361.1	26	231.2	37.3	75.2	18.9	385.7	6.5	1314.2	457.9
Gastropoda	1746.3	330.6	5896.9	187.7	2741.1	115.7	1501.5	266.1	5435.8	325.9	4473.9	168.9
Bivalvia	135.1	87.6	1052.8	65.2	256.8	106	91.9	76.8	1151.7	141.6	938.4	56.8
Hirudinea	595.9	230	317.6	93	252.3	98.5	499.8	80.9	408.6	201.9	511.3	155.9
Oligochaeta	74.2	9.4	32.4	4.1	30	1.1	41.4	5.1	25.1	2	29.8	2.1
Nematomorpha	0	0	0	0	0	0	0	0	0	0	0	0
Turbellaria	2.2	0.6	0	0	3.1	1.8	0.9	0.2	0	0	2.9	0.8
Coleoptera	0	0	0.2	0	0.1	0.1	0	0	0.2	0	0.2	0.1
Diptera	26.7	17.6	873.2	23.9	110.2	15.2	22	16.5	1083.4	50.2	59.2	11.2
Chironomidae	728.7	11	386.7	10.5	166.6	36.4	748.3	66.2	418.8	43.3	210.5	42.6
EPT	55.6	26.4	2315	201.2	528.1	107.9	76.1	26.4	2653.1	336.4	1254.8	82
Megaloptera	41.5	41.3	16.7	10.5	0.3	0.1	19.4	18.9	10.6	9.1	1.7	2.3
Odonata	1	0.3	0.2	0.3	2.4	0.8	1.2	0	0	0	21.1	5.4
Hemiptera	0	0	0	0	0	0	0	0	0	0	0	0
Neuroptera	0	0	0	0	0	0	0	0	0	0	0	0
Arachnida	95.3	21.6	84.2	6.3	218.8	29	100.8	5.8	118.2	17.1	280.1	17.4
TP	3591.1	583	11337	212	4541.2	937	3178.5	512	11691.2	311.1	9098.4	529

Table 5.3. Mean (SD) secondary production (mgDM m^{-2}) for each macroinvertebrate feeding group in each study reach for the 1st and 2nd post-rehabilitation years.

	Degraded 2015		Natural 2015		Rehabilitated 2015		Degraded 2016		Natural 2016		Rehabilitated 2016	
Feeding groups	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Absorber	42.3	0.1	31.7	2.5	28	7.6	47.7	22	32	4.4	36.9	3.2
Deposit-feeder	266	17.4	408.9	18.4	164.2	50.2	263.7	91.7	486.6	28.1	260.9	5.4
Shredders	849	212.2	4912.7	75.2	1973	151.2	810.7	219.9	4849.7	259.8	3276.2	152.2
Scraper	687.6	178.3	3920.9	140.3	1505.7	137.6	585.7	149.5	3679.8	196.3	2682.6	134.8
Filter-feeder	787.7	25.8	1150.3	43.2	244.8	124.7	686	136.2	1367.6	182.5	1386.3	121
Piercer	167.8	61	42.8	35.3	47.6	6	139.2	13.6	46.6	42.1	204.5	47.5
Predator	534.1	145.4	836.8	130.6	552.6	300.3	413.5	96.2	1189.8	347.7	1171.1	503.7
Parasite	256.6	16.6	32.9	9.2	25.3	8.1	231.9	71.8	39	11	80	11
TP	3591.1	583	11337	212	4541.2	937	3178.5	512	11691.15	311.1	9098.4	529

Table 5.4. Percentage secondary production contributed by each macroinvertebrate taxonomic group to the study reaches total production. EPT: Ephemeroptera, Plecoptera, Trichoptera.

Taxonomic groups	Degraded 2015	Natural 2015	Rehabilitated 2015	Degraded 2016	Natural 2016	Rehabilitated 2016
Malacostraca	2.5	3.2	5.1	2.4	3.3	14.4
Gastropoda	48.6	52	60.4	47.2	46.5	49.2
Bivalvia	3.8	9.3	5.7	2.9	9.9	10.3
Hirudinea	16.6	2.8	5.6	15.7	3.5	5.6
Oligochaeta	2.1	0.3	0.7	1.3	0.2	0.3
Nematomorpha	0	0	0	0	0	0
Turbellaria	0.1	0	0.1	0	0	0
Coleoptera	0	0	0	0	0	0
Diptera	0.7	7.7	2.4	0.7	9.3	0.7
Chironomidae	20.3	3.4	3.7	23.5	3.6	2.3
EPT	1.5	20.4	11.6	2.4	22.7	13.8
Megaloptera	1.2	0.1	0	0.6	0.1	0
Odonata	0	0	0.1	0	0	0.2
Hemiptera	0	0	0	0	0	0
Neuroptera	0	0	0	0	0	0
Arachnida	2.7	0.7	4.8	3.2	1	3.1

Table 5.5. Percentage secondary production contributed by each macroinvertebrate feeding group to the study reaches total production for the 1st and 2nd post-rehabilitation years.

Feeding groups	Degraded 2015	Natural 2015	Rehabilitated 2015	Degraded 2016	Natural 2016	Rehabilitated 2016
Absorber	1.2	0.3	0.6	1.5	0.3	0.4
Deposit-feeder	7.4	3.6	3.6	8.3	4.2	2.9
Shredders	23.6	43.3	43.4	25.5	41.5	36
Scraper	19.1	34.6	33.2	18.4	31.5	29.5
Filter-feeder	21.9	10.1	5.4	21.6	11.7	15.2
Piercer	4.7	0.4	1	4.4	0.4	2.2
Predator	14.9	7.4	12.2	13	10.2	12.9
Parasite	7.1	0.3	0.6	7.3	0.3	0.9

5.5. Discussion

This short-term study demonstrated that rehabilitation of the Welland River had clear beneficial effects on the rehabilitated reach's functionality. Increases in the rehabilitated reach's in-stream biotope number and diversity (see Section 4.4.1; Chapter 4) resulted in a significant increase of the reach's secondary production during the 2nd post-rehabilitation year. This result provides a clear message to river rehabilitation practitioners: rehabilitation of the function of a physically degraded river ecosystem is possible if the rehabilitation actively returns the lost in-stream biotope diversity. The relationship between this kind of river rehabilitation process and ecosystem function may require a nuanced interpretation, however, because the effect was not on a particular macroinvertebrate taxonomic group, or a functional feeding group. The rehabilitated reach of the Welland River yielded higher production estimates for Malacostraca, Gastropoda, Bivalvia, EPT and Arachnida, and a lower estimate for Chironomidae than did the degraded reach. The rehabilitated reach also had a higher estimate of production for shredder, scraper, filter-feeder and predator feeding groups than did the degraded reach. These outcomes demonstrate the recovery of the reach's entire macroinvertebrates community structure and function after rehabilitation.

Higher estimates of EPT production in the rehabilitated reach than in the degraded reach also indicate that conditions in the rehabilitated reach had improved compared to the conditions in the degraded reach. EPT taxa are considered sensitive to a wide array of environmental stressors on multiple scales, including in-stream biotope quality and water quality, and have been widely used as a measure of stream biotic condition (Richards, Host & Arthur 1993; Sponseller, Benfield & Valett 2001).

Higher estimates of shredder and scraper production in the rehabilitated reach than in the degraded reach indicate that the quality of the installed coarse biotopes and food resource availability for macroinvertebrates were improved by rehabilitation. In the rehabilitated reach of the River Welland, installed coarse biotopes (formed in installed riffle areas) had less area was covered by silt than coarse biotopes in the degraded reach (Chapter 4). Reduced embeddedness of coarse biotopes (cobbles and gravels) in the rehabilitated reach may improve their suitability for shredder and scraper macroinvertebrates due to: (a) increased substrate stability, (b) reduced negative respiratory effects associated with silty deposition, and (c) increased availability of food sources - such as epilithic biofilms - associated with coarse substrates (Wood & Armitage 1997). Secondary production often increases with the availability of stable substrate by providing scraper macroinvertebrates with areas to forage and grow (e.g. Benke *et al.* 1992; Benke & Wallace 2003). The significant increase in shredder production in the Welland also reflects the ecological effects of increased trapped leaf-litter in the rehabilitated reach, especially in spring 2016 (see Appendix 4.6). This provides suitable in-stream biotopes for shredder colonization, and also serves as a food resource. Low retention of leaf-litter has been shown to limit shredder production in headwater streams (Roeding & Smock 1989; Jones Jr & Smock 1991).

There are relatively few comparable case studies available in the literature. The present study examines entire-channel rehabilitation in an urbanised stream which tried to return back the lost in-stream biotopes. Dolph *et al.* (2015) assessed effects of stream rehabilitation activities limited to riparian revegetation and installation of boulder weirs and LWM in highly modified agricultural regions, in three streams in Southern Minnesota, USA. They aimed to: a) stabilise the stream channel by preventing bank erosion and habitat loss, and b) increase availability and heterogeneity of instream biotopes and food resources by increasing the availability of overhanging vegetation and boulder and wood surfaces. After rehabilitation, TP increased significantly so that it was 2 to 3 times higher in rehabilitated than non-rehabilitated reaches. Higher productivity in the rehabilitated reaches was largely a result of the disproportionate success of a few dominant, tolerant taxa (e.g. Hydropsychidae caddisflies and Simuliidae black flies). This outcome is thus somewhat different to that observed in the Welland, where most macroinvertebrates taxonomic groups and FFGs production values responded significantly. This was because the Welland rehabilitation actively affected the whole study reach's in-stream biotope heterogeneity. Macroinvertebrate species often have different specific biotope requirements at different stages of their life, requiring that all these biotopes must be present and of sufficient quality to guarantee re-colonisation and development of sustainable populations (Verdonschot *et al.* 2015). The way of collecting macroinvertebrate samples in the study of Dolph *et al.* (2015) may have failed to record any positive effects on most macroinvertebrate taxa, because they did not collect samples from all available biotopes, they collected only 5 samples from 5 habitat types (riffle, overhanging banks, emerged vegetation, woody material and wood dam) in each visit.

In an earlier study, Wallace, Webster and Meyer (1995) assessed the effects of LWM installation in a second order, forested stream in North Carolina, USA. They reported an increase in detritivore production after LWM was installed. The installed woody dams which spanned the entire channel changed riffle habitats to depositional habitats, and longer-lived taxa were replaced by Chironomidae. By contrast, Entrekin *et al*. (2009) reported an increase in scraper production, and little change in detritivore production after LWD installation after LWM installation in three first-order, forested systems in the Ontonagon River basin in Michigan, USA. They. This difference in the biological outcomes was thought to be due to the way that the LWM had been installed. In the Michigan streams, LWM was placed haphazardly within the streams, with part of the log resting on the stream bank, and never spanned the entire channel. This did not result in the creation of extensive depositional habitat, which enhanced detritivory. Neither of the above two studies collected macroinvertebrate samples to represent all available biotopes. Wallace, Webster and Meyer (1995) study depended on riffle and woody material habitat samples, with three replicate samples from each habitat per sampling visit. Entrekin *et al.* (2009) study depended on 5 randomly taken benthic samples.

Entrekin *et al.* (2009) also found much greater TP in “woody accumulation” (small woody material and leaf-litter) samples than in the main channel “mineral” samples. This indicates that increased retention of small woody material and leaf-litter has the potential to increase macroinvertebrate production. Entrekin *et al.* (2009) argued that it is likely to take years for measurable changes in in-stream morphology, organic matter retention or macroinvertebrate production to become apparent; and that monitoring should span more than 5 years after LWM installation. The Welland River project demonstrated that active return of the entire lost in-stream biotope heterogeneity could induce measurable changes in macroinvertebrate production more quickly and decrease the supposed recovery time.

Understanding how macroinvertebrate community production responds to hydromorphological rehabilitation processes can provide a valuable framework with which to monitor the success of stream rehabilitation projects in enhancing the functioning of a rehabilitated reach's ecosystem. Further study is nevertheless needed to evaluate the long-term trends in total production of the macroinvertebrate community of the rehabilitated reach of the River Welland, as the in-stream biotope composition and heterogeneity are continuously changing.

The temporal scale of this study was short because of the constructions of a PhD study (only 1st and 2nd years following the rehabilitation process), which may have limited the ability of the study to detect responses in the production of some taxa, or longer-term trends. One potential deficiency in this study was the absence of pre-rehabilitation values of production in the study reach, meaning that I could not compare the status of the reaches before and after rehabilitation. To address this problem, I had to use a control-rehabilitated-reference experiment design in which the control reach represented the pre-rehabilitation physically degraded condition, while the reference reach represented a minimally disturbed condition, which served as the target goal for the rehabilitated reach.

Chapter 6. General Discussion

The overall aim of this thesis has been to quantify the ecological effects of hydromorphological rehabilitation projects. One was on the effects of added large woody material and the other on entire-channel hydromorphological rehabilitation. In the following sections, I summarise and discuss the work carried out to address the 6 specific objectives, as introduced in the General Introduction.

1) *"Explore available literature on the ecological effects of stream hydromorphological rehabilitation processes, and define the factors limiting effective rehabilitation".*

It is widely believed that the apparent lack of effect of many hydromorphological rehabilitation projects on macroinvertebrate communities is due to: (a) a failure of the rehabilitation measure applied to enhance hydromorphology; (b) swamping of small changes by large-scale external drivers; or (c) a combination of the two. I conducted a global literature review of all published rehabilitation studies in the literature from 1984 to 2016 to identify the limiting factors of effective rehabilitation. Seventy seven papers that reported outcomes of 359 independent projects met my criteria (see Table 2.5, Chapter 2). I found, however, that methods used to evaluate the outcomes of rehabilitation projects may also have failed to properly assess the outcomes (see Section 2.4, Chapter 2), which has led to a poor diagnosis of both the "problem" and the effectivness of any "solution". The lack of appropriate monitoring has meant that the effectiveness of stream rehabilitation has generally not been rigorously demonstrated.

Failure of rehabilitation projects to enhance physical and hydrological heterogeneity has been regarded as the main factor to explain the lack of effect on the macroinvertebrate community in many projects (e.g. Tullos *et al.* 2009; Violin *et al.* 2011; Leal 2012; Verdonschot *et al.* 2015). For example, Verdonschot *et al.* (2015) found that the 'missing effect' of 19 rehabilitation projects in 10 European countries assessed on macroinvertebrate richness and diversity, might be due to failure of the rehabilitation measure applied. They found that rehabilitation by meandering and/or widening increased 'visually appealing' macrohabitat conditions but had no significant effect on in-stream biotope diversity relevant for macroinvertebrate communities. Catchment-scale pressures that were not mitigated in many rehabilitation projects were also found to negatively affect the recovery of stream macroinvertebrate taxa richness and diversity (e.g. Larson, Booth & Morley 2001; Harrison *et al.* 2004; Roni *et al.* 2006; Louhi *et al.* 2011; McManamay, Orth & Dolloff 2013).

Monitoring rehabilitation projects effectively requires two distinct evaluations (Barmuta 2002). First, rehabilitated reaches should be compared to their pre-rehabilitation conditions to assess whether the rehabilitation affected the response variables of interest. Second, rehabilitated reaches should be compared to target conditions to assess whether the rehabilitation achieved its purpose. The dearth of pre-rehabilitation data has pushed researchers to use a surrogate methodology - so-called Control-Impact (CI) study designs - in 73% of monitored rehabilitation projects reviewed in detail (see Section 2.4.3.3, Chapter 2). This can be misleading (Miller, Budy & Schmidt 2010) and "renders [supposed] impacts on macroinvertebrates questionable" (Feld *et al.* 2011). This limited approach might confound responses to rehabilitation activities with differences between macroinvertebrate communities (Laasonen, Muotka & Kivijärvi 1998; Negishi & Richardson 2003), because macroinvertebrate community metrics vary naturally at small spatial scales for reasons unrelated to rehabilitation activities (Negishi & Richardson 2003; Miller, Budy & Schmidt 2010). Only 17% of monitored projects tracked the direction of changes in rehabilitated reaches' macroinvertebrate community toward a natural target condition (see Section 2.4.3.3, Chapter 2).

Most of the reviewed evaluation studies sampled only riffle or riffle-pool habitats, which do not cover all available in-stream biotopes. A full multi-habitat sampling protocol, as outlined in the official European Union Water Framework Directive (EU WFD), would reflect the proportion of the in-stream biotopes that are present with ≥5% cover; but this comprehansive approach has been rarely applied (e.g. Pedersen *et al.* 2007; Jähnig *et al.* 2010; Louhi *et al.* 2011; Haase *et al.* 2013; Verdonschot *et al.* 2015; Winking 2015) (see Section 2.4.3.4, Chapter 2). Even in these cases however, most studies did not sample rivers before and after rehabilitation for multiple years, and for at least 2 seasons of each year to account for seasonal variations that could affect macroinvertebrate community composition. The only exception is the study of (Louhi *et al.* 2011).

Despite calls for a broader range of macroinvertebrate metrics (structural and functional) to be used to understand ecological effects of stream rehabilitation outcomes (Palmer *et al.* 2005; Feld *et al.* 2011; Dolph *et al.* 2015; Muhar *et al.* 2015), recovery of stream biodiversity is one of the most critical needs faced by rehabilitation managers. Macroinvertebrate taxa richness and diversity has commonly been used as monitoring metrics, even though these may fail to identify other consequential changes in ecosystem structure and function. Monitoring ecosystem functions through assessment of macroinvertebrate density, biomass and secondary production has been rarely undertaken. Few studies have tracked hydromorphological rehabilitation impacts on macroinvertebrates productivity as a functional metric (Wallace, Webster & Meyer 1995; Entrekin *et al.* 2009; Dolph *et al.* 2015).

2) *"Understand the role of installed LWM in a small rural stream in enhancing stream hydromorphology, in-stream biotope number and diversity, and macroinvertebrate assemblage composition, structure and function".*

For the Rolleston Brook rehabilitation (Figure 6.1), pieces of LWM >10 cm diameter and 1 m in length were installed during summer 2014 in order to enhance the channel complexity, biotope heterogeneity and biodiversity. The LWM was installed: a) parallel to the flow (from one or both sides) to narrow the channel, reduce ponding, and enhance the water flow; b) perpendicular (70-90°) to the channel to create meander patterns and promote riffle-pool sequences, increase hydraulic roughness (which affects flow velocity, stream power and appearance of new biotope); c) downstream faced (30°) as deflectors to kick flow over to one side to promote bank scour for outer meander bend development; d) as wing deflectors from both sides spanning the stream channel to create steps along the channel profile, regulate sediment movements through the channel system, and enhance leaf-litter retention.

To evaluation ecological outcomes, I addressed the methodological limitations highlighted in my literature review and above through applying a rigorous study design. A BACI design was used to assess inherent differences between the control and rehabilitated reaches depending on pre-rehabilitation data, and to partition the effects of the applied rehabilitation measures from natural sources of variation (e.g. seasonal and inter-annual variability) (see Table 3.2; Chapter 3 for sampling dates). Monitoring of rehabilitation outcomes needs to consider not only the extent but also the direction of change of biotic communities (Downes *et al.* 2002) – which requires knowledge of target natural, non-degraded, conditions. The target set for the Rolleston Brook rehabilitated reach was to emulate the conditions found in its nearby natural tributary. Morphological enhancements were assessed at both channel morphological features (Coefficient of variation of channel water depth and width (CV_depth, and CV_width), and wet surface area (m^2)) and in-stream biotope level (number of biotopes, coverage area of each biotope, and biotope diversity (SWI_biotope)). Macroinvertebrate samples were collected in a random sampling protocol stratified at in-stream biotope-level. Three replicate samples were taken from all existing biotopes that covered at least 1% area of the riverbed. Assessing the outcomes of the project depended on a broad range of macroinvertebrate structural and functional metrics (see Section 3.3.8; Chapter 3).

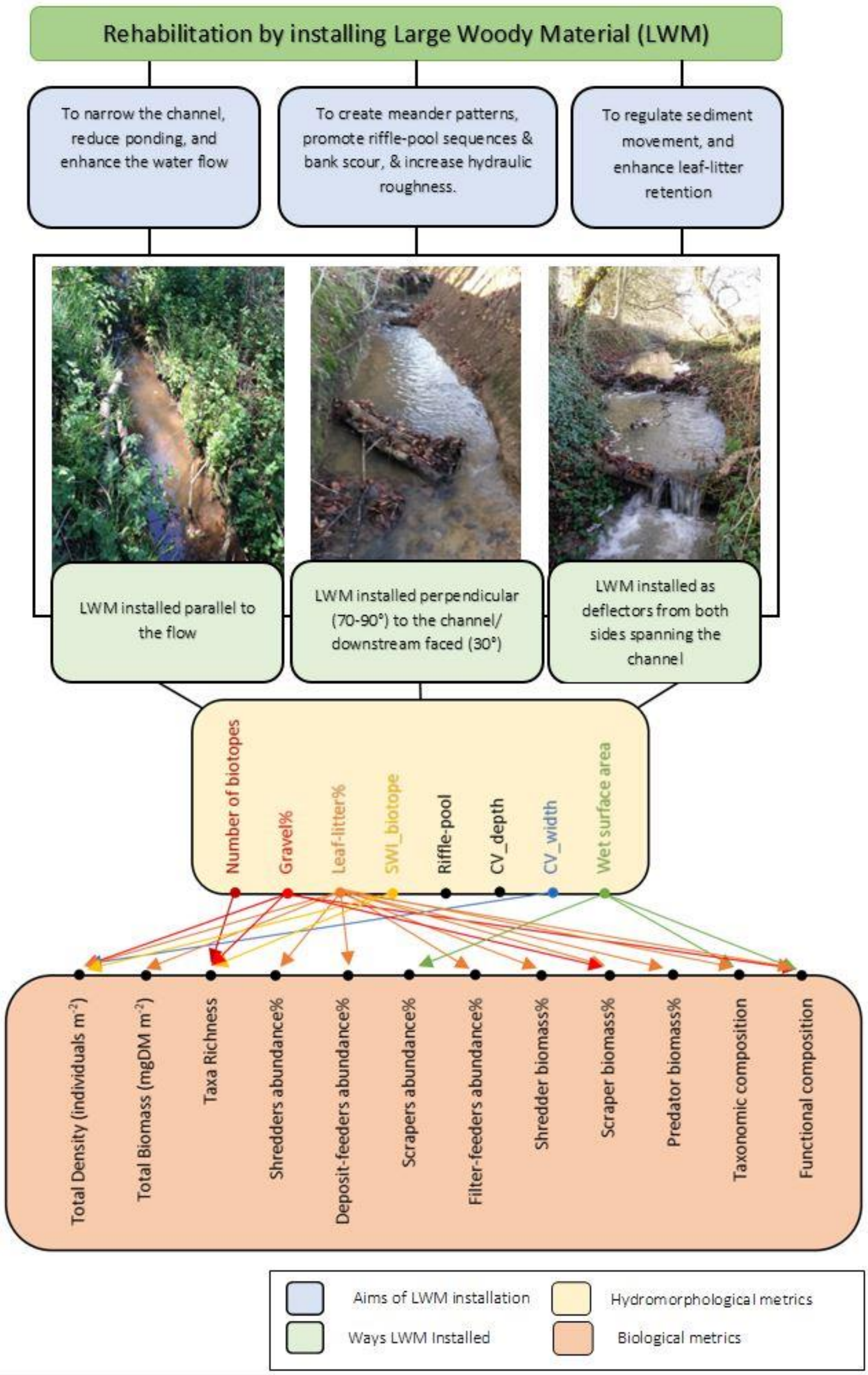


Figure 6.1. A diagram illustrating the three aims of LWM installation (blue boxes), and the relationships between the different methods of installation of LWM (green boxes), eight positively affected hydromorphological metrics (beige box) and twelve macroinvertebrate metrics (red box). The arrows show where there was a significant positive relationship between a hydromorphological metric and a biological metric.

Installed LWM was successful in reducing downstream transport of leaf-litter and was particularly important in increasing leaf-litter biotope proportion at the reach-level, especially during leaf-fall in autumn. Installed LWM was also successful in (a) dissipating flow energy, (b) enhancing the stability of the streambed through controlling the distribution of silt, (c) generating coarse in-stream biotopes for different species, and (d) increasing the in-stream biotope diversity. However, the rehabilitated stream had a high sediment load, which was not addressed by LWM installation. Therefore, LWM played a secondary role, controlling only the local distribution of silt, as also observed in a study of lowland streams by Thompson (2015).

In the Rolleston Brook project, despite the limitations, it nevertheless demonstrated that assessment of rehabilitation is important even when the project is not a complete success, as it can guide further rehabilitation efforts as well as the choice of attributes to monitor in future projects. There was significant enhancement in the rehabilitated reach's macroinvertebrate community taxonomic and FFG composition (Count m^{-2} and Biomass m^{-2}) toward the conditions in the natural tributary. I showed significant increases in macroinvertebrate total density, total biomass, taxon richness, EPT Count%, EPT Biomass%; average abundance and biomass of most of feeding groups were contrary to the growing body of literature which reports only minor effects of stream rehabilitation processes on macroinvertebrates (see Table 2.3, Chapter 2). These outcomes are evidence of the effectiveness of this study design and sampling protocol in finding positive effects induced through LWM installation, even though the rehabilitated stream suffered from a high sediment load and longitudinal barriers that were not addressed by LWM installation. It also did not have an upstream source population for recolonisation; dispersal of stream invertebrates into a rehabilitated reach requires the proximity of healthy headwaters with source populations of appropriate taxa (Parkyn & Smith 2011; Sundermann, Stoll & Haase 2011), which was absent here. Dispersal of aquatic stages of benthic invertebrates is limited, and generally believed to be more effective downstream because of passive drift (Williams & Williamce 1993). In a case like that of Rolleston Brook, reestablishment of a macroinvertebrate community must primarily rely on immigration of adults and upstream migration of non-insects from other systems (Milner 1996;

Hansen, Friberg & Baattrup-Pedersen 1999), which was probably the adjacent natural tributary.

The LWM installation project at the Rolleston Brook was not properly sustained, as installed LWM washed away during monitoring. LWM was put into the rehabilitated reach unanchored, were washed away and trapped by the concrete barriers. They also blocked the channel. Anchoring LWM in the stream bed by burying parts of it or otherwise anchoring it with cables could prevent this from happening. Anchoring installed LWM (e.g. Shields et al. 2003; Hrodey, Kalb & Sutton 2008) gives the rehabilitation team more control and may produce a better outcome (Leal 2012).

3) *"Understand the scientific basis of entire-channel hydromorphological rehabilitation and its role in an urbanised river to enhance stream morphology, in-stream biotope number and diversity, and macroinvertebrate assemblage composition, structure and function".*

In the Welland River rehabilitation project (Figure 6.2), the rehabilitation process sought to recreate the in-stream biotopes as natural 'jigsaw' pieces that were formerly removed by degradation and which therefore needed to be returned in order to reintroduce channel complexity, biotope heterogeneity and biodiversity. Rehabilitation included removing weirs, which had trapped sediments (hence decrease the proportion of coarse biotopes) and also acted as barriers to fish and eel movements. A meander running around a patch of woodland was re-opened where a flood channel had previously bypassed it. The channel was meandered and narrowed, with a distinct low-flow channel created by building berms constructed from the spoil derived from the digging of pools. These were dug in meander bends and the material excavated also deposited between the bends, creating a series of riffle-pool sequences. LWM was added. The overall objectives were to create a gradual gradient (by the meandering and weir removal), provide more marginal space for plants (to increase marginal plant biotope), provide safer access to the river for the community and reduce the risk of erosion. Some native macrophytes were planted to initially stabilise the new berms.

The target of the Welland Park rehabilitation was to mimic a natural upstream reach of the Welland River at Lubbenham. Morphological enhancements were assessed at both channel morphological features and in-stream biotope level. In a BACI design, macroinvertebrate samples were collected in a random sampling protocol stratified at in-stream biotope-level (see Table 4.1; Chapter 4 for sampling dates). Three replicate samples were taken from all existing biotopes that covered at least 1% area of the riverbed. Assessing the outcomes of the project depended on a broad range of macroinvertebrate structural and functional metrics.

Rehabilitation of the Welland River increased the variability of channel depth and width, in-stream biotope number and diversity (Chapter 4). These consequences for the hydromorphological variability are similar to results from other rehabilitation projects in lowland rivers (Friberg *et al.* 1998; Pedersen *et al.* 2007; Lorenz, Jahnig & Hering 2009; Jähnig *et al.* 2010). The rehabilitated reach yielded higher macroinvertebrate taxon richness, taxon diversity, total density, total biomass, EPT richness, EPT diversity, EPT count%, and EPT biomass% than before rehabilitation, and than the degraded reach. There was significant enhancement in the rehabilitated reach's macroinvertebrate community taxonomic and FFG composition (Count m^{-2} and Biomass m^{-2}) toward the conditions in the natural reach. The significant increases in macroinvertebrate average abundance and biomass of most of feeding groups were contrary to the growing body of literature which reports only minor effects of stream rehabilitation processes on macroinvertebrates (see Table 2.4, Chapter 2). The rehabilitated reach attained conditions typical of the natural reach by the second post-rehabilitation spring and summer. This evidence points to significant structural and functional recovery of macroinvertebrate populations/communities in the rehabilitated reach. Such strong effects have not been evident in any other rehabilitation studies. Some have indicated that hydromorphological rehabilitation did not promote macroinvertebrate biodiversity, even if habitat changes were considerable (Lepori *et al.* 2005; Jähnig *et al.* 2010; Friberg *et al.* 2013; Haase *et al.* 2013; Pedersen, Kristensen & Friberg 2014), whilst others reported only moderate levels of improvement (Purcell, Friedrich & Resh 2002; Harrison *et al.* 2004; Schiff, Benoit & Macbroom 2011). The failure of some rehabilitation projects to affect biotope composition and diversity was a key factor explaining the consequent lack of positive response by macroinvertebrates (Jähnig & Lorenz 2008; Verdonschot *et al.* 2015). The significant post-rehabilitation increases in macroinvertebrate taxa richness recorded here was the result of an increase in the contribution of gravel and marginal plants, and biotope diversity. The significant increases in macroinvertebrate taxa diversity was the result of an increase of variation in channel depth, and increases in the contribution of gravel and marginal plants. Vegetation biotopes are known to support higher taxon richness and diversity (Friberg *et al.* 1994; Friberg *et al.* 1998; Harrison *et al.* 2004; Friberg *et al.* 2013; Verdonschot *et al.* 2015). Other reasons why the reviewed studies mentioned above did not capture positive effects of rehabilitation on macroinvertebrate biodiversity could be the design of the monitoring study or the methods used to sample macroinvertebrates.

Figure 6.2. A diagram illustrating the aims of the project (pink shading), the rehabilitation techniques applied (beige shading), positively affected hydromorphological metrics (orange shading) and significantly affect macroinvertebrate metrics (green shading).

4) *“Explore the effects of the Welland River rehabilitation project on aquatic macroinvertebrate secondary production and suitability of this functional metric for monitoring rehabilitation projects success”.*

This short-term case study demonstrated that rehabilitation of the Welland River had clear beneficial effects on the rehabilitated reach’s functionality. It demonstrated that active return of the entire lost in-stream biotope heterogeneity could induce measurable changes in macroinvertebrate production more quickly and decrease the supposed recovery time.

The rehabilitated reach of the Welland River yielded higher production estimates for Malacostraca, Gastropoda, Bivalvia, EPT and Arachnida, and a lower estimate for Chironomidae than did the degraded reach. The rehabilitated reach also had a higher estimate of production for shredder, scraper, filter-feeder and predator feeding groups than did the degraded reach. These outcomes demonstrate the recovery of the reach’s entire macroinvertebrates community structure and function after rehabilitation. This result provides a clear message to river rehabilitation practitioners: rehabilitation of the function of a physically degraded river ecosystem is possible if the rehabilitation actively returns the lost in-stream biotope diversity.

One deficiency in the macroinvertebrate secondary production study was the absence of pre-rehabilitation values of production. Here, I could not compare pre-/post-rehabilitation status of the study reaches. Lack of pre-rehabilitation data prompted the use of a control-rehabilitated-reference experiment design. In this design, the control reach represented the pre-rehabilitation physically degraded condition, while the reference reach represented a minimally disturbed condition, which served as the target goal for the rehabilitated reach.

5) *"Discover which macroinvertebrate metrics (*structural or functional metrics*) provide a robust understanding of ecological effects of stream rehabilitation on macroinvertebrate assemblages?"*

The range of responses of macroinvertebrate metrics to enhanced biotope conditions in both rehabilitation projects strengthens the call to use a broader range of structural and functional metrics. In the present study, macroinvertebrate community structural and functional metrics both have been affected significantly by stream rehabilitation processes, as the processes themself influced the rehabiliteted reach's in-stream biotope composision. In the Welland River project, the enhanced biotope heterogenity (see Section 4.4.1, Chapter 4) increased the reach's macroinvertebrate taxon richness, taxon diversity, EPT richness, and EPT diversity (see Section 4.4.2, Chapter 4). In the Rolleston Brook project, however, the upstream recolonisation source was absent, and the enhancement of biotope heterogenity was limited: the coverage areas of only a few in-stream biotopes were affected (gravel, silt, and leaf-litter) (see Section 3.4.1, Chapter 3), increases in macroinvertebrate taxon richness was also significant (see Section 3.4.2, Chapter 3). Those highlighted that, if rehabilitation activly affects the rehabilitated reaches' in-stream biotope heterogenity and provides wide array of both mineral and organic biotopes, the liklihood of increasing biodiversity will be significant.

These results indicate that, both structural and functional metrics could be effective measures to assess the biological effectes of stream rehabilitation, and provide a robust understanding of ecological effects of stream rehabilitation on macroinvertebrate assemblages.

Monitoring of stream rehabilitation process needs to focus more on assessing natural processes and their dynamic shifts toward the targeted rehabilitation endpoint through the inclusion of both structural and functional measures (Palmer *et al.* 2005; Feld *et al.* 2011).

6) *"Highlight the suitability of sampling at in-stream biotope level and BACI study design as approaches to assess the ecological success of hydromorphological rehabilitation projects".*

There have been many criticisms of river rehabilitation projects for not meeting their goals or for not being monitored sufficiently well to determine whether their goals were met (see Section 2.4, Chapter 2). The UK River Restoration Centre (RRC) is acutely aware of this and, together with other similar organisations, is actively promoting technical methods for accurate rehabilitation and methods for post-rehabilitation monitoring http://www.therrc.co.uk/guidance. The two case studies of this thesis demonstrated that, in order to effectively rehabilitate a stream's ecosystem, the spatial unit being treated and the ecological measures used to detect outcomes both need to be carefully considered. The studies demonstrated that rehabilitation of in-stream biotopes provides a useful approach in stream rehabilitation even after short residence times. Collecting stratified samples at biotope level in a BACI study design was an effective way of assessing ecological changes induced by the rehabilitation process, and gauging the direction of the changes toward conditions typical of the natural reach, which was used as an ecological baseline.

In the Rolleston Brook rehabilitation project, overall changes in the rehabilitated reach's channel morphology did not explain a significant proportion of the changes in macroinvertebrate taxonomic or functional univariate metrics (see Section 3.4.7, Chapter 3). At the in-stream biotope-level, however, the limited changes in the rehabilitated reach's biotope composition were significantly related to changes in measured macroinvertebrate community metrics. In the Welland River rehabilitation project, post-rehabilitation changes in the rehabilitated reach's channel morphology (SWI_biotope, CV_depth, and CV_width) explained significant variations in some of the measured macroinvertebrate community metrics (see Section 4.4.6, Chapter 4). At biotope level, increases in Gravel%, Marginal plant%, Woody material%, and Leaf-litter% were related positively to increases in most of the measured macroinvertebrate community metrics. Temporal variations in macroinvertebrate FFGs abundance and biomass were also explained mainly by post-rehabilitation changes in in-stream biotope percentages rather than by measured channel morphology. These observations reveal that the effects on macroinvertebrates univariate metrics were related to changes in the cover of those specific biotope types in the rehabilitated reaches. Verdonschot *et al.* (2015) also found that 'the effects on macroinvertebrates could be related to changes in the cover of specific biotope types in the rehabilitated section'. Macroinvertebrate species often have specific and changing in-stream biotope requirements throughout their life, so all these biotopes must be present and of sufficient quality to guarantee recolonisation and the development of sustainable populations (Verdonschot *et al.* 2015). It is, therefore, necessary to sample all available in-stream biotopes to collect biotic data representative of the study reach's biotic community to enable us to (a) quantify the changes, (b) develop a greater understanding of biotic responses to river rehabilitation activities, and (c) guide more effective rehabilitation strategies. These rehabilitation projects have also shown that biotope mapping could be a sensible design tool for rehabilitation, as well as a low-cost, rapid method for monitoring outcomes.

These case studies also confirm that inadequate sampling could be a limiting factor behind the rare positive outcomes of previous studies (see Section 2.4, Chapter 2). For example, evaluation studies often collect biotic samples in riffles, and yet these habitats are less likely to change as a result of most habitat enhancement projects (Brooks *et al.* 2002; Palmer, Menninger & Bernhardt 2010). When sampling is stratified by biotope type, however, improvements can be more evident (e.g. Nakano & Nakamura 2008; Sundermann, Stoll & Haase 2011; Winking 2015).

A BACI design was essential to quantify improvement using macroinvertebrate structural and functional metrics. Positive changes in rehabilitated reach metrics could be attributed clearly to the morphological effects of the rehabilitation applied to that reach because there were no comparable changes in the natural (non-manipulated) reaches. Seasonal changes in macroinvertebrate community taxonomic and functional compositions, especially of the natural reaches, revealed that repeated seasonal samples are a fundamental requirement of an effective monitoring design because a stream's biotic community usually follows a cyclical pattern. If post-rehabilitation evaluation is conducted during a peak or lull in the cycle, misleading results can be obtained (Leal 2012). Seasonal variability was evident in both case studies. The measured metrics best describing the effects of stream rehabilitation varied by season, as recovery of in-stream biotope number and diversity and covariance in water depth and width changed seasonally. Thus, biotic samples should be collected in all four seasons; we cannot depend on data from only one season to compare between reaches. Comparing changes in the macroinvertebrate community of the rehabilitated reaches with those of the natural reaches was a successful tool to gauge the direction of the change, and to determine success or failures of the project.

It should be noted that the current research project was limited by the absence of replicate studies of the same kind of rehabilitation processes. This was due to unavailability of technically same rehabilitation project in the catchment area. The temporal scale of this study was also short (1st and 2nd years following the rehabilitation processes), which may have limited the ability of the study to detect responses in some taxa or longer-term trends (Lester, Wright & Jones-Lennon 2007). Assessing macroinvertebrate responses at community level is time-consuming process. Collected macroinvertebrate samples need to be sorted while they are still alive. Identifying macroinvertebrate specimens both taxonomically and functionally need time and experience. During my short PhD time, I tried to do morphological mapping, collect and sort biotic samples, and attend many training courses to be able to identify macroinvertebrate specimens correctly.

These findings can serve as a guide for more effective rehabilitation strategies and monitoring protocols. The methodology developed in this dissertation is broadly applicable and extensible to other river systems and ecosystem functions. The findings can be used to understand complex control of in-stream biotope deterioration, assess stream rehabilitation outcomes, and inform river rehabilitation strategies. The Welland River study shows quantitatively how rehabilitation projects could be designed from the bottom up, using biotopes as the natural 'jigsaw' pieces that needs to be returned back to physically degraded river channels. Biotope mapping appears to be a sensible design tool for rehabilitation, as well as a low-cost, rapid method of monitoring outcomes. BACI study designs incorporating a natural reach as the target state are essential to quantify improvement, using macroinvertebrate structural and functional metrics. Random sampling protocols stratified at in-stream biotope-level are necessary to collect macroinvertebrate samples truly representative of the study reaches' communities.

Appendix 1. Species names for macroinvertebrates, dry mass conversions and linear measures used: DM = dry mass; HW = head capsule width; BL = body length; SW = shell width; TL = first thoracic segment length; PL = pleotelson length. y, dependent variable, x, independent variable.

Taxa	Level	y	x	Regression equation	R^2	Reference
Gammarus pulex	*Gammarus pulex*	logDM(mg)	logTL(mm)	y=0.8238+2.9642x	0.997	Poepperl (1998)
Asellus aquaticus	*Asellus aquaticus*	logDM(mg)	logPL(mm)	y=-0.4211+2.4870x	0.994	Poepperl (1998)
Asellus meridianus	*Asellus aquaticus*	logDM(mg)	logPL(mm)	y=-0.4211+2.4870x	0.994	Poepperl (1998)
Lymnaea (Radix) peregra	*Radix peregra*	lnDM(mg)	lnSW(mm)	y=-3.63+3.15x	0.96	Baumgärtner and Rothhaupt (2003)
Lymnaea glabra	*Radix peregra*	lnDM(mg)	lnSW(mm)	y=-3.63+3.15x	0.96	Baumgärtner and Rothhaupt (2003)
Lymnaea stagnalis	*Radix peregra*	lnDM(mg)	lnSW(mm)	y=-3.63+3.15x	0.96	Baumgärtner and Rothhaupt (2003)
Lymnaea truncatula	*Radix peregra*	lnDM(mg)	lnSW(mm)	y=-3.63+3.15x	0.96	Baumgärtner and Rothhaupt (2003)
Valvata piscinalis	Gastropoda	lnDM(mg)	lnSW(mm)	y=-3.95+3.30x	0.95	Baumgärtner and Rothhaupt (2003)
Valvata macrostoma	Gastropoda	lnDM(mg)	lnSW(mm)	y=-3.95+3.30x	0.95	Baumgärtner and Rothhaupt (2003)
Valvata cristata	Gastropoda	lnDM(mg)	lnSW(mm)	y=-3.95+3.30x	0.95	Baumgärtner and Rothhaupt (2003)
Viviparus fasciatus	Gastropoda	lnDM(mg)	lnSW(mm)	y=-3.95+3.30x	0.95	Baumgärtner and Rothhaupt (2003)
Potamopyrgus antipodarum	*Potamopyrgus antipodarum*	logDM(mg)	logSL(mm)	y=-0.8166+2.3761x	0.997	Poepperl (1998)
Bithynia tentaculata	*Bithynia tentaculata*	lnDM(mg)	lnSW(mm)	y=-4.54+3.66x	0.95	Baumgärtner and Rothhaupt (2003)
Bithynia leachii	*Bithynia tentaculata*	lnDM(mg)	lnSW(mm)	y=-4.54+3.66x	0.95	Baumgärtner and Rothhaupt (2003)
Physa fontinalis	Gastropoda	lnDM(mg)	lnSW(mm)	y=-3.95+3.30x	0.95	Baumgärtner and Rothhaupt (2003)
Theodoxus fluviatilis	Gastropoda	lnDM(mg)	lnSW(mm)	y=-3.95+3.30x	0.95	Baumgärtner and Rothhaupt (2003)
Planorbis contortus	*Planorbis contortus*	logDW(mg)	logSL(mm)	y=-2.331+2x	0.69	Calow (1975)
Planorbis corneus	*Planorbis contortus*	logDW(mg)	logSL(mm)	y=-2.331+2x	0.69	Calow (1975)
Planorbis crista	*Planorbis contortus*	logDW(mg)	logSL(mm)	y=-2.331+2x	0.69	Calow (1975)
Ancylus fluviatilis	*Ancylus fluviatilis*	lnDM(mg)	lnSL(mm)	y=-3.3319+3.1403x	0.98	Meyer (1989)
Ancylus lacustris	*Ancylus fluviatilis*	lnDM(mg)	lnSL(mm)	y=-3.3319+3.1403x	0.98	Meyer (1989)
Pisidium sp.	*Pisidium* sp.	logDM(mg)	logBL(mm)	y=-0.9722+2.9132x	0.999	Poepperl (1998)

Sphaerium sp.	*Sphaerium corneum*	logDM(mg)	logBL(mm)	y=-1.5407+3.4024x	0.994	Poepperl (1998)
Anadonta sp.	*Anodonta cataracta*	DM(mg)	BL(mm)	$y=0.0038*(x^{2.915})$		Cameron, Cameron and Paterson (1979)(Cited in Benke *et al.* (1999)
Glossiphonia complanata	*Glossiphonia complanata*	lnDM(mg)	lnBL(mm)	y=-2.12+2x	0.64	Edwards *et al.* (2009)
Glossiphonia heteroclita	*Glossiphonia complanata*	lnDM(mg)	lnBL(mm)	y=-2.12+2x	0.64	Edwards *et al.* (2009)
Theromyzon tessulatum	Leech	lnDM(mg)	lnBL(mm)	y=-2.69+2.11x	0.62	Edwards *et al.* (2009)
Helobdella stagnalis	*Helobdella stagnalis*	lnDM(mg)	lnBL(mm)	y=-2.74+2.12x	0.62	Edwards *et al.* (2009)
Erpobdella octoculata	*Erpobdella octoculata*	lnDM(mg)	lnBL(mm)	y=-3.20+2.22x	0.78	Edwards *et al.* (2009)
Erpobdella testacea	*Erpobdella octoculata*	lnDM(mg)	lnBL(mm)	y=-3.20+2.22x	0.78	Edwards *et al.* (2009)
Polycelis tenuis	*Polycelis sp.*	lnDM(mg)	lnBL(mm)	y=-3.6344+1.8545x	0.617	Meyer (1989)
Polycelis felina	*Polycelis sp.*	lnDM(mg)	lnBL(mm)	y=-3.6344+1.8545x	0.617	Meyer (1989)
Polycelis nigra	*Polycelis sp.*	lnDM(mg)	lnBL(mm)	y=-3.6344+1.8545x	0.617	Meyer (1989)
Dugesia lugubris	*Dugesia tigrina*	DM(mg)	BL(mm)	$y=0.0089*(x^{2.145})$	0.81	Benke *et al.* (1999)
Elmidae	Elmidae (Larvae)	lnDM(mg)	lnBL(mm)	y=-6.078+3.092x	0.83	Towers, Henderson and Veltman (1994)
Scirtidae	Coleoptera (larvae)	lnDM(mg)	lnBL(mm)	y=-4.4518+2.4724x	0.57	Meyer (1989)
Helophoridae	Coleoptera (larvae)	lnDM(mg)	lnBL(mm)	y=-4.4518+2.4724x	0.57	Meyer (1989)
Helodidae	Coleoptera (larvae)	lnDM(mg)	lnBL(mm)	y=-4.4518+2.4724x	0.57	Meyer (1989)
Haliplidae	Coleoptera (larvae)	lnDM(mg)	lnBL(mm)	y=-4.4518+2.4724x	0.57	Meyer (1989)
Hydraenidae	Coleoptera (larvae)	lnDM(mg)	lnBL(mm)	y=-4.4518+2.4724x	0.57	Meyer (1989)
Dytiscidae	Coleoptera (larvae)	lnDM(mg)	lnBL(mm)	y=-4.4518+2.4724x	0.57	Meyer (1989)
Hydrophilidae	Coleoptera (larvae)	lnDM(mg)	lnBL(mm)	y=-4.4518+2.4724x	0.57	Meyer (1989)
Gyrinidae	Coleoptera (larvae)	lnDM(mg)	lnBL(mm)	y=-4.4518+2.4724x	0.57	Meyer (1989)
Curculionidae	Coleoptera (larvae)	lnDM(mg)	lnBL(mm)	y=-4.4518+2.4724x	0.57	Meyer (1989)
Muscidae	Diptera (larvae)	lnDM(mg)	lnBL(mm)	y=-6.21+2.52x	0.83	Burgherr and Meyer (1997)
Psychodidae	Diptera (larvae)	lnDM(mg)	lnBL(mm)	y=-6.21+2.52x	0.83	Burgherr and Meyer (1997)
Ptychopteridae	Diptera (larvae)	lnDM(mg)	lnBL(mm)	y=-6.21+2.52x	0.83	Burgherr and Meyer (1997)
Dixidae	Diptera (larvae)	lnDM(mg)	lnBL(mm)	y=-6.21+2.52x	0.83	Burgherr and Meyer (1997)

Tabanidae	Diptera (larvae)	lnDM(mg)	lnBL(mm)	y=-6.21+2.52x	0.83	Burgherr and Meyer (1997)
Stratiomyidae	Diptera (larvae)	lnDM(mg)	lnBL(mm)	y=-6.21+2.52x	0.83	Burgherr and Meyer (1997)
Empididae	Diptera (larvae)	lnDM(mg)	lnBL(mm)	y=-6.21+2.52x	0.83	Burgherr and Meyer (1997)
Tipulidae	*Tipula abdominalis* (Say)	lnW(mg)	lnBL(mm)	y=-5.30+2.36x	0.93	Smock (1980)
Pediciidae	*Dicranota* sp.	lnDM(mg)	lnBL(mm)	y=-5.53+1.91x	0.54	Burgherr and Meyer (1997)
Simuliidae	*Simulium* sp.	lnDM(mg)	lnBL(mm)	y=-5.84+2.49x	0.83	Burgherr and Meyer (1997)
Limoniidae	*Tipula abdominalis* (Say)	lnW(mg)	lnBL(mm)	y=-5.298+2.36x	0.93	Smock (1980)
Ceratopogonidae	Ceratopogonidae	lnDM(mg)	lnBL(mm)	y=-9.3774+3.7948x	0.839	Meyer (1989)
Chironominae	Chironomidae	lnDM(mg)	lnHW(mm)	y=0.77+2.41x	0.6	Burgherr and Meyer (1997)
Prodiamesinae	Chironomidae	lnDM(mg)	lnHW(mm)	y=0.77+2.41x	0.6	Burgherr and Meyer (1997)
Orthocladiinae	Chironomidae	lnDM(mg)	lnHW(mm)	y=0.77+2.41x	0.6	Burgherr and Meyer (1997)
Diamesinae	Chironomidae	lnDM(mg)	lnHW(mm)	y=0.77+2.41x	0.6	Burgherr and Meyer (1997)
Tanypodinae	Tanypodinae	lnDM(mg)	lnHW(mm)	y=1.37+3.25x	0.41	Burgherr and Meyer (1997)
Tinodes sp.	*Tinodes waeneri*	logDM(mg)	logHW(mm)	y=-0.1593+5.4712x	0.973	Poepperl (1998)
Lype sp.	*Lype phaeopa*	logDM(mg)	logHW(mm)	y=-0.2519+1.8162x	0.994	Poepperl (1998)
Hydropsyche sp.	*Hydropsyche* spp.	lnDM(mg)	lnHW(mm)	y=0.2080+2.8606x	0.827	Meyer (1989)
Hydropsyche siltatay	*Hydropsyche* spp.	lnDM(mg)	lnHW(mm)	y=0.2080+2.8606x	0.827	Meyer (1989)
Hydropsyche instabilus	*Hydropsyche* spp.	lnDM(mg)	lnHW(mm)	y=0.2080+2.8606x	0.827	Meyer (1989)
Halesus radiatus.	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)
Halesus digitatus	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)
Limnephilus lunatus.	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)
Limnephilus nigriceps	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)
Limnephilus flavicornis	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)
Anabolia nervosa	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)
Chaetopteryx villosa	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)
Glyphotaelius pellucidus	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)

Phacopteryx brevipennis	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)
Micropterna sp.	Limnephilidae	lnDM(mg)	lnHW(mm)	y=0.4109+3.1678x	0.83	Meyer (1989)
Potamophylax sp.	*Potamophylax* sp.	lnDM(mg)	lnHW(mm)	y=0.6272+3.6358x	0.767	Meyer (1989)
Molanna albicans	*Molanna angustata*	logDM(mg)	logHW(mm)	y=0.6120+5.1315x	0.916	Poepperl (1998)
Mystacides longicornis(azurea)	*Mystacides* sp.	logDM(mg)	logHW(mm)	y=0.5689+3.5539x	0.918	Poepperl (1998)
Ceraclea sp.	*Ceraclea* sp.	lnDM(mg)	lnHW(mm)	y=1.00+3.52x	0.94	Baumgärtner and Rothhaupt (2003)
Athripsodes cinereus	*Athripsodes* sp.	logDM(mg)	logHW(mm)	y=0.6221+4.0212x	0.964	Poepperl (1998)
Athripsodes aterrimus	*Athripsodes* sp.	logDM(mg)	logHW(mm)	y=0.6221+4.0212x	0.964	Poepperl (1998)
Crunoecia irrorata	Tricoptera, cased	lnDM(mg)	lnHW(mm)	y=1.30+3.62x	0.82	Baumgärtner and Rothhaupt (2003)
Lepidostoma hirtum	Tricoptera, cased	lnDM(mg)	lnHW(mm)	y=1.30+3.62x	0.82	Baumgärtner and Rothhaupt (2003)
Lasiocephala basalis	Tricoptera, cased	lnDM(mg)	lnHW(mm)	y=1.30+3.62x	0.82	Baumgärtner and Rothhaupt (2003)
Sericostoma personatum	*Sericostoma* spp.	lnDM(mg)	lnHW(mm)	y=0.1692+2.9153x	0.885	Meyer (1989)
Agapetus fuscipes	*Glossosoma* spp.	lnDM(mg)	lnHW(mm)	y=0.96+2.98x	0.71	Meyer (1989)
Hydroptilidae	Tricoptera, cased	lnDM(mg)	lnBL(mm)	y=-4.48+2.57x	0.8	Baumgärtner and Rothhaupt (2003)
Plectrocnemia conspersa	*Polycentropus flavomaculatus*	lnDM(mg)	lnHW(mm)	y=-0.51+3.03x	0.87	Baumgärtner and Rothhaupt (2003)
Polycentropus flavomaculatus	*Polycentropus flavomaculatus*	lnDM(mg)	lnHW(mm)	y=-0.51+3.03x	0.87	Baumgärtner and Rothhaupt (2003)
Apatania muliebris	Tricoptera, cased	lnDM(mg)	lnHW(mm)	y=1.30+3.62x	0.82	Baumgärtner and Rothhaupt (2003)
Beraea pullata	Tricoptera, cased	lnDM(mg)	lnHW(mm)	y=1.30+3.62x	0.82	Baumgärtner and Rothhaupt (2003)
Silo pallipes	Goeridae	lnDM(mg)	lnHW(mm)	y=0.8613+3.5755x	0.75	Meyer (1989)
Goera pilosa	Goeridae	lnDM(mg)	lnHW(mm)	y=0.8613+3.5755x	0.75	Meyer (1989)
Rhyacophila sp.	*Rhyacophila* spp.	lnDM(mg)	lnHW(mm)	y=0.5327+2.9503x	0.726	Meyer (1989)
Rhyacophila dorsalis	*Rhyacophila* spp.	lnDM(mg)	lnHW(mm)	y=0.5327+2.9503x	0.726	Meyer (1989)
Rhyacophila septensipis	*Rhyacophila* spp.	lnDM(mg)	lnHW(mm)	y=0.5327+2.9503x	0.726	Meyer (1989)
Baetis rhodani	*Baetis* spp.	lnDM(mg)	lnBL(mm)	y=-5.55+2.67x	0.91	Burgherr and Meyer (1997)
Cloeon dipterum	*Cloeon dipterum*	DM(mg)	BL(mm)	$y=0.0010*(x^{3.68})$	0.95	Cianciara (1980)
Procloeon pennulatum	*Cloeon dipterum*	DM(mg)	BL(mm)	$y=0.0010*(x^{3.68})$	0.95	Cianciara (1980)

Centroptilum luteolum	*Centroptilum luteolum*	logDM(mg)	logHW(mm)	y=-0.4286+1.7023x	0.97	Poepperl (1998)
Caenis macrura	*Caenis* sp.	logDM(mg)	logHW(mm)	y=-0.4873+2.8496x	0.996	Poepperl (1998)
Caenis luctuosa	*Caenis* sp.	logDM(mg)	logHW(mm)	y=-0.4873+2.8496x	0.996	Poepperl (1998)
Ephemera vulgata	*Ephemera danica*	logDM(mg)	logHW(mm)	y=-0.1908+3.3883x	0.996	Poepperl (1998)
Ephemera danica	*Ephemera danica*	logDM(mg)	logHW(mm)	y=-0.1908+3.3883x	0.996	Poepperl (1998)
Serratella ignita	*Serratella* sp.	DM(mg)	BL(mm)	$y=0.0088*(x^{2.584})$	0.76	Benke *et al.* (1999)
Habrophlebia fusca	Leptophlebiidae	lnDM(mg)	lnBL(mm)	y=-8.62+4.20x	0.93	Burgherr and Meyer (1997)
Paraleptophlebia werneri	Leptophlebiidae	lnDM(mg)	lnBL(mm)	y=-8.62+4.20x	0.93	Burgherr and Meyer (1997)
Potamanthus luteus	Ephemeroptera	lnDM(mg)	lnBL(mm)	y=-4.85+2.74x	0.77	Baumgärtner and Rothhaupt (2003)
Nemurella pictetii	*Nemura* sp.	lnDM(mg)	lnBL(mm)	y=-4.1057+1.9858x	0.669	Meyer (1989)
Nemurella cambrica	*Nemura* sp.	lnDM(mg)	lnBL(mm)	y=-4.1057+1.9858x	0.669	Meyer (1989)
Amphinemura sp.	*Amphinemura* spp.	lnDM(mg)	lnBL(mm)	y=-5.90+3.32x	0.93	Burgherr and Meyer (1997)
Sialis lutaria	*Sialis lutaria*	logDM(mg)	logHW(mm)	y=-0.2908+2.9758x	0.996	Poepperl (1998)
Calopteryx virgo	*Calopteryx* sp.	DM(mg)	BL(mm)	$y=0.0050*(x^{2.742})$	0.83	Benke *et al.* (1999)
Platycnemis pennipes	Odonata	lnW(mg)	lnBL(mm)	y=-4.269+2.78x	0.94	Smock (1980)
Coenagrion sp.	Coenagrionidae	DM(mg)	BL(mm)	$y=0.0051*(x^{2.785})$	0.83	Benke *et al.* (1999)
Sigara sp.	*Sigara sp.*	lnW(mg)	lnBL(mm)	y=-3.270+2.53x	0.8	Smock (1980)
Velia caprai	Hemiptera	lnW(mg)	lnBL(mm)	y=-3.461+2.40x	0.93	Smock (1980)
Lebirtia porosa	Acari	lnDM(mg)	lnBW(mm)	y=-1.69+1.69x	0.55	Baumgärtner and Rothhaupt (2003)
Hygrobates sp.	Acari	lnDM(mg)	lnBW(mm)	y=-1.69+1.69x	0.55	Baumgärtner and Rothhaupt (2003)
Sperchon sp.	Acari	lnDM(mg)	lnBW(mm)	y=-1.69+1.69x	0.55	Baumgärtner and Rothhaupt (2003)
diplodontus despiciens	Acari	lnDM(mg)	lnBW(mm)	y=-1.69+1.69x	0.55	Baumgärtner and Rothhaupt (2003)
Limnesia sp	Acari	lnDM(mg)	lnBW(mm)	y=-1.69+1.69x	0.55	Baumgärtner and Rothhaupt (2003)
Arrenurus truncatellus	Acari	lnDM(mg)	lnBW(mm)	y=-1.69+1.69x	0.55	Baumgärtner and Rothhaupt (2003)
Mideopsis orbicularis	Acari	lnDM(mg)	lnBW(mm)	y=-1.69+1.69x	0.55	Baumgärtner and Rothhaupt (2003)

Appendix 2. Assigning of macroinvertebrate taxa count and biomass into functional feeding groups according to Tachet *et al.* (2010) fuzzy codding.

Class	Order	Family	Taxa	Absorber	Deposit-feeder	Shredder	Scraper	Filter-feeder	Piercer	Predator	Parasite
Malacostraca	Amphipoda	Gammaridae	*Gammarus pulex*	0	0	0.75	0.25	0	0	0	0
Malacostraca	Isopoda	Asellidae	*Asellus aquaticus*	0	0	1	0	0	0	0	0
Malacostraca	Isopoda	Asellidae	*Asellus meridianus*	0	0	1	0	0	0	0	0
Gastropoda	Lymnaeoidea	Lymnaeidae	*Lymnaea (Radix) peregra*	0	0	0.25	0.75	0	0	0	0
Gastropoda	Lymnaeoidea	Lymnaeidae	*Lymnaea glabra*	0	0	0.167	0.5	0	0	0.3333	0
Gastropoda	Lymnaeoidea	Lymnaeidae	*Lymnaea stagnalis*	0	0	0.167	0.5	0	0	0.3333	0
Gastropoda	Lymnaeoidea	Lymnaeidae	*Lymnaea truncatula*	0	0	0.167	0.5	0	0	0.3333	0
Gastropoda	Heterostropha	Valvatidae	*Valvata piscinalis*	0	0	0.2	0.4	0.4	0	0	0
Gastropoda	Heterostropha	Valvatidae	*Valvata macrostoma*	0	0	0.2	0.4	0.4	0	0	0
Gastropoda	Heterostropha	Valvatidae	*Valvata cristata*	0	0	0.2	0.4	0.4	0	0	0
Gastropoda	Architaenioglossa	Viviparidae	*Viviparus fasciatus*	0	0	0.2	0.4	0.4	0	0	0
Gastropoda	Rissooidea	Hydrobiidae	*Potamopyrgus antipodarum*	0	0	0.6	0.4	0	0	0	0
Gastropoda	Rissooidea	Bithyniidae	*Bithynia tentaculata*	0	0	0	0.3333	0.6667	0	0	0
Gastropoda	Rissooidea	Bithyniidae	*Bithynia leachii*	0	0	0	0.3333	0.6667	0	0	0
Gastropoda	Rissooidea	Physidae	*Physa fontinalis*	0	0	0.25	0.75	0	0	0	0
Gastropoda	Rissooidea	Neritidae	*Theodoxus fluviatilis*	0	0	0.25	0.75	0	0	0	0
Gastropoda	Planorboidea	Planorbidae	*Planorbis contortus*	0	0	0.333	0.6667	0	0	0	0
Gastropoda	Planorboidea	Planorbidae	*Planorbis corneus*	0	0	0.75	0.25	0	0	0	0
Gastropoda	Planorboidea	Planorbidae	*Planorbis crista*	0	0	0.333	0.6667	0	0	0	0

Gastropoda	Planorboidea	Planorbidae	*Ancylus fluviatilis*	0	0	0	1	0	0	0	0
Gastropoda	Planorboidea	Planorbidae	*Ancylus lacustris*	0	0	0	1	0	0	0	0
Bivalvia	Veneroida	Pisidiidae	*Pisidium sp.*	0	0	0	0	1	0	0	0
Bivalvia	Veneroida	Sphaeriidae	*Sphaerium sp.*	0	0	0	0	1	0	0	0
Bivalvia	Unionoida	Unionidae	*Anadonta sp.*	0	0	0	0	0.6	0.2	0	0.2
Hirudinea	Rhynchobdellida	Glossiphoniidae	*Glossiphonia complanata*	0	0	0	0	0	0.75	0	0.25
Hirudinea	Rhynchobdellida	Glossiphoniidae	*Glossiphonia heteroclita*	0	0	0	0	0	0.75	0	0.25
Hirudinea	Rhynchobdellida	Glossiphoniidae	*Theromyzon tessulatum*	0	0	0	0	0	0	0	1
Hirudinea	Rhynchobdellida	Glossiphoniidae	*Helobdella stagnalis*	0	0	0	0	0	1	0	0
Hirudinea	Arhynchobdellida	Erpobdellidae	*Erpobdella octoculata*	0	0	0	0	0	0	1	0
Hirudinea	Arhynchobdellida	Erpobdellidae	*Erpobdella testacea*	0	0	0	0	0	0	1	0
Oligochaeta	Lumbriculida	Lumbriculidae	*Lumbriculidae*	0.25	0.75	0	0	0	0	0	0
Oligochaeta	Lumbricina	Lumbricidae	*Lumbricidae*	0.25	0.75	0	0	0	0	0	0
Oligochaeta	Haplotaxida	Glossoscolecidae	*Glossoscolecidae*	0.25	0.75	0	0	0	0	0	0
Oligochaeta	Haplotaxida	Tubificidae	*Tubificidae*	0.25	0.75	0	0	0	0	0	0
Oligochaeta	Haplotaxida	Naididae	*Nais sp.*	0	0.6	0	0.4	0	0	0	0
Oligochaeta	Haplotaxida	Naididae	*Stylaria lacustris*	0	0.4	0	0.6	0	0	0	0
Nematomorpha	Gordioidea	Gordiidae	*Gordius aquaticus*	0	0	0	0	0	0	0	1
Turbellaria	Tricladida	Planariidae	*Polycelis tenuis*	0	0	0	0	0	0	1	0
Turbellaria	Tricladida	Planariidae	*Polycelis felina*	0	0	0	0	0	0	1	0
Turbellaria	Tricladida	Planariidae	*Polycelis nigra*	0	0	0	0	0	0	1	0
Turbellaria	Tricladida	Dugesiidae	*Dugesia lugubris*	0	0	0	0	0	0	1	0
Insecta	Coleoptera	Elmidae	Elmidae	0	0	0.25	0.75	0	0	0	0
Insecta	Coleoptera	Scirtidae	Scirtidae	0	0	0.25	0.75	0	0	0	0
Insecta	Coleoptera	Helophoridae	Helophoridae	0	0	0.25	0.75	0	0	0	0

Insecta	Coleoptera	Helodidae	Helodidae	0	0	0.25	0.75	0	0	0	0
Insecta	Coleoptera	Haliplidae	Haliplidae	0	0	0.5	0	0	0.5	0	0
Insecta	Coleoptera	Hydraenidae	Hydraenidae	0	0	0.25	0.75	0	0	0	0
Insecta	Coleoptera	Dytiscidae	Dytiscidae	0	0	0.5	0	0	0.5	0	0
Insecta	Coleoptera	Hydrophilidae	Hydrophilidae	0	0	0.75	0	0	0	0.25	0
Insecta	Coleoptera	Gyrinidae	Gyrinidae	0	0	0.5	0	0	0.5	0	0
Insecta	Coleoptera	Curculionidae	Curculionidae	0	0	1	0	0	0	0	0
Insecta	Diptera	Muscidae	Muscidae	0	0	0	0	0	1	0	0
Insecta	Diptera	Psychodidae	Psychodidae	0	0.3333	0.5	0.1667	0	0	0	0
Insecta	Diptera	Ptychopteridae	Ptychopteridae	0	0.6	0.4	0	0	0	0	0
Insecta	Diptera	Dixidae	Dixidae	0	0	0.143	0	0.4286	0	0.4286	0
Insecta	Diptera	Tabanidae	Tabanidae	0	0	0.25	0	0	0.75	0	0
Insecta	Diptera	Stratiomyidae	Stratiomyidae	0	0.2857	0.429	0.1429	0	0	0.1429	0
Insecta	Diptera	Empididae	Empididae	0	0	0	0	0	0	1	0
Insecta	Diptera	Tipulidae	Tipulidae	0	0.2857	0.429	0	0	0	0.2857	0
Insecta	Diptera	Pediciidae	Pediciidae	0	0	0	0	0	0	1	0
Insecta	Diptera	Simuliidae	Simuliidae	0	0	0	0.25	0.75	0	0	0
Insecta	Diptera	Limoniidae	Limoniidae	0	0.2	0.6	0	0	0	0	0.2
Insecta	Diptera	Ceratopogonidae	Ceratopogonidae	0	0.2	0.2	0	0	0	0.6	0
Insecta	Diptera	Chironomidae	Chironominae	0	0.3	0.2	0.1	0.2	0	0.1	0.1
Insecta	Diptera	Chironomidae	Prodiamesinae	0	0.3	0.2	0.1	0.2	0	0.1	0.1
Insecta	Diptera	Chironomidae	Orthocladiinae	0	0.1667	0	0.5	0.1667	0	0	0.167
Insecta	Diptera	Chironomidae	Diamesinae	0	0.3	0.2	0.1	0.2	0	0.1	0.1
Insecta	Diptera	Chironomidae	Tanypodinae	0	0	0	0	0	0	1	0
Insecta	Trichoptera	Psychomyiidae	*Tinodes sp.*	0	0.1429	0	0.4286	0.2856	0	0.1429	0
Insecta	Trichoptera	Psychomyiidae	*Lype sp.*	0	0	0	0.75	0.25	0	0	0
Insecta	Trichoptera	Hydropsychidae	*Hydropsyche sp.*	0	0	0	0	0.75	0	0.25	0

Insecta	Trichoptera	Hydropsychidae	*Hydropsyche siltatay*	0	0	0	0	0.75	0	0.25	0
Insecta	Trichoptera	Hydropsychidae	*Hydropsyche instabilus*	0	0	0	0	0.75	0	0.25	0
Insecta	Trichoptera	Limnephilidae	*Halesus radiatus.*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Limnephilidae	*Halesus digitatus*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Limnephilidae	*Limnephilus lunatus.*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Limnephilidae	*Limnephilus nigriceps*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Limnephilidae	*Limnephilus flavicornis*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Limnephilidae	*Anabolia nervosa*	0	0.1429	0.429	0.2856	0	0	0.1429	0
Insecta	Trichoptera	Limnephilidae	*Chaetopteryx villosa*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Limnephilidae	*Glyphotaelius pellucidus*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Limnephilidae	*Phacopteryx brevipennis*	0	0	0	0.3333	0.5	0	0.1667	0
Insecta	Trichoptera	Limnephilidae	*Micropterna sp.*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Limnephilidae	*Potamophylax sp.*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Molannidae	*Molanna albicans*	0	0.2	0	0.2	0	0	0.6	0
Insecta	Trichoptera	Leptoceridae	*Mystacides longicornis(azurea)*	0	0.1667	0.5	0.3333	0	0	0	0
Insecta	Trichoptera	Leptoceridae	*Ceraclea sp.*	0	0.1428	0.429	0.1429	0	0	0.1429	0.143
Insecta	Trichoptera	Leptoceridae	*Athripsodes cinereus*	0	0	0.75	0.25	0	0	0	0
Insecta	Trichoptera	Leptoceridae	*Athripsodes aterrimus*	0	0	0.75	0.25	0	0	0	0
Insecta	Trichoptera	Lepidostomatidae	*Crunoecia irrorata*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Lepidostomatidae	*Lepidostoma hirtum*	0	0	0.75	0.25	0	0	0	0

Insecta	Trichoptera	Lepidostomatidae	*Lasiocephala basalis*	0	0	1	0	0	0	0	0
Insecta	Trichoptera	Sericostomatidae	*Sericostoma personatum*	0	0	0.75	0.25	0	0	0	0
Insecta	Trichoptera	Glossosomatidae	*Agapetus fuscipes*	0	0	0.75	0.25	0	0	0	0
Insecta	Trichoptera	Hydroptilidae	*Hydroptilidae*	0	0.1667	0.167	0.1667	0	0.5	0	0
Insecta	Trichoptera	Polycentropodidae	*Plectrocnemia conspersa*	0	0	0	0	0.25	0	0.75	0
Insecta	Trichoptera	Polycentropodidae	*Polycentropus flavomaculatus*	0	0	0.2	0	0.2	0	0.6	0
Insecta	Trichoptera	Apataniidae	*Apatania muliebris*	0	0.2	0	0.6	0	0	0.2	0
Insecta	Trichoptera	Beraeidae	*Beraea pullata*	0	0.25	0.75	0	0	0	0	0
Insecta	Trichoptera	Goeridae	*Silo pallipes*	0	0	0.25	0.75	0	0	0	0
Insecta	Trichoptera	Goeridae	*Goera pilosa*	0	0	0.25	0.75	0	0	0	0
Insecta	Trichoptera	Rhyacophilidae	*Rhyacophila sp.*	0	0	0	0	0	0	1	0
Insecta	Trichoptera	Rhyacophilidae	*Rhyacophila dorsalis*	0	0	0	0	0	0	1	0
Insecta	Trichoptera	Rhyacophilidae	*Rhyacophila septensipis*	0	0	0	0	0	0	1	0
Insecta	Ephemeroptera	Baetidae	*Baetis rhodani*	0	0.25	0	0.75	0	0	0	0
Insecta	Ephemeroptera	Baetidae	*Cloeon dipterum*	0	0.4286	0.143	0.4286	0	0	0	0
Insecta	Ephemeroptera	Baetidae	*Procloeon pennulatum*	0	0.3333	0	0.6667	0	0	0	0
Insecta	Ephemeroptera	Baetidae	*Centroptilum luteolum*	0	0.4	0	0.6	0	0	0	0
Insecta	Ephemeroptera	Caenidae	*Caenis macrura*	0	0.75	0.25	0	0	0	0	0
Insecta	Ephemeroptera	Caenidae	*Caenis luctuosa*	0	0.75	0.25	0	0	0	0	0
Insecta	Ephemeroptera	Ephemeridae	*Ephemera vulgata*	0	0.125	0.375	0	0.375	0	0.125	0
Insecta	Ephemeroptera	Ephemeridae	*Ephemera danica*	0	0.125	0.375	0	0.375	0	0.125	0
Insecta	Ephemeroptera	Ephemerellidae	*Serratella ignita*	0	0.1667	0.333	0.3333	0	0	0.1667	0
Insecta	Ephemeroptera	Leptophlebiidae	*Habrophlebia fusca*	0	0.25	0.75	0	0	0	0	0

Insecta	Ephemeroptera	Leptophlebiidae	*Paraleptophlebia werneri*	0	0.4	0.4	0.2	0	0	0	0
Insecta	Ephemeroptera	Potamanthidae	*Potamanthus luteus*	0	0.4	0.6	0	0	0	0	0
Insecta	Plecoptera	Nemouridae	*Nemurella pictetii*	0	0	1	0	0	0	0	0
Insecta	Plecoptera	Nemouridae	*Nemurella cambrica*	0	0	1	0	0	0	0	0
Insecta	Plecoptera	Nemouridae	*Amphinemura sp.*	0	0.25	0.75	0	0	0	0	0
Insecta	Megaloptera	Sialidae	*Sialis lutaria*	0	0	0	0	0	0	1	0
Insecta	Odonata	Calopterygidae	*Calopteryx sp.*	0	0	0	0	0	0	1	0
Insecta	Odonata	Platycnemididae	*Platycnemis pennipes*	0	0	0	0	0	0	1	0
Insecta	Odonata	Coenagrionidae	*Coenagrion sp.*	0	0	0	0	0	0	1	0
Insecta	Hemiptera	Corixidae	*Sigara sp.*	0	0	0.429	0.2857	0	0.286	0	0
Insecta	Hemiptera	Veliidae	*Velia caprai*	0	0	0	0	0	0.75	0.25	0
Insecta	Neuroptera	Osmylidae	*Osmylus sp.*	0	0	0	0	0	0.75	0.25	0
Insecta	Neuroptera	Sisyridae	*Sisyra sp*	0	0	0.143	0	0	0.429	0	0.429
Arachnida	Acari	Libertiidae	*Lebirtia porosa*	0	0	0	0	0	0	1	0
Arachnida	Acari	Hygrobatidae	*Hygrobates sp (longu)*	0	0	0	0	0	0	1	0
Arachnida	Acari	Sperchontidae	*Sperchon sp.*	0	0	0	0	0	0	1	0
Arachnida	Acari	Hydryphantidae	*diplodontus despiciens*	0	0	0	0	0	0	1	0
Arachnida	Acari	Limnesiidae	*Limnesia sp*	0	0	0	0	0	0	1	0
Arachnida	Acari	Arrenuridae	*Arrenurus truncatellus*	0	0	0	0	0	0	1	0
Arachnida	Acari	Mideopsidae	*Mideopsis orbicularis*	0	0	0	0	0	0	1	0

Appendix 3. Data analysis of Chapter 3

Appendix 3.1 Summary of results from Principal Components Analysis (PCA) of channel morphology metrics between both reaches.

Eigenvalues					
PC	Eigenvalues	%Variation	Cumulative % Variation		
1	2.18	58.3	58.3		
2	1.17	31.2	89.5		
3	0.332	8.9	98.4		
4	0.0558	1.5	99.9		
5	0.00366	0.1	100.0		
Eigenvectors					
(Coefficients in the linear combinations of variables making up PCs)					
Variable	PC1	PC2	PC3	PC4	PC5
SWI_biotope	-0.613	0.264	-0.161	0.120	-0.717
CV_depth	-0.164	0.094	0.130	-0.973	-0.017
CV_width	-0.148	0.276	0.932	0.175	0.048
Wet surface area (m2)	-0.413	-0.889	0.196	0.010	-0.016
Number of biotopes	-0.636	0.235	-0.223	0.087	0.695

Appendix 3.2 Summary of results from Principal Components Analysis (PCA) of in-stream biotope composition between both reaches.

Eigenvalues					
PC	Eigenvalues	%Variation	Cumulative % Variation		
1	0.0675	92.9	92.9		
2	0.00265	3.7	96.5		
3	0.00187	2.6	99.1		
4	0.000449	0.6	99.7		
5	0.00012	0.2	99.9		
Eigenvectors					
(Coefficients in the linear combinations of variables making up PCs)					
Variable	PC1	PC2	PC3	PC4	PC5
Boulder %	-0.036	0.027	-0.041	0.137	-0.045
Cobbles %	-0.419	-0.562	-0.231	-0.454	-0.121
Gravels %	-0.386	0.101	0.526	0.450	-0.200
Sand %	-0.071	-0.136	0.455	-0.283	0.563
Silt %	0.791	-0.325	0.086	0.076	0.063
Tree root %	-0.057	-0.026	-0.266	0.059	0.088
Marginal plant %	-0.055	0.045	-0.587	0.321	0.042
Leaf litter %	0.058	0.733	-0.103	-0.467	0.112
Small woody debris %	-0.012	0.070	-0.072	0.336	0.186
Clay %	0.182	0.059	0.151	-0.223	-0.752

Appendix 3.3 Channel morphological variables and metrics of the study reaches. N, Natural Reach; R, Rehabilitated Reach.

	Status	Before LWM installation		After LWM installation											
	Year	2014		2015								2016			
	Season	Spring		Winter		Spring		Summer		Autumn		Winter		Spring	
Channel morphological features	Reach	N	R	N	R	N	R	N	R	N	R	N	R	N	R
CV_depth		0.66	0.41	0.68	0.62	0.65	0.7	0.7	0.61	0.7	0.7	0.69	0.61	0.64	0.34
CV_width		0.39	0.22	0.39	0.3	0.38	0.34	0.36	0.35	0.31	0.4	0.38	0.29	0.37	0.22
Number of biotopes		8	4	7	4	8	6	9	5	9	6	7	5	8	5
SWI_biotope		0.89	0.60	0.82	0.60	0.89	0.76	0.94	0.70	0.94	0.76	0.82	0.70	0.89	0.69
Wet surface area (m^2)		302	221	318	287	315	240	249	45	256	130	325	298	298	207

Appendix 3.4 In-stream biotope composition (biotope %) of the study reaches. N, Natural Reach; R, Rehabilitated Reach.

	Status	Before LWM installation		After LWM installation											
	Year	2014		2015								2016			
	Season	Spring		Winter		Spring		Summer		Autumn		Winter		Spring	
Biotopes	Reach	N	R	N	R	N	R	N	R	N	R	N	R	N	R
Boulder%		0.02	0	0.02	0	0.02	0.01	0.02	0	0.03	0.01	0.02	0	0.02	0
Cobbles%		0.38	0.16	0.38	0.14	0.38	0.18	0.33	0.13	0.28	0.12	0.38	0.15	0.39	0.17
Gravels%		0.36	0.2	0.47	0.17	0.37	0.29	0.35	0.27	0.42	0.24	0.47	0.24	0.36	0.24
Sand%		0	0	0.07	0	0	0	0	0	0	0	0.07	0	0	0
Silt%		0.08	0.52	0	0.57	0.08	0.36	0.09	0.4	0.07	0.38	0	0.39	0.08	0.44
Tree root%		0.04	0	0.02	0	0.04	0	0.05	0	0.03	0	0.02	0	0.04	0
Marginal plant%		0.05	0	0	0	0.05	0	0.08	0	0.05	0	0	0	0.05	0
Leaf litter%		0.04	0	0.02	0	0.04	0.04	0.05	0.09	0.07	0.13	0.02	0.11	0.04	0.03
Small woody debris%		0	0	0	0	0	0	0.01	0	0.03	0	0	0	0	0
Clay%		0.03	0.12	0.02	0.12	0.03	0.12	0.03	0.11	0.02	0.12	0.02	0.11	0.03	0.12

Appendix 3.5. Summary of the two-way PERMANOVA pair-wise analysis for seasonal differences in macroinvertebrate community structural and diversity univariate metrics between both reaches (Control-Impact design).

	Total Density (individual m^{-2})			Total Biomass (mgDM m^{-2})		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	6.4465	0.0031	461	11.369	0.0021	462
Wi.15	1.749	0.112	461	6.4642	0.0018	462
Sp.15	0.1192	0.903	7964	6.2233	0.0001	8067
Su.15	6.0077	0.0004	8135	2.8943	0.0127	8125
Au.15	3.7187	0.0005	9759	5.5274	0.0001	9806
Wi.16	3.5842	0.0027	462	3.6512	0.0039	462
Sp.16	4.1444	0.0025	462	6.0138	0.0019	462
	Taxa Richness			Taxa Diversity		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	10.441	0.0029	462	11.546	0.0025	461
Wi.15	11.701	0.0021	458	18.942	0.0025	461
Sp.15	16.2	0.0001	8051	11.113	0.0016	461
Su.15	18.108	0.0001	8111	21.437	0.0001	8161
Au.15	14.324	0.0001	9764	5.7231	0.0001	9822
Wi.16	13.33	0.0022	462	12.734	0.0022	461
Sp.16	19.915	0.0024	462	13.82	0.0026	462
	Evenness					
Season	t	*P*(perm)	Unique perms			
Sp.14	5.3626	0.0017	462			
Wi.15	7.86	0.0025	462			
Sp.15	5.182	0.0001	8081			
Su.15	8.3498	0.0001	8058			
Au.15	6.2154	0.0001	9810			
Wi.16	3.5788	0.0069	462			
Sp.16	8.3664	0.0031	461			
	EPT Richness			EPT Diversity		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	9.4605	0.0027	459	5.2888	0.0028	462
Wi.15	8.3302	0.0033	462	4.8947	0.0051	461
Sp.15	6.9462	0.0026	462	4.2222	0.0012	4310
Su.15	7.4252	0.0001	8079	6.5536	0.0002	8067
Au.15	6.6389	0.0001	9791	10.316	0.0001	9777
Wi.16	5.697	0.0014	462	3.6467	0.0162	462
Sp.16	8.9826	0.0016	462	4.7982	0.002	462
	EPT Count %			EPT Biomass %		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	16.679	0.003	462	5.7081	0.0019	462
Wi.15	6.9879	0.0021	462	0.069593	0.9417	462
Sp.15	14.652	0.0005	4302	7.229	0.0001	4248
Su.15	20.826	0.0001	8191	9.4075	0.0001	8128
Au.15	6.2412	0.0001	9813	0.40822	0.6958	9794
Wi.16	2.8771	0.0124	462	2.7686	0.0193	462
Sp.16	13.421	0.003	461	2.9489	0.0134	462

	Chironomidae Count%			Chironomidae Biomass%		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	8.7364	0.0029	462	5.1813	0.0025	462
Wi.15	13.609	0.0025	462	8.3687	0.0024	462
Sp.15	4.8106	0.0005	4302	2.5259	0.0282	4303
Su.15	16.893	0.0001	8132	22.494	0.0001	8125
Au.15	5.8767	0.0001	9782	4.8603	0.0003	9804
Wi.16	4.9979	0.0017	462	4.1786	0.0024	462
Sp.16	6.6424	0.0034	461	2.9056	0.0216	462

Appendix 3.6. Summary of the two-way PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate community structural and diversity univariate metrics for each reach separately (Before-After design). Bold font indicates significant ($P<0.05$) differences.

Natural reach seasonal variation				Rehabilitated reach seasonal variation			
Total Density (individual m^{-2})				Total Density (individual m^{-2})			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	7.1285	0.0017	462	Sp.14, Wi.15	0.61842	0.5361	461
Sp.14, Sp.15	0.27931	0.7864	4281	Sp.14, Sp.15	3.0636	**0.0059**	462
Sp.14, Su.15	0.28603	0.7746	4290	Sp.14, Su.15	8.3436	0.0001	4308
Sp.14, Au.15	3.6068	0.0023	7602	Sp.14, Au.15	1.4671	0.1539	7610
Sp.14, Wi.16	7.2614	0.002	462	Sp.14, Wi.16	2.7464	0.0191	462
Sp.14, Sp.16	0.078315	0.939	462	Sp.14, Sp.16	1.5346	0.1598	459
Wi.15, Sp.15	7.3847	0.0002	4289	Wi.15, Sp.15	2.3784	0.0325	4216
Wi.15, Su.15	6.3005	0.0004	4306	Wi.15, Su.15	8.7139	0.0003	4305
Wi.15, Au.15	2.7484	0.0163	7643	Wi.15, Au.15	1.2028	0.2441	7633
Wi.15, Wi.16	0.13438	0.8763	462	Wi.15, Wi.16	2.2731	**0.0468**	462
Wi.15, Sp.16	4.539	0.0064	462	Wi.15, Sp.16	2.2234	0.0479	462
Sp.15, Su.15	0.062675	0.9524	8109	Sp.15, Su.15	3.5077	0.0039	8085
Sp.15, Au.15	4.2937	0.0003	9670	Sp.15, Au.15	3.4379	0.003	9678
Sp.15, Wi.16	7.5248	0.0003	4303	Sp.15, Wi.16	3.5539	0.0029	4313
Sp.15, Sp.16	0.27916	0.7802	4305	Sp.15, Sp.16	2.5836	**0.0118**	4308
Su.15, Au.15	3.9803	0.0016	9703	Su.15, Au.15	7.5403	0.0001	9669
Su.15, Wi.16	6.4223	0.0002	4285	Su.15, Wi.16	9.666	0.0003	4269
Su.15, Sp.16	0.29487	0.7657	4281	Su.15, Sp.16	7.8159	0.0001	4289
Au.15, Wi.16	2.8784	0.0115	7694	Au.15, Wi.16	0.12662	0.9002	7588
Au.15, Sp.16	2.8197	0.0139	7648	Au.15, Sp.16	2.0287	0.0785	7602
Wi.16, Sp.16	4.633	0.0057	461	Wi.16, Sp.16	3.9788	0.0064	462

Total Biomass (mgDM m^{-2})

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	4.3633	0.0018	462
Sp.14, Sp.15	0.14432	0.8908	4327
Sp.14, Su.15	3.2938	0.0051	4277
Sp.14, Au.15	3.4529	0.0033	7653
Sp.14, Wi.16	4.3877	0.0028	462
Sp.14, Sp.16	0.27671	0.7108	462
Wi.15, Sp.15	10.023	0.0003	4280
Wi.15, Su.15	15.944	0.0002	4327
Wi.15, Au.15	0.95466	0.3475	7675
Wi.15, Wi.16	0.029734	0.9678	460
Wi.15, Sp.16	5.1538	0.0024	462
Sp.15, Su.15	7.0908	0.0002	8102
Sp.15, Au.15	4.9833	0.0001	9664
Sp.15, Wi.16	10.15	0.0003	4268
Sp.15, Sp.16	0.61667	0.5599	4284
Su.15, Au.15	9.1	0.0001	9642
Su.15, Wi.16	16.11	0.0004	4331
Su.15, Sp.16	3.1068	0.0076	4240
Au.15, Wi.16	0.97171	0.3459	7571
Au.15, Sp.16	3.9387	0.0013	7647
Wi.16, Sp.16	5.1841	0.0019	460

Total Biomass (mgDM m^{-2})

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.17407	0.8711	462
Sp.14, Sp.15	10.639	**0.0003**	4338
Sp.14, Su.15	7.2604	0.0003	4275
Sp.14, Au.15	1.2134	0.2477	7667
Sp.14, Wi.16	4.3922	0.0015	458
Sp.14, Sp.16	7.7038	**0.0024**	462
Wi.15, Sp.15	7.2229	0.0004	4300
Wi.15, Su.15	6.2884	0.0003	4283
Wi.15, Au.15	0.98998	0.3288	7672
Wi.15, Wi.16	3.0212	**0.0193**	461
Wi.15, Sp.16	4.7286	0.004	462
Sp.15, Su.15	2.1388	0.0521	8009
Sp.15, Au.15	4.7036	0.0003	9686
Sp.15, Wi.16	3.9625	0.0035	4249
Sp.15, Sp.16	2.5012	**0.0254**	4309
Su.15, Au.15	5.583	0.0001	9693
Su.15, Wi.16	4.0029	0.0016	4330
Su.15, Sp.16	3.0712	0.0087	4304
Au.15, Wi.16	1.5624	0.1341	7599
Au.15, Sp.16	2.6996	0.0146	7580
Wi.16, Sp.16	1.6803	0.1095	462

Taxa Richness

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	1.5966	0.149	462
Sp.14, Sp.15	0.18503	0.8515	4306
Sp.14, Su.15	0.84081	0.4137	4316
Sp.14, Au.15	0.38197	0.7021	7610
Sp.14, Wi.16	1.4033	0.2041	459
Sp.14, Sp.16	0.56297	0.5909	461
Wi.15, Sp.15	2.469	0.0306	4291
Wi.15, Su.15	1.4384	0.1708	4284
Wi.15, Au.15	3.1457	0.0083	7615
Wi.15, Wi.16	0.46488	0.662	462
Wi.15, Sp.16	3.662	0.0054	462
Sp.15, Su.15	1.0405	0.322	8116
Sp.15, Au.15	0.86748	0.3938	9634
Sp.15, Wi.16	2.1916	0.0468	4306
Sp.15, Sp.16	1.2283	0.2398	4311
Su.15, Au.15	1.9024	0.0744	9675
Su.15, Wi.16	1.1016	0.2955	4256
Su.15, Sp.16	2.1649	0.0525	4312
Au.15, Wi.16	2.8691	0.0099	7645
Au.15, Sp.16	0.41049	0.6789	7618
Wi.16, Sp.16	3.5858	0.0042	462

Taxa Richness

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.86589	0.4075	462
Sp.14, Sp.15	3.6308	**0.0035**	4256
Sp.14, Su.15	0.21498	0.8256	4293
Sp.14, Au.15	2.5676	0.0233	7608
Sp.14, Wi.16	2.895	0.0231	456
Sp.14, Sp.16	1.1332	0.3076	462
Wi.15, Sp.15	2.1167	0.0553	4267
Wi.15, Su.15	0.79033	0.4412	4311
Wi.15, Au.15	1.6401	0.1169	7660
Wi.15, Wi.16	1.5744	0.1403	460
Wi.15, Sp.16	0.064067	0.9573	462
Sp.15, Su.15	3.7654	0.0022	8077
Sp.15, Au.15	0.009433	0.9937	9696
Sp.15, Wi.16	0.30287	0.7696	4259
Sp.15, Sp.16	2.8474	**0.0147**	4290
Su.15, Au.15	2.8459	0.0126	9702
Su.15, Wi.16	2.948	0.0156	4316
Su.15, Sp.16	0.93567	0.358	4266
Au.15, Wi.16	0.21123	0.8365	7565
Au.15, Sp.16	1.8714	0.0801	7548
Wi.16, Sp.16	2.2318	0.0506	461

Taxa Diversity

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	2.6691	0.035	461
Sp.14, Sp.15	1.5998	0.1364	458
Sp.14, Su.15	4.1053	0.0023	4284
Sp.14, Au.15	3.1765	0.0055	7634
Sp.14, Wi.16	2.3034	0.0541	462
Sp.14, Sp.16	0.38597	0.7049	462
Wi.15, Sp.15	0.83143	0.4202	462
Wi.15, Su.15	2.0605	0.0595	4308
Wi.15, Au.15	1.1707	0.2558	7653
Wi.15, Wi.16	0.97895	0.3282	462
Wi.15, Sp.16	2.5444	0.0338	462
Sp.15, Su.15	2.3398	0.0371	4343
Sp.15, Au.15	1.6535	0.1167	7579
Sp.15, Wi.16	0.37274	0.7363	462
Sp.15, Sp.16	1.3282	0.2299	462
Su.15, Au.15	0.11564	0.9122	9668
Su.15, Wi.16	2.6878	0.0196	4333
Su.15, Sp.16	3.9764	0.0012	4339
Au.15, Wi.16	1.541	0.1426	7635
Au.15, Sp.16	2.9046	0.0111	7645
Wi.16, Sp.16	2.1208	0.0727	462

Taxa Diversity

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.29775	0.7839	462
Sp.14, Sp.15	0.97955	0.3422	462
Sp.14, Su.15	6.6206	0.0002	4271
Sp.14, Au.15	1.451	0.1645	7621
Sp.14, Wi.16	1.9	0.0937	462
Sp.14, Sp.16	0.09987	0.925	460
Wi.15, Sp.15	1.2938	0.2186	462
Wi.15, Su.15	7.9541	0.0003	4319
Wi.15, Au.15	1.3205	0.1985	7678
Wi.15, Wi.16	1.7715	0.0998	462
Wi.15, Sp.16	0.48132	0.6484	462
Sp.15, Su.15	4.0682	0.0011	4303
Sp.15, Au.15	2.0057	0.0651	7634
Sp.15, Wi.16	2.5756	0.0371	462
Sp.15, Sp.16	1.0247	0.3215	462
Su.15, Au.15	4.8104	0.0011	9601
Su.15, Wi.16	8.2427	0.0002	4283
Su.15, Sp.16	8.4247	0.0002	4316
Au.15, Wi.16	0.30202	0.7722	7680
Au.15, Sp.16	1.5246	0.1392	7587
Wi.16, Sp.16	2.2402	0.0501	461

Evenness

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.45976	0.6261	462
Sp.14, Sp.15	2.2098	0.4472	4246
Sp.14, Su.15	1.7564	0.1063	4309
Sp.14, Au.15	0.68505	0.508	7612
Sp.14, Wi.16	0.29859	0.7416	462
Sp.14, Sp.16	0.83435	0.4462	462
Wi.15, Sp.15	1.8122	0.0916	4306
Wi.15, Su.15	1.3131	0.2075	4277
Wi.15, Au.15	0.33138	0.7432	7577
Wi.15, Wi.16	0.78069	0.4361	462
Wi.15, Sp.16	0.5123	0.6448	462
Sp.15, Su.15	0.64994	0.5203	8052
Sp.15, Au.15	1.063	0.2967	9713
Sp.15, Wi.16	2.5677	0.026	4317
Sp.15, Sp.16	0.7929	0.4464	4305
Su.15, Au.15	0.62137	0.5361	9698
Su.15, Wi.16	2.1294	0.0535	4307
Su.15, Sp.16	0.3742	0.7149	4280
Au.15, Wi.16	0.93702	0.3506	7642
Au.15, Sp.16	0.17392	0.8542	7570
Wi.16, Sp.16	1.075	0.3204	462

Evenness

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.12686	0.9093	462
Sp.14, Sp.15	1.0536	0.309	4251
Sp.14, Su.15	4.2133	0.0014	4314
Sp.14, Au.15	0.24712	0.8181	7651
Sp.14, Wi.16	1.66	0.1284	462
Sp.14, Sp.16	1.0372	0.3309	462
Wi.15, Sp.15	1.0278	0.3241	4284
Wi.15, Su.15	4.291	0.0015	4291
Wi.15, Au.15	0.40265	0.702	7596
Wi.15, Wi.16	2.1229	0.0743	462
Wi.15, Sp.16	1.1665	0.2661	462
Sp.15, Su.15	3.6491	0.0025	8042
Sp.15, Au.15	1.5685	0.1345	9662
Sp.15, Wi.16	2.3579	0.0397	4292
Sp.15, Sp.16	0.38101	0.7067	4304
Su.15, Au.15	5.8243	0.0001	9673
Su.15, Wi.16	5.2257	0.001	4317
Su.15, Sp.16	3.8153	0.003	4296
Au.15, Wi.16	1.5778	0.1388	7628
Au.15, Sp.16	1.3492	0.2033	7657
Wi.16, Sp.16	3.1031	0.0066	462

EPT Richness

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	2.7106	0.0236	461
Sp.14, Sp.15	0.87251	0.3928	462
Sp.14, Su.15	2.174	0.052	4292
Sp.14, Au.15	0.63521	0.534	7648
Sp.14, Wi.16	2.5559	0.0361	462
Sp.14, Sp.16	0.40337	0.9691	462
Wi.15, Sp.15	1.6868	0.1164	462
Wi.15, Su.15	1.1001	0.285	4260
Wi.15, Au.15	1.5192	0.1513	7614
Wi.15, Wi.16	0.19447	0.8379	462
Wi.15, Sp.16	2.6059	0.0303	462
Sp.15, Su.15	1.0063	0.3545	4286
Sp.15, Au.15	0.13176	0.8972	7598
Sp.15, Wi.16	1.53	0.1565	461
Sp.15, Sp.16	0.87433	0.3958	462
Su.15, Au.15	1.0207	0.3331	9678
Su.15, Wi.16	0.8855	0.3694	4289
Su.15, Sp.16	2.1215	0.0487	4338
Au.15, Wi.16	1.3868	0.1834	7700
Au.15, Sp.16	0.66074	0.5215	7649
Wi.16, Sp.16	2.4586	0.0341	462

EPT Richness

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.38487	0.6931	462
Sp.14, Sp.15	1.3875	0.2028	462
Sp.14, Su.15	2.2139	0.048	4264
Sp.14, Au.15	1.8173	0.0881	7647
Sp.14, Wi.16	1.5588	0.1573	462
Sp.14, Sp.16	0.41246	0.6801	462
Wi.15, Sp.15	1.7654	0.1146	462
Wi.15, Su.15	2.6144	0.0226	4292
Wi.15, Au.15	2.1644	0.0439	7662
Wi.15, Wi.16	1.9188	0.0778	462
Wi.15, Sp.16	0.80894	0.4206	462
Sp.15, Su.15	0.73591	0.4714	4280
Sp.15, Au.15	0.54346	0.5988	7669
Sp.15, Wi.16	0.23382	0.8488	462
Sp.15, Sp.16	1.0239	0.3072	462
Su.15, Au.15	0.10973	0.9126	9691
Su.15, Wi.16	0.45898	0.6522	4315
Su.15, Sp.16	1.8353	0.0866	4307
Au.15, Wi.16	0.31104	0.7599	7631
Au.15, Sp.16	1.4733	0.1583	7639
Wi.16, Sp.16	1.2161	0.2534	462

EPT Diversity

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	2.9347	0.0193	462
Sp.14, Sp.15	1.7436	0.1107	4294
Sp.14, Su.15	1.9759	0.0686	4267
Sp.14, Au.15	0.30086	0.7694	7604
Sp.14, Wi.16	2.6771	0.0303	462
Sp.14, Sp.16	0.39777	0.6934	462
Wi.15, Sp.15	1.2044	0.2578	4284
Wi.15, Su.15	2.4978	0.0301	4316
Wi.15, Au.15	3.7797	0.0014	7597
Wi.15, Wi.16	0.31004	0.7517	462
Wi.15, Sp.16	2.1206	0.054	461
Sp.15, Su.15	0.3242	0.7597	8057
Sp.15, Au.15	2.1242	0.0467	9690
Sp.15, Wi.16	0.96755	0.3798	4290
Sp.15, Sp.16	1.1551	0.2742	4282
Su.15, Au.15	2.327	0.0337	9678
Su.15, Wi.16	2.001	0.0659	4306
Su.15, Sp.16	1.1853	0.2674	4326
Au.15, Wi.16	3.4293	0.0044	7582
Au.15, Sp.16	0.29155	0.7756	7655
Wi.16, Sp.16	1.9148	0.0876	462

EPT Diversity

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.70767	0.5225	462
Sp.14, Sp.15	0.57685	0.5622	461
Sp.14, Su.15	1.3365	0.2241	4310
Sp.14, Au.15	1.1992	0.2459	7606
Sp.14, Wi.16	0.17362	0.8746	462
Sp.14, Sp.16	1.3078	0.2092	462
Wi.15, Sp.15	0.14431	0.9104	461
Wi.15, Su.15	2.0303	0.0625	4287
Wi.15, Au.15	0.39915	0.6904	7717
Wi.15, Wi.16	0.37777	0.7154	462
Wi.15, Sp.16	0.4509	0.6599	462
Sp.15, Su.15	1.9146	0.075	4277
Sp.15, Au.15	0.56792	0.5797	7674
Sp.15, Wi.16	0.26842	0.779	462
Sp.15, Sp.16	0.63406	0.5265	462
Su.15, Au.15	2.841	0.0103	9685
Su.15, Wi.16	1.2747	0.23	4306
Su.15, Sp.16	2.7392	0.0105	4322
Au.15, Wi.16	0.80986	0.438	7577
Au.15, Sp.16	0.052229	0.9571	7614
Wi.16, Sp.16	0.75949	0.4773	462

EPT Count%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	1.5638	0.1621	462
Sp.14, Sp.15	0.27492	0.7848	4310
Sp.14, Su.15	0.38238	0.7106	4270
Sp.14, Au.15	3.7505	0.0022	7620
Sp.14, Wi.16	1.5582	0.1478	461
Sp.14, Sp.16	1.2787	0.2186	462
Wi.15, Sp.15	1.9531	0.0715	4314
Wi.15, Su.15	1.473	0.1677	4297
Wi.15, Au.15	1.2053	0.2432	7637
Wi.15, Wi.16	0.059698	0.9522	462
Wi.15, Sp.16	2.2833	0.0474	462
Sp.15, Su.15	0.68664	0.5012	8091
Sp.15, Au.15	4.4774	0.0003	9673
Sp.15, Wi.16	1.9388	0.0743	4296
Sp.15, Sp.16	1.1118	0.2778	4315
Su.15, Au.15	3.7749	0.0023	9709
Su.15, Wi.16	1.4402	0.1698	4344
Su.15, Sp.16	1.6411	0.1214	4274
Au.15, Wi.16	1.3224	0.2091	7641
Au.15, Sp.16	4.6556	0.0005	7624
Wi.16, Sp.16	2.2995	0.0495	462

EPT Count%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.72131	0.4838	462
Sp.14, Sp.15	0.84394	0.3964	462
Sp.14, Su.15	4.0983	0.001	4278
Sp.14, Au.15	4.0785	0.0018	7588
Sp.14, Wi.16	5.3921	0.0037	459
Sp.14, Sp.16	0.10959	0.9144	462
Wi.15, Sp.15	0.30529	0.7584	462
Wi.15, Su.15	6.8623	0.0002	4293
Wi.15, Au.15	3.779	0.0014	7669
Wi.15, Wi.16	5.3157	0.0044	462
Wi.15, Sp.16	0.54906	0.6039	461
Sp.15, Su.15	5.212	0.0003	4271
Sp.15, Au.15	3.3964	0.0036	7606
Sp.15, Wi.16	4.8514	0.0089	462
Sp.15, Sp.16	0.70262	0.4938	462
Su.15, Au.15	7.8868	0.0001	9661
Su.15, Wi.16	9.1526	0.0003	4273
Su.15, Sp.16	4.0015	0.0022	4313
Au.15, Wi.16	2.4583	0.0264	7647
Au.15, Sp.16	3.9436	0.0021	7597
Wi.16, Sp.16	5.2488	0.0037	462

EPT Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	4.8597	0.0027	462
Sp.14, Sp.15	1.0963	0.2909	4280
Sp.14, Su.15	0.89759	0.395	4269
Sp.14, Au.15	2.2864	0.0412	7640
Sp.14, Wi.16	4.8405	0.002	461
Sp.14, Sp.16	0.28525	0.7682	462
Wi.15, Sp.15	4.2516	0.0012	4269
Wi.15, Su.15	7.0067	0.0002	4309
Wi.15, Au.15	1.8951	0.0771	7616
Wi.15, Wi.16	0.014565	0.9792	461
Wi.15, Sp.16	3.7688	0.0041	462
Sp.15, Su.15	2.3119	0.0332	8040
Sp.15, Au.15	1.7219	0.1027	9695
Sp.15, Wi.16	4.2321	0.0019	4313
Sp.15, Sp.16	0.60846	0.5433	4279
Su.15, Au.15	3.5207	0.0032	9672
Su.15, Wi.16	6.9813	0.0003	4313
Su.15, Sp.16	1.0688	0.3011	4326
Au.15, Wi.16	1.8811	0.0767	7672
Au.15, Sp.16	1.8632	0.0807	7608
Wi.16, Sp.16	3.7537	0.0062	461

EPT Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.61034	0.5475	462
Sp.14, Sp.15	1.5669	0.1423	462
Sp.14, Su.15	0.8992	0.3842	4270
Sp.14, Au.15	2.1071	0.0486	7609
Sp.14, Wi.16	3.4047	0.0094	462
Sp.14, Sp.16	0.58963	0.5484	462
Wi.15, Sp.15	2.4607	0.0391	462
Wi.15, Su.15	1.5702	0.1425	4229
Wi.15, Au.15	1.775	0.0894	7613
Wi.15, Wi.16	3.0994	0.0151	462
Wi.15, Sp.16	0.17636	0.8613	462
Sp.15, Su.15	0.58887	0.5874	4302
Sp.15, Au.15	3.0591	0.0084	7627
Sp.15, Wi.16	5.2611	0.0016	462
Sp.15, Sp.16	1.7415	0.1081	462
Su.15, Au.15	3.1563	0.0043	9692
Su.15, Wi.16	4.465	0.0006	4274
Su.15, Sp.16	1.3847	0.1899	4295
Au.15, Wi.16	0.19132	0.8507	7633
Au.15, Sp.16	1.4975	0.1502	7681
Wi.16, Sp.16	2.0455	0.0671	461

Chironomidae Count%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	2.4196	0.0355	462
Sp.14, Sp.15	0.89459	0.3859	4288
Sp.14, Su.15	1.1406	0.2715	4320
Sp.14, Au.15	2.2602	0.038	7650
Sp.14, Wi.16	2.4449	0.0379	462
Sp.14, Sp.16	0.20376	0.8478	462
Wi.15, Sp.15	3.4038	0.0046	4305
Wi.15, Su.15	1.8436	0.0899	4295
Wi.15, Au.15	1.478	0.1643	7647
Wi.15, Wi.16	0.035064	0.961	461
Wi.15, Sp.16	3.0659	0.0084	461
Sp.15, Su.15	2.3031	0.0371	8052
Sp.15, Au.15	3.6461	0.0014	9678
Sp.15, Wi.16	3.4299	0.0041	4295
Sp.15, Sp.16	1.2388	0.243	4327
Su.15, Au.15	1.0307	0.3089	9646
Su.15, Wi.16	1.8788	0.0794	4283
Su.15, Sp.16	1.2044	0.2394	4287
Au.15, Wi.16	1.5252	0.1452	7646
Au.15, Sp.16	2.7471	0.0128	7660
Wi.16, Sp.16	3.095	0.0094	460

Chironomidae Count%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	1.3797	0.2046	462
Sp.14, Sp.15	1.503	0.1822	462
Sp.14, Su.15	1.9857	0.0709	4280
Sp.14, Au.15	2.3967	0.0264	7608
Sp.14, Wi.16	3.7748	0.0023	461
Sp.14, Sp.16	5.2398	**0.0028**	462
Wi.15, Sp.15	0.95255	0.3488	462
Wi.15, Su.15	3.171	0.0048	4285
Wi.15, Au.15	2.0931	0.0573	7574
Wi.15, Wi.16	3.3323	**0.0022**	462
Wi.15, Sp.16	4.3016	0.0027	462
Sp.15, Su.15	2.4057	0.0373	4298
Sp.15, Au.15	1.4506	0.162	7629
Sp.15, Wi.16	2.1762	0.0596	462
Sp.15, Sp.16	1.9958	0.0677	462
Su.15, Au.15	3.2546	0.0027	9663
Su.15, Wi.16	5.1067	0.0003	4311
Su.15, Sp.16	7.273	0.0006	4295
Au.15, Wi.16	0.44232	0.6567	7665
Au.15, Sp.16	0.16527	0.8688	7638
Wi.16, Sp.16	0.77489	0.4461	462

Chironomidae Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.91514	0.368	461
Sp.14, Sp.15	0.49345	0.6257	4279
Sp.14, Su.15	1.3908	0.1917	4306
Sp.14, Au.15	0.26345	0.7845	7711
Sp.14, Wi.16	0.98861	0.3322	457
Sp.14, Sp.16	0.13611	0.893	462
Wi.15, Sp.15	1.7829	0.0995	4272
Wi.15, Su.15	0.50895	0.6143	4242
Wi.15, Au.15	1.4132	0.1695	7629
Wi.15, Wi.16	0.13687	0.8953	462
Wi.15, Sp.16	1.1867	0.2885	462
Sp.15, Su.15	2.4979	0.027	8072
Sp.15, Au.15	1.1532	0.2653	9680
Sp.15, Wi.16	1.8774	0.0856	4266
Sp.15, Sp.16	0.7717	0.4521	4326
Su.15, Au.15	2.2016	0.0431	9673
Su.15, Wi.16	0.36262	0.7223	4278
Su.15, Sp.16	1.8131	0.0823	4288
Au.15, Wi.16	1.5646	0.1406	7693
Au.15, Sp.16	0.10033	0.9171	7667
Wi.16, Sp.16	1.3092	0.2336	462

Chironomidae Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	2.336	0.0321	462
Sp.14, Sp.15	0.99154	0.3135	462
Sp.14, Su.15	2.6673	0.0172	4309
Sp.14, Au.15	1.9879	0.0649	7672
Sp.14, Wi.16	4.5962	0.0029	462
Sp.14, Sp.16	8.4131	**0.0028**	462
Wi.15, Sp.15	0.015262	0.9921	462
Wi.15, Su.15	5.6193	0.0005	4310
Wi.15, Au.15	0.57883	0.573	7589
Wi.15, Wi.16	2.5606	**0.0392**	462
Wi.15, Sp.16	4.6643	0.0047	462
Sp.15, Su.15	2.1722	0.0501	4244
Sp.15, Au.15	0.41791	0.6683	7595
Sp.15, Wi.16	1.295	0.1913	460
Sp.15, Sp.16	1.6866	0.1715	462
Su.15, Au.15	3.7919	0.0017	9658
Su.15, Wi.16	8.0002	0.0002	4314
Su.15, Sp.16	16.362	0.0004	4349
Au.15, Wi.16	1.3274	0.1924	7682
Au.15, Sp.16	1.841	0.09	7702
Wi.16, Sp.16	0.59524	0.5601	462

Appendix 3.7. Summary of the two-way PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate community taxonomic composition (Count m^{-2}, and Biomass m^{-2}), between both reaches (Control-Impact design).

	Taxa Count m^{-2}			Taxa Biomass m^{-2}		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	5.4422	0.0031	462	4.6266	0.0022	462
Wi.15	4.1383	0.0021	462	3.5816	0.0022	462
Sp.15	4.5924	0.0001	8170	4.1848	0.0001	8128
Su.15	5.1108	0.0001	8108	5.0869	0.0001	8146
Au.15	4.9269	0.0001	9900	4.8246	0.0001	9933
Wi.16	3.4178	0.0021	462	3.5271	0.002	462
Sp.16	4.1515	0.0025	462	3.9393	0.0026	461

Appendix 3.8. Summary of the two-way PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate community taxonomic composition (Count m^{-2}, and Biomass m^{-2}), for each reach separately (Before-After design). Bold font indicates significant ($P<0.05$) differences.

Natural reach seasonal variations				Rehabilitated reach seasonal variations			
Count m^{-2}				Count m^{-2}			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	2.5627	0.0025	462	Sp.14, Wi.15	1.4563	0.0742	462
Sp.14, Sp.15	0.94478	0.5222	4349	Sp.14, Sp.15	2.196	**0.0002**	4325
Sp.14, Su.15	1.9894	0.0025	4305	Sp.14, Su.15	3.4882	0.0001	4348
Sp.14, Au.15	2.5845	0.0002	7688	Sp.14, Au.15	2.605	0.0002	7723
Sp.14, Wi.16	2.562	0.0022	462	Sp.14, Wi.16	2.1227	0.0029	462
Sp.14, Sp.16	1.022	0.3541	462	Sp.14, Sp.16	1.9524	**0.0184**	461
Wi.15, Sp.15	2.566	0.0003	4314	Wi.15, Sp.15	1.8716	0.0005	4325
Wi.15, Su.15	3.0012	0.0004	4342	Wi.15, Su.15	3.2196	0.0002	4308
Wi.15, Au.15	2.5279	0.0001	7752	Wi.15, Au.15	2.3045	0.0004	7717
Wi.15, Wi.16	0.12099	0.945	462	Wi.15, Wi.16	1.93	**0.0023**	461
Wi.15, Sp.16	2.2823	0.0018	462	Wi.15, Sp.16	1.4547	0.1127	462
Sp.15, Su.15	2.1783	0.0002	8132	Sp.15, Su.15	2.7667	0.0002	8166
Sp.15, Au.15	2.73	0.0001	9764	Sp.15, Au.15	2.4421	0.0001	9760
Sp.15, Wi.16	2.5395	0.0001	4334	Sp.15, Wi.16	2.0896	0.0001	4271
Sp.15, Sp.16	0.96624	0.4093	4306	Sp.15, Sp.16	1.522	**0.0491**	4316
Su.15, Au.15	3.1997	0.0001	9763	Su.15, Au.15	2.8023	0.0001	9773
Su.15, Wi.16	3.0081	0.0004	4323	Su.15, Wi.16	2.6179	0.0005	4307
Su.15, Sp.16	1.8442	0.0054	4325	Su.15, Sp.16	2.3695	0.0007	4349
Au.15, Wi.16	2.4941	0.0001	7695	Au.15, Wi.16	1.4691	0.0604	7657
Au.15, Sp.16	2.3451	0.0005	7720	Au.15, Sp.16	2.0184	0.0004	7635
Wi.16, Sp.16	2.2592	0.0022	462	Wi.16, Sp.16	1.6757	0.0459	462
Biomass m^{-2}				Biomass m^{-2}			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	2.4963	0.0017	462	Sp.14, Wi.15	1.3285	0.1354	462
Sp.14, Sp.15	0.80644	0.6747	4296	Sp.14, Sp.15	2.157	**0.0002**	4308
Sp.14, Su.15	2.2402	0.0003	4265	Sp.14, Su.15	3.2372	0.0004	4310
Sp.14, Au.15	2.5149	0.0002	7658	Sp.14, Au.15	2.5097	0.0001	7700
Sp.14, Wi.16	2.4954	0.0025	462	Sp.14, Wi.16	2.1453	0.0016	462
Sp.14, Sp.16	1.0282	0.3664	461	Sp.14, Sp.16	1.7048	**0.0261**	462
Wi.15, Sp.15	2.4647	0.0002	4350	Wi.15, Sp.15	1.919	0.0002	4322
Wi.15, Su.15	3.2693	0.0005	4364	Wi.15, Su.15	3.1285	0.0001	4309
Wi.15, Au.15	2.3095	0.0003	7684	Wi.15, Au.15	2.1212	0.0003	7722
Wi.15, Wi.16	0.085682	0.943	461	Wi.15, Wi.16	1.8594	**0.0026**	462
Wi.15, Sp.16	2.3002	0.0025	462	Wi.15, Sp.16	1.3626	0.1174	462
Sp.15, Su.15	2.312	0.0001	8115	Sp.15, Su.15	2.4334	0.0003	8132
Sp.15, Au.15	2.4954	0.0002	9769	Sp.15, Au.15	2.3315	0.0001	9783
Sp.15, Wi.16	2.443	0.0005	4304	Sp.15, Wi.16	1.9385	0.0004	4332
Sp.15, Sp.16	0.76172	0.7306	4299	Sp.15, Sp.16	2.7471	**0.0128**	4305
Su.15, Au.15	3.1776	0.0002	9781	Su.15, Au.15	2.8055	0.0001	9790
Su.15, Wi.16	3.2912	0.0004	4307	Su.15, Wi.16	2.4876	0.0005	4338
Su.15, Sp.16	1.9837	0.0005	4291	Su.15, Sp.16	2.1658	0.0008	4321
Au.15, Wi.16	2.2873	0.0001	7642	Au.15, Wi.16	1.4014	0.0745	7665
Au.15, Sp.16	2.2814	0.0008	7706	Au.15, Sp.16	1.7805	0.0074	7710
Wi.16, Sp.16	2.2978	0.0022	462	Wi.16, Sp.16	1.4351	0.0944	462

Appendix 3.9. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Taxa Count m^{-2}) 4th root transformed data, identifying taxa contributing at least 70% of the spatial dissimilarity in macroinvertebrate community composition between the natural and rehabilitated reach, reaches were compared seasonally before and after the LWM installation. Average abundances presented in individual m^{-2} (4th root transformed).

Spring 2014 (before LWM installation)				
Average dissimilarity between both reaches = 65.42				
	Average Abundance			
Taxa	Natural	Rehabilitated	Contribution%	Cumulative%
Centroptilum luteolum	2.47	0.00	3.13	3.13
Ephemera danica	2.52	0.20	3.02	6.16
Asellus meridianus	2.24	0.00	2.90	9.05
Hygrobates sp (longu)	2.14	0.00	2.74	11.79
Tubificidae	2.12	0.00	2.72	14.51
Nais sp.	2.03	0.00	2.68	17.18
Lymnaea (Radix) peregra	2.00	0.00	2.56	19.75
Sphaerium sp.	1.94	0.00	2.44	22.19
Orthocladiinae	2.08	3.98	2.40	24.60
Beraea pullata	1.87	0.00	2.39	26.99
Prodiamesinae	2.04	0.20	2.36	29.35
Rhyacophila dorsalis	1.83	0.00	2.36	31.71
Ancylus fluviatilis	1.81	0.00	2.33	34.04
Crunoecia irrorata	1.84	0.00	2.33	36.37
Sialis lutaria	1.80	0.00	2.28	38.65
Limnephilus lunatus.	1.78	0.00	2.26	40.91
Sericostoma personatum	1.75	0.00	2.25	43.16
Lasiocephala basalis	1.64	0.00	2.15	45.30
Asellus aquaticus	1.54	0.00	2.01	47.31
Lumbriculidae	1.60	0.00	1.98	49.29
Paraleptophlebia werneri	1.49	0.00	1.92	51.22
Chaetopteryx villosa	2.10	0.63	1.90	53.11
Limnephilus nigriceps	1.43	0.00	1.83	54.94
Ancylus lacustris	1.39	0.00	1.83	56.77
Baetis rhodani	3.11	1.74	1.79	58.56
Micropterna sp.	2.10	0.76	1.76	60.32
Tanypodinae	2.43	1.22	1.66	61.98
Polycelis felina	1.25	0.00	1.59	63.57
Ptychopteridae	1.38	0.20	1.58	65.15
Potamopyrgus antipodarum	1.30	0.00	1.51	66.66
Ceraclea sp.	1.21	0.00	1.46	68.12
Halesus radiatus.	1.15	0.00	1.44	69.55
Elmidae	1.12	0.00	1.41	70.96
Winter 2015				
Average dissimilarity between both reaches = 56.75				
	Average Abundance			
Taxa	Natural	Rehabilitated	Contribution%	Cumulative%
Asellus aquaticus	2.04	0.00	3.64	3.64
Centroptilum luteolum	1.93	0.00	3.43	7.07
Orthocladiinae	1.94	3.80	3.32	10.40
Potamopyrgus antipodarum	1.85	0.00	3.32	13.71
Ancylus fluviatilis	1.80	0.00	3.21	16.92
Sialis lutaria	1.68	0.00	2.98	19.91

Ephemera danica	2.04	0.42	2.94	22.85
Limnephilus lunatus.	1.53	0.00	2.74	25.59
Lymnaea truncatula	1.51	0.00	2.70	28.29
Chironominae	1.82	3.33	2.68	30.96
Lymnaea (Radix) peregra	1.46	0.00	2.61	33.57
Chaetopteryx villosa	1.39	0.00	2.47	36.04
Tanypodinae	1.91	0.62	2.46	38.50
Hydropsyche instabilus	1.22	0.00	2.17	40.67
Sphaerium sp.	1.25	0.18	2.11	42.78
Elmidae	1.42	0.38	2.10	44.89
Beraea pullata	1.18	0.00	2.09	46.98
Tubificidae	2.29	1.32	2.07	49.04
Empididae	1.14	0.00	2.06	51.10
Nais sp.	2.10	0.95	2.05	53.15
Paraleptophlebia werneri	1.13	0.00	2.01	55.15
Diamesinae	1.25	0.18	1.94	57.09
Simuliidae	1.91	0.89	1.90	58.99
Agapetus fuscipes	1.81	0.83	1.87	60.86
Ptychopteridae	1.57	0.58	1.86	62.71
Limnesia sp	1.35	0.57	1.81	64.53
Lebirtia porosa	1.09	0.18	1.81	66.33
Lumbriculidae	0.99	0.19	1.76	68.10
Polycentropus flavomaculatus	1.13	0.52	1.73	69.83
Habrophlebia fusca	3.00	2.04	1.7	71.53

Spring 2015

Average dissimilarity between both reaches = 54.63

	Average Abundance			
Taxa	Natural	Rehabilitated	Contribution%	Cumulative%
Ephemera danica	2.56	0.16	3.40	3.40
Potamopyrgus antipodarum	2.09	0.00	2.96	6.36
Asellus meridianus	1.94	0.00	2.74	9.09
Hygrobates sp (longu)	1.99	0.11	2.66	11.76
Prodiamesinae	1.81	0.00	2.58	14.34
Tanypodinae	2.55	0.74	2.55	16.89
Sphaerium sp.	1.79	0.00	2.53	19.42
Rhyacophila dorsalis	1.73	0.00	2.45	21.87
Beraea pullata	1.87	0.22	2.41	24.28
Centroptilum luteolum	1.79	0.16	2.30	26.58
Sericostoma personatum	1.57	0.00	2.22	28.81
Chironominae	2.79	4.03	2.18	30.98
Asellus aquaticus	1.53	0.00	2.18	33.16
Paraleptophlebia werneri	1.53	0.00	2.17	35.33
Diamesinae	1.75	1.15	2.16	37.49
Lymnaea (Radix) peregra	1.88	0.44	2.05	39.54
Lymnaea truncatula	1.54	0.15	2.05	41.59
Ancylus fluviatilis	1.44	0.00	2.03	43.63
Lumbriculidae	1.53	0.12	2.03	45.66
Orthocladiinae	2.10	3.47	1.95	47.60
Sialis lutaria	1.38	0.00	1.94	49.54
Agapetus fuscipes	0.83	1.83	1.88	51.42
Crunoecia irrorata	1.37	0.17	1.81	53.24
Planorbis contortus	1.24	0.00	1.78	55.02
Baetis rhodani	3.52	2.34	1.68	56.70
Polycelis felina	1.13	0.00	1.60	58.30
Simuliidae	1.42	0.34	1.53	59.83
Erpobdella octoculata	0.11	1.12	1.50	61.32

Chaetopteryx villosa	2.21	1.18	1.47	62.80
Tubificidae	2.04	1.25	1.46	64.25
Lebirtia porosa	1.27	0.45	1.45	65.70
Limnephilus lunatus.	1.54	0.55	1.43	67.13
Limnephilus nigriceps	1.29	0.32	1.39	68.52
Bithynia leachii	0.96	0.00	1.49	70.01
Summer 2015				
Average dissimilarity between both reaches = 63.61				
	Average Abundance			
Taxa	Natural	Rehabilitated	Contribution%	
	Cumulative%			
Chironominae	2.81	6.71	5.09	5.09
Ephemera danica	2.88	0.27	3.43	8.52
Ceraclea sp.	2.04	0.00	2.67	11.20
Lymnaea (Radix) peregra	1.95	0.00	2.55	13.74
Sialis lutaria	1.94	0.00	2.53	16.28
Lymnaea truncatula	1.92	0.00	2.51	18.78
Potamopyrgus antipodarum	1.89	0.00	2.47	21.25
Bithynia leachii	1.88	0.00	2.45	23.70
Baetis rhodani	2.41	0.58	2.44	26.14
Asellus meridianus	1.80	0.00	2.36	28.50
Sphaerium sp.	1.88	0.13	2.35	30.84
Beraea pullata	1.90	0.12	2.33	33.17
Ancylus fluviatilis	1.62	0.00	2.11	35.29
Pisidium sp.	1.58	0.00	2.07	37.36
Habrophlebia fusca	3.33	1.77	2.06	39.42
Diamesinae	1.63	0.12	1.97	41.40
Rhyacophila dorsalis	1.36	0.00	1.75	43.15
Nais sp.	1.24	1.69	1.71	44.86
Tanypodinae	2.40	1.24	1.70	46.56
Asellus aquaticus	1.23	0.00	1.64	48.19
Planorbis contortus	1.26	0.00	1.63	49.83
Ceratopogonidae	1.70	0.88	1.58	51.41
Hygrobates sp (longu)	1.54	0.37	1.57	52.98
Hydropsyche instabilus	1.23	0.00	1.56	54.54
Crunoecia irrorata	1.14	0.00	1.53	56.06
Glossiphonia complanata	1.13	0.00	1.48	57.54
Elmidae	1.38	0.51	1.41	58.96
Scirtidae	0.68	1.53	1.40	60.36
Limnephilus lunatus.	1.51	0.50	1.40	61.76
Lepidostoma hirtum	1.01	0.00	1.36	63.12
Prodiamesinae	1.11	0.32	1.29	64.41
Valvata macrostoma	0.98	0.00	1.28	65.69
Orthocladiinae	1.05	0.83	1.28	66.98
Erpobdella octoculata	0.10	0.99	1.23	68.21
Lumbriculidae	0.93	0.00	1.20	69.41
Tubificidae	1.89	1.03	1.15	70.57
Autumn 2015				
Average dissimilarity between both reaches = 60.85				
	Average Abundance			
Taxa	Natural	Rehabilitated	Contribution%	
	Cumulative%			
Beraea pullata	2.38	0.00	3.52	3.52
Ephemera danica	2.32	0.00	3.43	6.94
Paraleptophlebia werneri	2.02	0.00	3.00	9.94
Centroptilum luteolum	1.76	0.00	2.58	12.52
Sialis lutaria	1.65	0.00	2.43	14.95

Lumbriculidae	1.62	0.00	2.41	17.36
Habrophlebia fusca	2.60	1.03	2.38	19.73
Asellus meridianus	1.59	0.00	2.35	22.09
Sericostoma personatum	1.50	0.00	2.20	24.29
Potamopyrgus antipodarum	1.58	0.10	2.18	26.48
Gammarus pulex	4.06	2.66	2.13	28.60
Ptychopteridae	1.43	0.00	2.12	30.72
Sphaerium sp.	1.67	0.28	2.11	32.83
Ceraclea sp.	1.82	0.47	2.04	34.87
Hydropsyche siltatay	1.38	0.00	2.04	36.91
Hygrobates sp (longu)	1.59	0.37	1.92	38.83
Baetis rhodani	1.93	0.65	1.91	40.74
Elmidae	2.08	0.86	1.85	42.59
Dytiscidae	1.25	0.00	1.84	44.43
Asellus aquaticus	1.20	0.00	1.79	46.22
Chironominae	2.30	3.21	1.78	47.99
Plectrocnemia conspersa	1.12	0.00	1.67	49.67
Erpobdella octoculata	0.33	1.35	1.66	51.33
Prodiamesinae	1.04	0.62	1.66	52.99
Nais sp.	1.92	0.99	1.64	54.63
Psychodidae	1.36	0.59	1.60	56.23
Agapetus fuscipes	1.16	1.87	1.52	57.75
Lymnaea (Radix) peregra	1.02	0.00	1.48	59.23
Polycelis felina	0.98	0.00	1.45	60.68
Pediciidae	0.89	0.52	1.44	62.12
Sperchon sp.	1.07	0.21	1.43	63.55
Scirtidae	1.21	0.41	1.42	64.97
Apatania muliebris	0.14	0.88	1.39	66.36
Orthocladiinae	2.02	1.58	1.34	67.70
Micropterna sp.	0.81	1.20	1.28	68.98
Halesus digitatus	0.86	0.00	1.26	70.2

Winter 2016

Average dissimilarity between both reaches = 53.38

Taxa	Average Abundance Natural	Rehabilitated	Contribution%	Cumulative%
Nais sp.	2.07	0.00	3.59	3.59
Asellus aquaticus	2.05	0.00	3.55	7.14
Ephemera danica	2.04	0.00	3.53	10.67
Centroptilum luteolum	1.95	0.00	3.37	14.04
Ancylus fluviatilis	1.80	0.00	3.11	17.15
Sialis lutaria	1.70	0.00	2.93	20.09
Baetis rhodani	2.37	0.74	2.82	22.91
Ptychopteridae	1.56	0.00	2.71	25.61
Potamopyrgus antipodarum	1.85	0.33	2.66	28.28
Lymnaea truncatula	1.50	0.00	2.61	30.89
Lymnaea (Radix) peregra	1.46	0.00	2.53	33.42
Tubificidae	2.25	0.93	2.35	35.77
Limnesia sp	1.29	0.00	2.24	38.01
Simuliidae	1.91	0.61	2.22	40.23
Habrophlebia fusca	2.98	1.71	2.19	42.42
Lumbriculidae	1.23	0.00	2.14	44.56
Hydropsyche instabilus	1.22	0.00	2.11	46.67
Sphaerium sp.	1.27	0.19	2.08	48.74
Paraleptophlebia werneri	1.17	0.00	2.02	50.76
Chironominae	1.80	2.99	2.01	52.78
Prodiamesinae	1.27	1.16	2.01	54.78

Empididae	1.14	0.00	1.99	56.77
Erpobdella octoculata	0.25	1.30	1.95	58.72
Psychodidae	0.00	1.05	1.80	60.52
Beraea pullata	1.18	0.56	1.76	62.28
Limnephilus lunatus.	1.56	0.58	1.70	63.98
Lebirtia porosa	1.22	0.55	1.69	65.67
Elmidae	1.63	0.78	1.59	67.25
Hydropsyche siltatay	0.89	0.00	1.56	68.82
Tanypodinae	1.87	1.14	1.56	70.38

Spring 2016

Average dissimilarity between both reaches = 62.22

	Average Abundance			
Taxa	Natural	Rehabilitated	Contribution%	Cumulative%
Baetis rhodani	3.48	1.10	3.12	3.12
Ephemera danica	2.30	0.00	2.95	6.07
Centroptilum luteolum	2.24	0.00	2.90	8.97
Potamopyrgus antipodarum	2.16	0.00	2.76	11.73
Sphaerium sp.	2.08	0.00	2.67	14.40
Beraea pullata	1.98	0.00	2.58	16.98
Lymnaea truncatula	2.00	0.00	2.57	19.55
Crunoecia irrorata	2.00	0.00	2.57	22.12
Asellus meridianus	2.04	0.00	2.57	24.69
Ceraclea sp.	1.91	0.00	2.47	27.16
Ancylus fluviatilis	1.88	0.00	2.43	29.59
Tanypodinae	2.50	0.64	2.42	32.01
Lymnaea (Radix) peregra	1.86	0.00	2.38	34.39
Sericostoma personatum	1.75	0.00	2.29	36.68
Hygrobates sp (longu)	1.68	0.00	2.15	38.83
Limnephilus lunatus.	1.80	0.15	2.14	40.97
Bithynia tentaculata	1.56	0.00	2.06	43.03
Asellus aquaticus	1.51	0.00	1.97	45.01
Rhyacophila dorsalis	1.52	0.00	1.95	46.95
Paraleptophlebia werneri	1.46	0.00	1.89	48.84
Elmidae	1.36	0.00	1.76	50.60
Orthocladiinae	2.20	3.50	1.66	52.26
Prodiamesinae	1.78	1.28	1.66	53.91
Sialis lutaria	1.26	0.00	1.58	55.49
Habrophlebia fusca	2.89	1.73	1.54	57.03
Micropterna sp.	2.13	0.96	1.52	58.55
Pediciidae	1.18	1.15	1.52	60.07
Chaetopteryx villosa	2.31	1.25	1.51	61.57
Diamesinae	1.35	0.25	1.48	63.06
Erpobdella octoculata	0.16	1.18	1.41	64.46
Lumbriculidae	1.13	0.00	1.40	65.86
Polycentropus flavomaculatus	1.43	0.44	1.40	67.26
Ceratopogonidae	1.95	0.86	1.40	68.66
Pisidium sp.	1.12	0.00	1.37	70.03

Appendix 3.10. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Count m^{-2}) data, identifying families contributing 70% of the spatial dissimilarity in community composition between the both reaches, reaches were compared seasonally before and after the LWM installation. Average abundances presented in individuals m^{-2}.

Spring 2014 (before LWM installation)				
Average dissimilarity between both reaches= 68.74				
	Average Abundance			
Family	Natural	Before-Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	110	402	25.91	25.91
Baetidae	141	9	11.93	37.84
Leptophlebiidae	95.32	14.62	7.18	45.02
Gammaridae	161.33	89.37	6.60	51.62
Limnephilidae	62.81	5.23	5.17	56.79
Ephemeridae	44.43	0.36	4.03	60.82
Asellidae	33.87	0.00	3.09	63.91
Tanypodinae	40.05	8.03	2.96	66.87
Lymnaeidae	31.85	0.00	2.83	69.69
Naididae	24.33	0.00	2.27	71.96
Winter 2015				
Average dissimilarity between both reaches = 66.34				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	34.24	340.31	39.59	39.59
Leptophlebiidae	87.41	18.19	8.84	48.43
Baetidae	54.88	11.36	5.83	54.26
Gammaridae	129.86	106.53	5.68	59.94
Tubificidae	28.82	13.92	3.17	63.12
Sialidae	24.06	0.00	2.81	65.92
Asellidae	20.32	0.00	2.67	68.59
Ephemeridae	19.03	0.91	2.43	71.03
Spring 2015				
Average dissimilarity between both reaches = 58.27				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	163	820	37.85	37.85
Baetidae	174.93	31.25	12.09	49.93
Gammaridae	162.60	274.05	9.25	59.18
Leptophlebiidae	106.35	37.12	5.76	64.94
Ephemeridae	49.24	0.43	3.95	68.89
Tanypodinae	47.22	2.47	3.61	72.50
Summer 2015				
Average dissimilarity between both reaches = 76.43				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	83.52	2165	66.86	66.86
Gammaridae	308.52	548.73	8.58	75.44

Autumn 2015				
Average dissimilarity between both reaches = 71.27				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Gammaridae	280.23	63.77	25.33	25.33
Chironomidae (non- Tanypodinae)	57.97	237.87	21.25	46.57
Leptophlebiidae	67.26	3.97	7.45	54.03
Beraeidae	35.74	0.00	4.08	58.11
Ephemeridae	32.30	0.00	3.75	61.86
Baetidae	30.96	1.09	3.37	65.23
Glossosomatidae	7.05	27.34	2.67	67.90
Elmidae	19.68	2.37	2.02	69.93
Hydropsychidae	17.59	0.00	1.98	71.90
Winter 2016				
Average dissimilarity between both reaches = 59.24				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	34.32	129.61	15.82	15.82
Leptophlebiidae	86.18	11.15	12.47	28.29
Baetidae	56.20	1.51	9.45	37.73
Glossosomatidae	12.26	49.00	6.52	44.26
Gammaridae	125.71	117.23	5.18	49.44
Tubificidae	26.30	6.02	3.67	53.11
Sialidae	23.93	0.00	3.64	56.75
Asellidae	20.91	0.00	3.61	60.36
Naididae	19.31	0.00	3.32	63.69
Ephemeridae	18.94	0.00	3.32	67.01
Lymnaeidae	17.48	0.00	3.11	70.12
Spring 2016				
Average dissimilarity between both reaches = 62.28				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Baetidae	182.24	5.54	17.01	17.01
Gammaridae	158.19	311.27	14.86	31.87
Chironomidae (non- Tanypodinae)	94.42	245.03	14.25	46.12
Leptophlebiidae	78.83	15.01	6.06	52.18
Limnephilidae	70.25	18.02	4.95	57.13
Asellidae	43.55	0.00	4.03	61.16
Tanypodinae	42.56	4.59	3.49	64.65
Lymnaeidae	34.77	0.00	3.08	67.73
Ephemeridae	33.24	0.00	2.93	70.66

Appendix 3.11. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomic composition (Biomass m^{-2}) data, identifying families contributing 70% of the spatial dissimilarity in community composition between both reach, reaches were compared seasonally before and after the LWM installation. Average Biomass presented in mgDM m^{-2}.

Spring 2014 (before LWM installation)				
Average dissimilarity between both reaches = 84.70				
	Average Biomass			
Family	Natural	Before-Rehabilitated	Contribution%	Cumulative%
Limnephilidae	259	12	24.66	24.66
Lymnaeidae	146	0	15.50	40.16
Baetidae	77	4	7.96	48.12
Planorbidae	50	0	5.66	53.78
Gammaridae	101	57	5.65	59.43
Hydrobiidae	67.28	0	5.10	64.53
Ptychopteridae	57.75	1.37	4.66	69.19
Ephemeridae	40.72	0.72	3.97	73.17
Winter 2015				
Average dissimilarity between both reaches = 72.86				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Lymnaeidae	106.07	0	23.61	23.61
Pisidiidae	40.50	0	8.55	32.16
Limnephilidae	47.25	15.13	8.40	40.56
Ptychopteridae	35.90	4.84	7.48	48.04
Gammaridae	73.66	57.87	6.54	54.58
Erpobdellidae	12.60	25.58	6.43	61.01
Hydrobiidae	22.07	0	5.11	66.12
Planorbidae	20.33	0	4.48	70.60
Spring 2015				
Average dissimilarity between both reaches = 64.32				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Lymnaeidae	174.34	17.10	16.21	16.21
Limnephilidae	213.69	82	13.35	29.56
Gammaridae	124.73	218	10.94	40.50
Chironomidae (non-Tanypodinae)	12.12	93	8.05	48.55
Hydrobiidae	64.54	0	6.57	55.12
Bithyniidae	62.37	0	6.49	61.61
Baetidae	79	17	6.43	68.04
Erpobdellidae	8.87	48	4.71	72.75
Summer 2015				
Average dissimilarity between both reaches = 73.86				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Limnephilidae	508.30	122.68	21.41	21.41
Gammaridae	233.69	579.75	17.24	38.66
Chironomidae (non-Tanypodinae)	6.70	258.79	12.36	51.02
Lymnaeidae	213.31	0	11.37	62.39
Pisidiidae	162.68	0	8.57	70.95

Autumn 2015				
Average dissimilarity between both reaches = 78.27				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Gammaridae	146.11	43.60	19.48	19.48
Ephemeridae	69.44	0	12.20	31.68
Lymnaeidae	70.57	0	10.19	41.87
Limnephilidae	52.34	41.12	8.12	49.99
Erpobdellidae	8.39	49.62	7.32	57.31
Pisidiidae	48.28	0	6.79	64.10
Bithyniidae	24.89	0	3.59	67.69
Hydrobiidae	23.01	0.10	3.52	71.21
Winter 2016				
Average dissimilarity between both reaches = 67.70				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Lymnaeidae	105.57	0	20.46	20.46
Limnephilidae	46.87	83.31	10.50	30.96
Gammaridae	74.37	108.37	8.66	39.62
Erpobdellidae	12.53	46.26	8.40	48.02
Pisidiidae	40.29	0	7.50	55.52
Ptychopteridae	34.53	0	6.97	62.49
Hydrobiidae	22.08	2.91	4.20	66.70
Planorbidae	19.35	0	3.74	70.44
Spring 2016				
Average dissimilarity between both reaches = 73.69				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Limnephilidae	266.15	78.44	18.14	18.14
Lymnaeidae	185.03	0	15.56	33.69
Gammaridae	106.94	194	10.42	44.12
Bithyniidae	82.80	0	7.61	51.73
Erpobdellidae	0.57	73.35	6.96	58.69
Baetidae	73.45	1.70	6.84	65.53
Hydrobiidae	83.25	0	6.58	72.11

Appendix 3.12. Summary of the two-way PERMANOVA pair-wise results for most affected macroinvertebrate family Density and Biomass for each reach separately

Natural reach				Rehabilitated reach			
Gammaridae (individual m^{-2})				**Gammaridae (individual m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.11893	0.9024	4280	Sp.14, Sp.15	10.079	**0.0002**	4306
Sp.14, Sp.16	0.20457	0.8545	462	Sp.14, Sp.16	10.78	**0.0025**	462
Wi.15, Wi.16	0.25983	0.8243	462	Wi.15, Wi.16	0.62567	0.5394	462
Sp.15, Sp.16	0.36324	0.7223	4318	Sp.15, Sp.16	1.0954	0.33	4310
Chironomidae (individual m^{-2})				**Chironomidae (individual m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.82687	0.414	4348	Sp.14, Sp.15	1.51897	**0.0406**	4280
Sp.14, Sp.16	0.65418	0.5184	461	Sp.14, Sp.16	2.8645	**0.0215**	462
Wi.15, Wi.16	0.02882	0.965	462	Wi.15, Wi.16	3.1471	**0.0016**	462
Sp.15, Sp.16	1.3	0.2186	4322	Sp.15, Sp.16	1.4642	**0.0166**	4299
Gammaridae (mgDM m^{-2})				**Gammaridae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.80209	0.4555	4315	Sp.14, Sp.15	5.9797	**0.0005**	4311
Sp.14, Sp.16	0.12681	0.9748	462	Sp.14, Sp.16	4.4652	**0.0027**	462
Wi.15, Wi.16	0.044775	0.9493	461	Wi.15, Wi.16	2.1816	0.0588	462
Sp.15, Sp.16	0.68298	0.5037	4278	Sp.15, Sp.16	0.62393	0.5468	4289
Chironomidae (mgDM m^{-2})				**Chironomidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.208	0.2466	4310	Sp.14, Sp.15	2.7326	**0.0165**	462
Sp.14, Sp.16	0.0385	0.9897	462	Sp.14, Sp.16	0.77606	**0.0453**	4300
Wi.15, Wi.16	0.0618	0.9507	462	Wi.15, Wi.16	0.58744	0.6006	462
Sp.15, Sp.16	1.2163	0.2517	4302	Sp.15, Sp.16	1.5255	**0.0169**	4305
Limnephilidae (mgDM m^{-2})				**Limnephilidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.0838	0.3034	4317	Sp.14, Sp.15	2.0176	**0.012**	3380
Sp.14, Sp.16	0.4019	0.6857	462	Sp.14, Sp.16	1.7018	**0.0241**	336
Wi.15, Wi.16	0.017907	0.989	462	Wi.15, Wi.16	1.7111	**0.0022**	334
Sp.15, Sp.16	1.7243	0.112	4313	Sp.15, Sp.16	0.17017	0.9186	4308
Erpobdellidae (mgDM m^{-2})				**Erpobdellidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.30202	0.8269	8	Sp.14, Sp.15	3.6762	**0.0069**	338
Sp.14, Sp.16	0.00299	0.999	2	Sp.14, Sp.16	2.7212	**0.017**	32
Wi.15, Wi.16	0.00046	1	2	Wi.15, Wi.16	0.72989	0.2244	154
Sp.15, Sp.16	0.30436	0.8165	8	Sp.15, Sp.16	0.31536	0.8201	2564

Appendix 3.13. Summary of the two-way PERMANOVA pair-wise analysis for seasonal differences in macroinvertebrate FFGs density between both reaches, based on number individual m^{-2}.

	Absorber			Deposit-feeder		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	14.821	0.0019	32	5.888	0.002	462
Wi.15	2.3819	0.0348	336	0.42064	0.6704	462
Sp.15	2.9369	0.0053	6555	0.38661	0.7159	8112
Su.15	4.2942	0.0001	3098	9.9555	0.0001	8082
Au.15	2.5714	0.0068	9782	1.0757	0.3052	9804
Wi.16	3.4608	0.0025	210	2.9346	0.0031	462
Sp.16	2.2593	0.0418	335	5.8383	0.002	462
	Shredder			Scraper		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	13.105	0.0018	460	2.6278	0.0396	462
Wi.15	5.0701	0.0022	459	1.5263	0.1601	462
Sp.15	0.091122	0.9305	8079	0.26769	0.7889	8151
Su.15	2.2085	0.0395	8155	3.6382	0.0018	8127
Au.15	7.0562	0.0001	7990	4.9389	0.0001	9796
Wi.16	3.6166	0.0061	462	5.2396	0.0017	462
Sp.16	2.2946	0.0585	460	3.6239	0.0062	462
	Filter-feeder			Piercer		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	0.2398	0.8234	456	3.1496	0.0117	8
Wi.15	2.8573	0.0111	462	2.6598	0.0219	8
Sp.15	0.71655	0.4824	8055	2.1517	0.0247	256
Su.15	8.1252	0.0002	8135	17.699	0.0001	255
Au.15	1.4441	0.1595	9782	3.8374	0.0016	7911
Wi.16	2.0631	0.0579	462	1.2232	0.1936	16
Sp.16	2.2003	0.072	462	2.7699	0.0178	32
	Predator			Parasite		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	4.8995	0.0023	462	8.2019	0.0018	456
Wi.15	2.7095	0.011	460	12.985	0.0016	462
Sp.15	2.147	0.0476	8004	3.1659	0.0026	8144
Su.15	5.0685	0.0001	8066	13.138	0.0001	8087
Au.15	2.5826	0.0169	9793	2.2593	0.0418	9805
Wi.16	2.2593	0.0418	462	2.2686	0.0573	462
Sp.16	4.7871	0.0026	462	4.2159	0.0022	461

Appendix 3.14. Summary of the two-way PERMANOVA pair-wise results from univariate analysis of seasonal variation in macroinvertebrate FFGs for each reach separately, based on number individual m^{-2}.

Natural reach				Rehabilitated reach			
Absorber				**Absorber**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.5008	0.6149	4297	Sp.14, Sp.15	3.61	**0.0092**	95
Sp.14, Sp.16	0.91523	0.3798	462	Sp.14, Sp.16	3.0127	**0.0129**	8
Wi.15, Wi.16	0.13788	0.8756	462	Wi.15, Wi.16	0.63559	0.6151	63
Sp.15, Sp.16	0.64756	0.5317	4296	Sp.15, Sp.16	0.19099	0.8499	1049
Deposit-feeder				**Deposit-feeder**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.55337	0.5985	4310	Sp.14, Sp.15	1.5699	**0.0413**	4305
Sp.14, Sp.16	1.2914	0.2245	462	Sp.14, Sp.16	2.1943	0.0557	461
Wi.15, Wi.16	0.38996	0.707	462	Wi.15, Wi.16	2.7727	**0.0118**	462
Sp.15, Sp.16	1.4663	0.1664	4273	Sp.15, Sp.16	2.1614	**0.0488**	4293
Shredders				**Shredders**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.72072	0.479	4318	Sp.14, Sp.15	5.5399	**0.0002**	4292
Sp.14, Sp.16	0.23409	0.8282	462	Sp.14, Sp.16	7.5765	**0.002**	462
Wi.15, Wi.16	0.12035	0.9036	462	Wi.15, Wi.16	2.1901	0.0647	461
Sp.15, Sp.16	0.2479	0.8143	4304	Sp.15, Sp.16	1.3434	**0.0208**	4296
Scraper				**Scraper**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.88062	0.3862	4270	Sp.14, Sp.15	1.5484	**0.0142**	4291
Sp.14, Sp.16	1.7173	0.1238	462	Sp.14, Sp.16	0.16164	0.8742	462
Wi.15, Wi.16	0.030847	0.9762	462	Wi.15, Wi.16	6.2704	**0.002**	462
Sp.15, Sp.16	0.74441	0.4545	4298	Sp.15, Sp.16	1.4642	0.1677	4276
Filter-feeder				**Filter-feeder**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.084277	0.9781	4353	Sp.14, Sp.15	1.5895	**0.0456**	4297
Sp.14, Sp.16	0.12021	0.9369	462	Sp.14, Sp.16	2.8609	0.1921	462
Wi.15, Wi.16	0.15129	0.8745	461	Wi.15, Wi.16	2.9042	**0.0027**	462
Sp.15, Sp.16	0.098748	0.9566	4310	Sp.15, Sp.16	1.4867	**0.0156**	4285
Piercer				**Piercer**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.53581	0.5232	807	Sp.14, Sp.15	1.6018	0.2274	8
Sp.14, Sp.16	1.0604	0.3208	210	Sp.14, Sp.16	1	1	1
Wi.15, Wi.16	0.010819	0.9107	119	Wi.15, Wi.16	1	1	1
Sp.15, Sp.16	0.43563	0.6627	1393	Sp.15, Sp.16	0.88306	0.3253	16
Predator				**Predator**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.041104	0.9636	4286	Sp.14, Sp.15	0.7076	0.4816	4272
Sp.14, Sp.16	0.55043	0.582	461	Sp.14, Sp.16	0.78917	0.401	461
Wi.15, Wi.16	0.022785	0.984	462	Wi.15, Wi.16	0.132	0.8801	462
Sp.15, Sp.16	0.48033	0.6341	4289	Sp.15, Sp.16	1.2127	0.2419	4325
Parasite				**Parasite**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.77858	0.4542	4329	Sp.14, Sp.15	0.38817	0.692	4290
Sp.14, Sp.16	0.049363	0.9547	462	Sp.14, Sp.16	2.561	**0.0317**	462
Wi.15, Wi.16	0.12035	0.9036	4318	Wi.15, Wi.16	4.5305	**0.0015**	462
Sp.15, Sp.16	0.81305	0.4221	4246	Sp.15, Sp.16	1.4291	0.1799	4216

Appendix 3.15. Summary of the two-way PERMANOVA pair-wise analysis for seasonal differences in macroinvertebrate community FFGs biomass between both reaches, based on mgDM m^{-2}.

	Absorber			Deposit-feeder		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	13.481	0.0025	32	6.8387	0.0025	462
Wi.15	2.9907	0.0139	336	4.4356	0.0049	462
Sp.15	3.3118	0.0023	7325	1.3804	0.1767	8056
Su.15	4.3457	0.0001	6540	5.5562	0.0001	8107
Au.15	3.0343	0.0018	9777	3.5211	0.002	9780
Wi.16	3.6746	0.0075	210	5.67	0.0034	462
Sp.16	2.7234	0.0142	336	5.2563	0.0023	462
	Shredder			Scraper		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	11.179	0.0014	459	15.213	0.002	461
Wi.15	5.6063	0.0026	462	7.5364	0.0023	462
Sp.15	5.0434	0.0002	8070	8.0334	0.0001	8160
Su.15	2.0592	0.0598	8071	2.9201	0.0126	7995
Au.15	5.9339	0.0001	9780	6.0814	0.0001	9821
Wi.16	0.73592	0.4885	462	5.1269	0.0042	462
Sp.16	4.1088	0.004	462	6.889	0.0025	462
	Filter-feeder			Piercer		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	3.6187	0.0022	462	3.0533	0.0124	8
Wi.15	4.5285	0.0021	461	2.1354	0.06	8
Sp.15	4.218	0.0013	8064	0.60439	0.5378	255
Su.15	9.9041	0.0001	8126	18.023	0.0003	255
Au.15	6.8733	0.0001	9836	1.9347	0.0684	7813
Wi.16	3.0803	0.0184	462	1.77	0.101	16
Sp.16	7.98	0.002	462	2.7697	0.0182	32
	Predator			Parasite		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	4.5746	0.0054	462	2.3502	0.0397	462
Wi.15	0.62037	0.5344	462	0.77983	0.5362	462
Sp.15	0.02506	0.9791	8097	2.9907	0.0139	7989
Su.15	1.0585	0.3051	8087	6.3011	0.0001	8060
Au.15	0.40407	0.6948	9792	0.83809	0.408	9775
Wi.16	1.3868	0.1995	462	0.32372	0.8529	462
Sp.16	0.18852	0.8555	462	0.66255	0.5424	462

Appendix 3.16. Summary of the two-way PERMANOVA pair-wise results from univariate analysis of seasonal variation in macroinvertebrate FFGs biomass for each reach separately, based on mgDM m^{-2}.

Natural reach				Rehabilitated reach			
Absorber				**Absorber**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.29513	0.7744	4297	Sp.14, Sp.15	3.6497	**0.0076**	125
Sp.14, Sp.16	24538	0.816	462	Sp.14, Sp.16	3.0177	**0.014**	8
Wi.15, Wi.16	0.15379	0.8508	461	Wi.15, Wi.16	0.65877	0.5322	63
Sp.15, Sp.16	0.0097642	0.9905	4305	Sp.15, Sp.16	0.25686	0.8085	1406
Deposit-feeder				**Deposit-feeder**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.1023	0.2889	4262	Sp.14, Sp.15	4.2793	**0.0013**	4327
Sp.14, Sp.16	1.4791	0.1602	462	Sp.14, Sp.16	0.07261	0.9293	462
Wi.15, Wi.16	0.072131	0.9103	462	Wi.15, Wi.16	1.7448	0.1099	462
Sp.15, Sp.16	1.1302	0.2893	4290	Sp.15, Sp.16	3.9814	**0.0018**	4327
Shredders				**Shredders**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.62668	0.5278	4298	Sp.14, Sp.15	14.513	**0.0005**	4301
Sp.14, Sp.16	0.22374	0.8168	460	Sp.14, Sp.16	4.8821	**0.002**	462
Wi.15, Wi.16	0.017803	0.9872	462	Wi.15, Wi.16	2.834	**0.0201**	460
Sp.15, Sp.16	1.03	0.3156	4246	Sp.15, Sp.16	1.7171	0.1061	4274
Scraper				**Scraper**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.037352	0.9758	4302	Sp.14, Sp.15	7.8516	**0.0004**	4271
Sp.14, Sp.16	0.30711	0.7549	462	Sp.14, Sp.16	3.0538	**0.0138**	462
Wi.15, Wi.16	0.021665	0.9694	460	Wi.15, Wi.16	1.8939	0.0804	461
Sp.15, Sp.16	0.35809	0.714	4298	Sp.15, Sp.16	3.2684	**0.0063**	4290
Filter-feeder				**Filter-feeder**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.46897	0.6464	4327	Sp.14, Sp.15	1.5206	0.1839	4283
Sp.14, Sp.16	1.0204	0.3141	462	Sp.14, Sp.16	0.30132	0.7755	462
Wi.15, Wi.16	0.038598	0.9125	461	Wi.15, Wi.16	1.6983	0.0956	452
Sp.15, Sp.16	1.2397	0.2235	4279	Sp.15, Sp.16	1.5739	0.1511	4261
Piercer				**Piercer**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.40381	0.7101	817	Sp.14, Sp.15	1.5941	0.2345	8
Sp.14, Sp.16	0.9622	0.3504	210	Sp.14, Sp.16	No enough data for comparing		
Wi.15, Wi.16	0.0072637	0.9066	118	Wi.15, Wi.16	No enough data for comparing		
Sp.15, Sp.16	0.49811	0.6261	1379	Sp.15, Sp.16	1.0523	0.3307	16
Predator				**Predator**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.20667	0.8405	4318	Sp.14, Sp.15	3.7818	**0.0028**	4287
Sp.14, Sp.16	0.50224	0.6202	462	Sp.14, Sp.16	3.0538	**0.0139**	461
Wi.15, Wi.16	0.065503	0.9214	460	Wi.15, Wi.16	1.7263	0.1161	461
Sp.15, Sp.16	0.24335	0.803	4285	Sp.15, Sp.16	0.42619	0.6757	4280

Parasite				Parasite			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.2258	0.2515	4339	Sp.14, Sp.15	0.84268	0.4152	4252
Sp.14, Sp.16	0.95889	0.3777	461	Sp.14, Sp.16	2.1339	0.0471	461
Wi.15, Wi.16	0.010151	0.8487	424	Wi.15, Wi.16	1.245	0.2536	462
Sp.15, Sp.16	0.30757	0.7701	4320	Sp.15, Sp.16	1.0604	0.3208	4252

Appendix 3.17. Summary of the two-way PERMANOVA pair-wise results from multi-variate analysis between the natural and rehabilitated reach, depending on macroinvertebrate functional feeding group composition (FFG Count m^{-2}, and FFG Biomass m^{-2}).

	FFG Count m^{-2}			FFG Biomass m^{-2}		
Season	t	*P*(perm)	Unique perms	t	*P*(perm)	Unique perms
Sp.14	7.8864	0.0019	462	8.1308	0.0017	462
Wi.15	4.0951	0.003	462	4.3086	0.0023	462
Sp.15	1.3781	0.1685	8101	2.6118	0.0013	8150
Su.15	8.1734	0.0003	8164	5.8888	0.0002	8147
Au.15	2.7454	0.0032	9916	4.0774	0.0001	9930
Wi.16	2.7224	0.0028	462	3.2133	0.0026	462
Sp.16	3.6402	0.0017	461	4.2618	0.0021	462

Appendix 3.18. Summary of the two-way PERMANOVA pair-wise results from multi-variate analysis of seasonal variation in macroinvertebrate FFG composition (FFG Count m^{-2}, and Biomass m^{-2}) within each reaches.

Natural reach

FFG Count m^{-2}

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	3.3809	0.0019	462
Sp.14, Sp.15	0.3576	0.105	461
Sp.14, Su.15	2.416	0.0003	4315
Sp.14, Au.15	3.1263	0.0003	7684
Sp.14, Wi.16	3.434	0.0018	462
Sp.14, Sp.16	0.8759	0.4962	462
Wi.15, Sp.15	3.2913	0.0022	462
Wi.15, Su.15	4.0352	0.0002	4297
Wi.15, Au.15	2.6308	0.0003	7672
Wi.15, Wi.16	0.0345	0.9814	462
Wi.15, Sp.16	2.888	0.0023	462
Sp.15, Su.15	2.2789	0.0005	4314
Sp.15, Au.15	2.2346	0.0023	7689
Sp.15, Wi.16	3.3469	0.0018	462
Sp.15, Sp.16	0.39779	0.9529	462
Su.15, Au.15	2.6751	0.0005	9779
Su.15, Wi.16	4.0571	0.0005	4302
Su.15, Sp.16	1.723	0.0184	4354
Au.15, Wi.16	2.6465	0.0001	7586
Au.15, Sp.16	2.2382	0.0057	7683
Wi.16, Sp.16	2.9287	0.0022	462

FFG Biomass m^{-2}

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	1.9347	0.0087	461
Sp.14, Sp.15	0.57281	0.8497	4313
Sp.14, Su.15	2.9264	0.0023	4320
Sp.14, Au.15	2.241	0.0015	7647
Sp.14, Wi.16	1.9654	0.0066	462
Sp.14, Sp.16	0.85298	0.4488	462
Wi.15, Sp.15	2.3066	0.0002	4363
Wi.15, Su.15	4.7805	0.0002	4308
Wi.15, Au.15	1.7817	0.0171	7704
Wi.15, Wi.16	0.044595	0.9514	462
Wi.15, Sp.16	2.1472	0.0052	462
Sp.15, Su.15	3.3125	0.0001	8129
Sp.15, Au.15	2.78	0.0001	9777
Sp.15, Wi.16	2.3352	0.0003	4299
Sp.15, Sp.16	0.75539	0.6837	4341
Su.15, Au.15	4.8384	0.0001	9788
Su.15, Wi.16	4.8106	0.0001	4329
Su.15, Sp.16	2.2863	0.0048	4315
Au.15, Wi.16	1.8015	0.0148	7733
Au.15, Sp.16	2.2426	0.0023	7701
Wi.16, Sp.16	2.1675	0.0052	462

Rehabilitated reach

FFG Count m^{-2}

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	1.8145	0.0821	462
Sp.14, Sp.15	2.5808	**0.0093**	462
Sp.14, Su.15	8.2404	0.0003	4296
Sp.14, Au.15	2.3551	0.0151	7685
Sp.14, Wi.16	2.6874	0.0022	462
Sp.14, Sp.16	2.9587	**0.0023**	462
Wi.15, Sp.15	2.5081	0.0161	462
Wi.15, Su.15	7.6836	0.0003	4295
Wi.15, Au.15	1.6758	0.0931	7746
Wi.15, Wi.16	2.334	**0.0165**	462
Wi.15, Sp.16	1.7236	0.0654	462
Sp.15, Su.15	2.0146	0.0575	4344
Sp.15, Au.15	2.8626	0.0063	7695
Sp.15, Wi.16	3.1875	0.0023	462
Sp.15, Sp.16	2.1046	**0.046**	462
Su.15, Au.15	5.8281	0.0001	9799
Su.15, Wi.16	7.3143	0.0007	4334
Su.15, Sp.16	6.8694	0.0004	4345
Au.15, Wi.16	1.0976	0.3017	7702
Au.15, Sp.16	1.9041	0.0551	7673
Wi.16, Sp.16	2.0661	0.021	462

FFG Biomass m^{-2}

Seasons	t	P(perm)	perms
Sp.14, Wi.15	1.6129	0.0824	462
Sp.14, Sp.15	4.5131	**0.0003**	4327
Sp.14, Su.15	7.9066	0.0003	4313
Sp.14, Au.15	1.8951	0.0246	7646
Sp.14, Wi.16	2.533	0.0048	462
Sp.14, Sp.16	2.7141	**0.0026**	461
Wi.15, Sp.15	3.7393	0.0003	4325
Wi.15, Su.15	6.3872	0.0003	4297
Wi.15, Au.15	1.1928	0.2459	7728
Wi.15, Wi.16	1.7963	**0.0423**	462
Wi.15, Sp.16	1.9259	0.0139	462
Sp.15, Su.15	2.249	0.0121	8118
Sp.15, Au.15	2.9085	0.0006	9782
Sp.15, Wi.16	2.5079	0.0036	4329
Sp.15, Sp.16	1.9073	**0.0306**	4346
Su.15, Au.15	4.5966	0.0002	9803
Su.15, Wi.16	4.6762	0.0001	4313
Su.15, Sp.16	4.0214	0.0004	4338
Au.15, Wi.16	1.4257	0.1267	7703
Au.15, Sp.16	1.7372	0.0404	7665
Wi.16, Sp.16	0.97686	0.4343	462

Appendix 3.19. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community functional composition (FFG Count m^{-2}) 4th root transformed data, identifying feeding groups contributing 70% of the spatial dissimilarity in community composition between both reaches, reaches were compared seasonally before and after the LWM installation. Average abundances presented in individuals m^{-2} (4th root transformed).

Spring 2014 (before LWM installation)
Average dissimilarity between both reaches = 15.16

Feeding group	Average Abundance: Natural	Average Abundance: Rehabilitated	Contribution%	Cumulative%
Absorber	1.69	0.00	27.31	27.31
Shredder	4.49	3.29	19.49	46.79
Predator	3.42	2.57	13.80	60.59
Parasite	1.92	2.74	13.23	73.82

Winter 2015
Average dissimilarity between both reaches = 11.83

Feeding group	Average Abundance: Natural	Average Abundance: Rehabilitated	Contribution%	Cumulative%
Parasite	1.46	2.62	25.52	25.52
Absorber	1.73	0.93	19.44	44.96
Predator	2.96	2.32	14.72	59.67
Shredder	3.96	3.33	14.17	73.84

Spring 2015
Average dissimilarity between both reaches = 11.35

Feeding group	Average Abundance: Natural	Average Abundance: Rehabilitated	Contribution%	Cumulative%
Predator	3.42	2.82	16.42	16.42
Parasite	2.02	2.86	14.85	31.27
Filter-feeder	2.94	3.18	13.86	45.13
Deposit-feeder	3.63	3.73	13.60	58.73
Piercer	0.79	0.43	13.44	72.18

Summer 2015
Average dissimilarity between both reaches = 17.39

Feeding group	Average Abundance: Natural	Average Abundance: Rehabilitated	Contribution%	Cumulative%
Parasite	1.89	3.78	21.50	21.50
Deposit-feeder	3.22	5.03	20.57	42.07
Filter-feeder	3.13	4.49	15.45	57.52
Piercer	1.05	0.00	12.10	69.61
Absorber	1.43	0.73	8.10	77.71

Autumn 2015
Average dissimilarity between both reaches = 14.57

Feeding group	Average Abundance: Natural	Average Abundance: Rehabilitated	Contribution%	Cumulative%
Shredder	4.36	3.30	19.24	19.24
Piercer	1.23	0.49	14.58	33.82
Scraper	3.54	2.78	14.25	48.07
Filter-feeder	2.70	2.35	13.75	61.82
Parasite	1.73	1.95	11.69	73.51

Winter 2016				
Average dissimilarity between both reaches = 13.41				
	Average Abundance			
Feeding group	Natural	Rehabilitated	Contribution%	Cumulative%
Absorber	1.71	0.66	22.80	22.80
Predator	2.96	2.29	15.83	38.63
Deposit-feeder	3.13	2.55	12.79	51.42
Piercer	0.58	0.21	12.56	63.98
Scraper	3.39	2.86	11.18	75.16
Spring 2016				
Average dissimilarity between both reaches = 12.42				
	Average Abundance			
Feeding group	Natural	Rehabilitated	Contribution%	Cumulative%
Predator	3.35	2.40	19.76	19.76
Piercer	0.93	0.17	17.39	37.15
Absorber	1.56	0.90	15.23	52.38
Deposit-feeder	3.46	2.93	10.99	63.36
Parasite	1.91	2.41	10.49	73.85

Appendix 3.20. List of recorded macroinvertebrate taxa in presence/absence form from Rolleston Brook study reaches.

				Sp.14		Wi.15		Sp.15		Su.15		Au.15		Wi.16		Sp.16	
Order	Family	Genus	Taxa	N	R	N	R	N	R	N	R	N	R	N	R	N	R
Malacostraca	Gammaridae	Gammarus	Gammarus pulex	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Asellidae	Asellus	Asellus aquaticus	X		X		X		X		X		X		X	
			Asellus meridianus	X		X		X		X		X		X		X	
Gastropoda	Lymnaeidae	Lymnaea	Lymnaea (Radix) peregra	X		X		X	X	X		X		X		X	
			Lymnaea glabra													X	
			Lymnaea stagnalis							X		X					
			Lymnaea truncatula	X		X		X	X	X		X		X		X	
	Valvatidae	Valvata	Valvata macrostoma	X						X		X				X	
			Valvata cristata							X		X					
	Hydrobiidae	Potamopyrgus	Potamopyrgus antipodarum	X		X		X		X		X	X	X	X	X	
	Bithyniidae	Bithynia	Bithynia tentaculata	X				X		X		X				X	
			Bithynia leachii	X				X		X		X				X	
	Physidae	Physa	Physa fontinalis	X				X								X	
	Neritidae	Theodoxus	Theodoxus fluviatilis							X		X					
	Planorbidae	Planorbis	Planorbis contortus	X				X		X		X				X	
			Planorbis corneus									X					
		Ancylus	Ancylus fluviatilis	X		X		X		X		X		X		X	
			Ancylus lacustris	X				X		X		X				X	
Bivalvia	Pisidiidae	Pisidium	Pisidium sp.	X		X		X	X	X		X		X		X	
	Sphaeriidae	Sphaerium	Sphaerium sp.	X		X	X	X		X	X	X	X	X	X	X	
Hirudinea	Glossiphoniidae	Glossiphonia	Glossiphonia complanata	X		X		X	X	X		X	X	X		X	X
		Helobdella	Helobdella stagnalis						X				X				
	Erpobdellidae	Erpobdella	Erpobdella octoculata	X	X	X	X	X	X	X	X	X	X	X	X	X	X
			Erpobdella testacea					X			X	X					

Oligochaeta	Lumbriculidae	Lumbriculidae	Lumbriculidae	X		X	X	X	X	X		X		X		X	
	Glossoscolecidae	Glossoscolecidae	Glossoscolecidae			X		X		X		X		X		X	
	Tubificidae	Tubificidae	Tubificidae	X		X	X	X	X	X	X	X	X	X	X	X	X
	Naididae	Nais	Nais sp.	X		X	X	X	X	X	X	X	X	X		X	X
		Stylaria	Stylaria lacustris								X						
Nematomorpha	Gordiidae	Gordius	Gordius aquaticus							X	X						
Turbellaria	Planariidae	Polycelis	Polycelis tenuis					X				X	X			X	
			Polycelis felina	X		X		X		X		X		X		X	
Coleoptera	Elmidae	Elmidae	Elmidae	X		X	X	X	X	X	X	X	X	X	X	X	
Coleoptera	Scirtidae	Scirtidae	Scirtidae	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Helophoridae	Helophoridae	Helophoridae								X						
	Helodidae	Helodidae	Helodidae	X				X	X	X		X				X	
	Haliplidae	Haliplidae	Haliplidae									X					
	Dytiscidae	Dytiscidae	Dytiscidae	X		X		X		X		X		X		X	
Diptera	Muscidae	Muscidae	Muscidae										X		X		
	Psychodidae	Psychodidae	Psychodidae	X	X		X	X	X		X	X	X		X		X
	Ptychopteridae	Ptychopteridae	Ptychopteridae	X	X	X	X	X	X	X	X	X		X		X	X
	Dixidae	Dixidae	Dixidae		X			X		X		X				X	
	Stratiomyidae	Stratiomyidae	Stratiomyidae	X	X			X									
	Empididae	Empididae	Empididae	X		X		X	X					X		X	
	Tipulidae	Tipulidae	Tipulidae									X			X		
	Pediciidae	Pediciidae	Pediciidae	X	X	X	X	X	X	X	X	X	X	X		X	X
	Simuliidae	Simuliidae	Simuliidae	X	X	X	X	X	X	X		X		X	X	X	X
	Ceratopogonidae	Ceratopogonidae	Ceratopogonidae	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Chironomidae	Chironomidae	Chironominae	Chironominae	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Prodiamesinae	Prodiamesinae	X	X	X	X	X		X	X	X	X	X	X	X	X
		Orthocladiinae	Orthocladiinae	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Diamesinae	Diamesinae	X	X	X	X	X	X	X	X	X	X	X	X	X	X

		Tanypodinae	Tanypodinae	X	X	X	X	X	X	X	X	X	X	X	X	X	X
EPT	Psychomyiidae	Tinodes	Tinodes sp.	X				X		X		X				X	
	Hydropsychidae	Hydropsyche	Hydropsyche sp.					X								X	
		Hydropsyche	Hydropsyche siltatay	X		X		X	X	X		X		X		X	
	Hydropsychidae	Hydropsyche	Hydropsyche instabilus	X		X		X		X		X		X		X	
	Limnephilidae	Halesus	Halesus radiatus.	X		X		X	X	X	X			X		X	
		Halesus	Halesus digitatus	X		X		X		X	X	X		X		X	
		Limnephilus	Limnephilus lunatus.	X		X		X	X	X	X	X	X	X	X	X	X
		Limnephilus	Limnephilus nigriceps	X		X		X	X	X	X	X	X	X	X	X	X
		Limnephilus	Limnephilus flavicornis	X				X								X	
		Chaetopteryx	Chaetopteryx villosa	X	X	X		X	X	X	X	X	X	X	X	X	X
		Glyphotaelius	Glyphotaelius pellucidus	X	X	X		X	X	X	X	X		X		X	
		Phacopteryx	Phacopteryx brevipennis	X				X		X	X	X	X		X	X	X
		Micropterna	Micropterna sp.	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Potamophylax	Potamophylax sp.			X			X	X	X	X		X		X	
	Molannidae	Molanna	Molanna albicans									X					
	Leptoceridae	Mystacides	Mystacides longicornis(azurea)			X		X		X	X	X		X		X	
		Ceraclea	Ceraclea sp.	X		X		X	X	X		X	X	X	X	X	
		Athripsodes	Athripsodes cinereus	X						X		X					
		Athripsodes	Athripsodes aterrimus					X		X						X	
	Lepidostomatidae	Crunoecia	Crunoecia irrorata	X				X	X	X		X	X			X	
		Lepidostoma	Lepidostoma hirtum	X				X	X	X		X				X	
		Lasiocephala	Lasiocephala basalis	X				X	X	X		X				X	
	Sericostomatidae	Sericostoma	Sericostoma personatum	X		X		X		X	X	X		X		X	
	Glossosomatidae	Agapetus	Agapetus fuscipes	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Polycentropodidae	Plectrocnemia	Plectrocnemia conspersa	X	X	X	X	X	X	X		X		X	X	X	
		Polycentropus	Polycentropus flavomaculatus	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Apataniidae	Apatania	Apatania muliebris		X		X				X	X	X				

	Beraeidae	Beraea	Beraea pullata	X		X		X	X	X	X	X		X	X	X	
	Goeridae	Silo	Silo pallipes	X					X	X		X					
	Goeridae	Goera	Goera pilosa							X		X					
	Rhyacophilidae	Rhyacophila	Rhyacophila dorsalis	X		X		X		X		X		X		X	
	Baetidae	Baetis	Baetis rhodani	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Cloeon	Cloeon dipterum										X				
		Procloeon	Procloeon pennulatum							X							
		Centroptilum	Centroptilum luteolum	X		X		X	X	X		X		X		X	
	Caenidae	Caenis	Caenis luctuosa									X	X		X		
	Ephemeridae	Ephemera	Ephemera vulgata					X								X	
			Ephemera danica	X	X	X	X	X	X	X	X	X		X		X	
	Ephemerellidae	Serratella	Serratella ignita					X									
	Leptophlebiidae	Habrophlebia	Habrophlebia fusca	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Paraleptophlebia	Paraleptophlebia werneri	X		X		X		X		X		X		X	
	Nemouridae	Nemurella	Nemurella pictetii					X				X				X	
			Nemurella cambrica							X							
		Amphinemura	Amphinemura sp.		X	X	X							X	X		X
Megaloptera	Sialidae	Sialis	Sialis lutaria	X		X		X		X		X		X		X	
Neuroptera	Osmylidae	Osmylus	Osmylus sp.									X					
Arachnida	Libertiidae	Lebirtia	Lebirtia porosa	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Hygrobatidae	Hygrobates	Hygrobates sp (longu)	X		X	X	X	X	X	X	X	X	X		X	
	Sperchontidae	Sperchon	Sperchon sp.	X	X	X	X	X	X	X	X	X	X	X		X	X
	Hydryphantidae	diplodontus	diplodontus despiciens	X													
	Limnesiidae	Limnesia	Limnesia sp	X		X	X	X		X		X		X		X	
	Arrenuridae	Arrenurus	Arrenurus truncatellus			X				X		X		X			
	Mideopsidae	Mideopsis	Mideopsis orbicularis							X							

Appendix 2. Data analysis of Chapter 4

Appendix 4.1. Results of ANOSIM test on channel morphological metrics

Tests for differences between unordered Reach groups
Global Test
Sample statistic (R): 0.692
Significance level of sample statistic: 0.01%
Number of permutations: 9999 (Random sample from 66512160)
Number of permuted statistics greater than or equal to R: 0

Pairwise Tests

Groups	R Statistic	Significance Level %	Possible Permutations	Actual Permutations	Number >=Observed
Degraded, Natural	0.961	0.06	1716	1716	1
Degraded, Rehabilitated	0.716	0.06	1716	1716	1
Natural, Rehabilitated	0.373	5.2	1716	1716	37

Appendix 4.2. Summary of results from Principal Components Analysis (PCA) of channel morphology metrics between reaches

Eigenvalues

PC	Eigenvalues	%Variation	Cumulative % Variation
1	2.88	53.2	53.2
2	2.02	37.4	90.6

Eigenvectors
(Coefficients in the linear combinations of variables making up PCs)

Variable	PC1	PC2
SWI_biotope	0.616	-0.188
CV_depth	0.197	0.587
CV_width	0.444	0.338
Wet surface area	-0.055	0.687
Number of biotopes	0.617	-0.182

Appendix 4.3. Results of ANOSIM test on instream biotope composition

Tests for differences between unordered Reach groups
Global Test
Sample statistic (R): 0.719
Significance level of sample statistic: 0.01%
Number of permutations: 9999 (Random sample from 66512160)
Number of permuted statistics greater than or equal to R: 0

Pairwise Tests

Groups	R Statistic	Significance Level %	Possible Permutations	Actual Permutations	Number >=Observed
Degraded, Natural	0.895	0.06	1716	1716	1
Degraded, Rehabilitated	0.852	0.06	1716	1716	1
Natural, Rehabilitated	0.048	20.5	1716	1716	352

Appendix 4.4. Summary of results from Principal Components Analysis (PCA) of in-stream biotope composition between reaches

Eigenvalues

PC	Eigenvalues	%Variation	Cumulative % Variation
1	5.11	42.6	42.6
2	2.97	24.7	67.4

Eigenvectors
(Coefficients in the linear combinations of variables making up PCs)

Variable	PC1	PC2
Boulders%	0.388	-0.175
Cobbles%	0.167	-0.431
Gravel%	0.267	-0.437
Sand%	-0.168	-0.071
Silt/Mud%	-0.366	0.270
Tree root%	0.386	0.231
Marginal plant%	0.244	0.371
Leaf litter%	0.255	0.364
Woody debris%	0.332	0.127
Macrophytes-Emergent%	0.291	0.262
Macroalgae%	0.304	0.070
Macrophytes-Submerged, fine-leaved%	-0.202	0.319

Appendix 4.5 Channel morphological variables and metrics of the study reaches. D, Degraded reach; R, Rehabilitated reach; and N, Natural reach.

	Before rehabilitation						After rehabilitation																				
	2014						2015												2016								
	Spring			Summer			Winter			Spring			Summer			Autumn			Winter			Spring			Summer		
Channel morphology	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N
CV_depth	0.36	0.34	0.61	0.41	-	0.62	0.42	0.54	0.71	0.37	0.37	0.60	0.42	0.50	0.57	0.40	0.45	0.58	0.41	0.56	0.72	0.36	0.45	0.62	0.40	0.53	0.58
CV_width	0.13	0.14	0.33	0.15	-	0.37	0.17	0.29	0.35	0.12	0.29	0.32	0.16	0.36	0.34	0.16	0.31	0.34	0.17	0.30	0.33	0.13	0.35	0.34	0.15	0.37	0.35
Number of biotopes	5	6	7	4	-	6	4	4	5	5	7	7	5	10	7	3	10	7	4	7	5	5	9	7	4	10	6
SWI_biotope	0.67	0.76	0.82	0.68	-	0.76	0.47	0.57	0.66	0.67	0.82	0.82	0.68	0.98	0.82	0.76	0.98	0.67	0.47	0.82	0.66	0.67	0.94	0.81	0.69	0.99	0.76
Wet surface area (m^2)	815	887	968	810	-	821	825	1112	1045	821	862	984	821	785	786	818	735	997	828	1130	1053	818	875	970	812	780	780

Appendix 4.6 In-stream biotope composition (biotope %) of the study reaches. D, Degraded reach; R, Rehabilitated reach; and N, Natural reach.

	Before rehabilitation						After rehabilitation																				
	2014						2015												2016								
	Spring			Summer			Winter			Spring			Summer			Autumn			Winter			Spring			Summer		
Biotope%	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N
BL	0.0	1.2	1.7	0.0	-	2.0	0.0	3.8	1.8	0.0	3.7	1.8	0.0	3.5	2.0	0.0	2.0	1.9	0.0	3.5	1.8	0.0	3.4	1.8	0.0	3.4	2.0
CO	0.0	4.3	10.6	0.0	-	10.5	0.0	5.2	8.0	0.0	3.1	10.8	0.0	2.9	10.0	0.0	2.0	8.0	0.0	4.0	8.0	0.0	4.0	11.2	0.0	4.0	12.0
G	16	48.1	73.7	15.27	-	62.7	15.85	88.7	82.9	15.7	84.1	73.7	13	69.0	59.3	11.05	60.2	73.4	15.0	79.8	82.9	15.0	59.6	75.0	14.0	40.6	60.0
SA	5.0	13.5	4.4	0.0	-	0.0	10	0.0	6.2	5.4	2.3	4.2	0.0	1.0	0.0	0.0	0.0	4.9	8.5	2.4	6.3	8.5	4.0	4.9	0.0	5.0	0.0
SI	72	31.1	1.2	57.25	-	2.3	74.15	0.0	0.0	72.4	0.0	1.0	52	0.0	3.7	42.38	1.0	0.0	75.5	0.0	0.0	71.0	0.0	1.0	62.0	0.0	3.0
TR	0.0	1.7	0.0	0.0	-	0.0	0.0	2.3	0.0	0.0	1.8	0.0	0.0	2.2	0.0	0.0	4.7	0.0	0.0	3.3	0.0	0.0	3.0	0.0	0.0	3.0	0.0
MP	1.25	0.0	1.6	6.28	-	3.8	1.0	0.0	1.1	1.0	0.0	1.8	4.8	3.6	3.8	4.23	3.9	2.9	1.0	3.0	1.0	1.0	9.0	1.2	5.0	12.0	4.0
LL	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6	1.2	0.0	3.64	3.0	4.0	0.0	0.0	0.0	0.0	8.0	0.0	0.0	11.0	0.0
WD	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	2.9	1.1	0.0	3.2	0.0	0.0	4.0	0.0	0.0	2.0	0.0	0.0	3.0	0.0
ME	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
MA	0.0	0.0	6.7	0.0	-	18.8	0.0	0.0	0.0	0.0	2.0	6.7	0.0	12.7	20.2	0.0	19.0	5.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	17.0	19.0
MSF	5.75	0.0	0.0	21.2	-	0.0	0.0	0.0	0.0	5.5	0.0	0.0	30.2	0.0	0.0	38.25	0.0	0.0	0.0	0.0	0.0	19.0	4.5	0.0	19.0	0.0	0.0

Appendix 4.7. Average and Standard Deviation of macroinvertebrate community structural and functional univariate metrics.

Community metrics	Seasons	Degraded reach		Rehabilitated reach		Natural Reach	
		Mean	SD	Mean	SD	Mean	SD
Total Density	Sp.14	853.7	176.7	429.9	91.0	1816.9	119.6
	Su.14	1023.6	291.9			3259.4	190.3
	Wi.15	1230.5	316.8	143.7	39.5	773.3	94.5
	Sp.15	1054.8	277.6	651.6	199.0	1782.5	184.6
	Su.15	1400.3	204.9	1396.2	265.8	3319.5	54.2
	Au.15	972.6	342.3	956.3	239.8	2789.5	864.4
	Wi.16	1374.6	946.4	816.9	349.3	798.6	80.4
	Sp.16	868.7	208.9	1188.1	234.7	1894.9	170.8
	Su.16	1056.8	164.3	2017.7	759.7	3251.6	133.5
Total Biomass	Sp.14	253.8	67.8	300.2	205.8	2618.3	532.1
	Su.14	999.1	781.8			1947.3	368.3
	Wi.15	380.2	332.2	48.0	14.5	754.9	248.3
	Sp.15	304.9	137.9	317.2	158.2	2834.1	380.7
	Su.15	1534.0	710.6	1538.7	292.9	2149.0	678.2
	Au.15	831.3	508.6	1366.9	666.9	5528.9	2875.9
	Wi.16	221.8	175.6	805.9	546.9	815.3	227.2
	Sp.16	207.3	81.0	1858.4	397.0	3238.0	640.1
	Su.16	1183.1	565.5	3051.3	1668.0	2554.5	423.6
Taxa Richness	Sp.14	3.2	0.5	5.8	0.3	7.1	0.4
	Su.14	4.1	0.4			6.2	0.5
	Wi.15	2.0	0.4	5.7	0.7	7.7	0.5
	Sp.15	3.4	0.5	5.6	0.6	6.8	0.8
	Su.15	3.8	0.3	5.5	0.6	6.1	0.3
	Au.15	2.4	0.6	5.9	0.8	6.5	0.3
	Wi.16	1.7	0.5	6.3	0.6	7.5	0.3
	Sp.16	3.1	0.4	6.6	0.3	6.6	0.6
	Su.16	4.0	0.4	6.1	0.5	6.1	0.4
Taxa Diversity	Sp.14	7.0	1.9	7.0	0.9	20.9	1.5
	Su.14	8.6	1.1			13.1	0.7
	Wi.15	4.2	1.4	9.3	2.5	21.5	1.8
	Sp.15	6.5	1.5	13.1	2.1	20.0	3.0
	Su.15	7.4	1.5	13.8	2.3	13.0	0.5
	Au.15	7.2	1.3	16.3	5.4	9.7	4.3
	Wi.16	3.9	1.2	17.5	1.9	23.6	2.8
	Sp.16	6.7	1.8	23.2	1.4	20.8	3.4
	Su.16	9.3	1.7	20.1	2.0	12.8	1.7
Evenness	Sp.14	0.6	0.1	0.5	0.0	0.8	0.0
	Su.14	0.6	0.0			0.7	0.0
	Wi.15	0.5	0.1	0.7	0.1	0.8	0.0
	Sp.15	0.6	0.1	0.7	0.1	0.8	0.0
	Su.15	0.6	0.1	0.7	0.0	0.7	0.0
	Au.15	0.7	0.1	0.7	0.1	0.6	0.1
	Wi.16	0.5	0.1	0.8	0.0	0.8	0.0
	Sp.16	0.6	0.1	0.8	0.0	0.8	0.0
	Su.16	0.7	0.0	0.8	0.0	0.6	0.0
EPT Richness	Sp.14	1.4	0.7	2.0	0.7	3.5	0.1
	Su.14	1.3	0.8			3.5	0.4
	Wi.15	0.5	0.3	2.6	0.3	4.1	0.4
	Sp.15	1.0	0.5	3.0	0.8	3.2	0.3

	Su.15	1.1	0.7	2.1	0.4	3.5	0.2
	Au.15	0.7	2.6	1.8	0.6	3.6	0.3
	Wi.16	0.2	0.6	2.6	0.4	4.2	0.2
	Sp.16	1.0	0.7	3.0	0.1	3.0	0.5
	Su.16	1.5	0.9	2.4	0.3	3.3	0.3
EPT Diversity	Sp.14	2.5	0.5	5.6	1.6	8.5	1.3
	Su.14	2.8	1.0			8.6	1.3
	Wi.15	1.8	0.5	4.5	1.1	9.9	1.8
	Sp.15	2.7	0.9	6.7	1.5	8.5	1.9
	Su.15	2.5	0.8	5.4	1.5	8.9	1.0
	Au.15	1.1	0.3	4.1	2.1	10.3	2.4
	Wi.16	1.5	1.1	6.0	0.9	10.8	2.7
	Sp.16	2.2	0.8	11.7	1.2	7.8	2.9
	Su.16	2.7	0.9	6.9	2.2	8.6	2.2
EPT Count%	Sp.14	1.8	1.5	3.5	1.1	39.8	7.0
	Su.14	0.6	0.4			19.9	0.9
	Wi.15	0.8	0.4	10.2	5.3	41.6	8.0
	Sp.15	1.8	1.4	10.3	4.0	35.8	6.1
	Su.15	0.7	0.6	12.7	9.4	18.8	2.0
	Au.15	0.1	0.3	26.4	14.5	18.1	10.0
	Wi.16	0.4	0.8	25.1	8.3	41.5	3.4
	Sp.16	1.6	1.4	16.9	1.0	32.8	7.3
	Su.16	0.6	0.5	11.9	2.2	16.7	2.5
Chironomidae Count%	Sp.14	51.3	11.2	48.5	7.0	5.6	1.2
	Su.14	43.8	11.1			36.4	1.5
	Wi.15	27.1	16.0	21.2	12.2	4.8	1.6
	Sp.15	49.7	8.0	21.7	8.8	10.6	6.3
	Su.15	48.2	16.6	26.7	14.3	37.5	1.2
	Au.15	33.6	9.1	6.4	4.0	11.9	5.1
	Wi.16	21.0	12.1	8.0	6.7	7.5	2.0
	Sp.16	56.9	9.2	12.7	2.0	11.0	6.6
	Su.16	39.8	5.1	16.8	3.3	33.6	1.3
EPT Biomass%	Sp.14	6.7	13.5	10.1	9.2	25.1	10.2
	Su.14	1.8	1.9			27.7	4.9
	Wi.15	1.7	2.0	21.4	16.9	22.3	11.7
	Sp.15	6.7	14.2	17.3	10.3	21.8	7.8
	Su.15	0.5	0.5	19.8	8.7	24.6	7.6
	Au.15	0.0	0.1	2.5	2.5	3.5	1.3
	Wi.16	0.4	0.7	15.7	17.2	30.9	9.6
	Sp.16	8.2	17.0	9.8	2.4	17.5	2.3
	Su.16	1.0	1.3	11.2	4.1	16.2	4.0
Chironomidae Biomass%	Sp.14	18.2	11.5	11.4	6.9	0.2	0.1
	Su.14	9.5	4.3			3.7	0.4
	Wi.15	10.2	8.6	5.2	3.6	0.5	0.4
	Sp.15	16.4	5.6	4.2	3.3	0.5	0.5
	Su.15	11.9	7.8	2.7	1.8	3.7	0.7
	Au.15	9.1	10.8	0.6	0.5	0.7	0.3
	Wi.16	22.2	14.0	1.0	0.9	1.0	0.7
	Sp.16	22.4	11.4	1.0	0.4	0.6	0.4
	Su.16	8.3	3.0	1.1	0.5	2.8	0.4

Appendix 4.8. Summary of the PERMANOVA pair-wise analysis for between reach differences in macroinvertebrate community structural univariate metrics. Reaches compared seasonally. Bold font indicates significant (P<0.05) differences.

Community metrics	Seasons	PERMANOVA results			
Total Density	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	10.369	0.0026	462
		Degraded, Rehabilitated	5.7018	0.0015	461
		Natural, Rehabilitated	20.103	0.0028	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.559	0.0015	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.6653	0.0025	462
		Degraded, Rehabilitated	11.923	0.0015	446
		Natural, Rehabilitated	16.077	0.0018	461
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.1287	0.0002	8073
		Degraded, Rehabilitated	3.5995	0.0036	8057
		Natural, Rehabilitated	11.637	0.0001	8058
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	20.883	0.0001	8078
		Degraded, Rehabilitated	0.89745	0.4947	8171
		Natural, Rehabilitated	7.4097	0.0006	7927
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.3274	0.0001	9821
		Degraded, Rehabilitated	0.05910	0.9533	9791
		Natural, Rehabilitated	7.7715	0.0001	9802
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.1886	0.2127	462
		Degraded, Rehabilitated	1.1168	0.2623	462
		Natural, Rehabilitated	0.0905	0.9257	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.39	0.0021	461
		Degraded, Rehabilitated	2.5032	0.0307	460
		Natural, Rehabilitated	5.8018	0.0012	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	21.083	0.0024	461
		Degraded, Rehabilitated	3.5457	0.0022	462
		Natural, Rehabilitated	3.9253	0.0136	462
Total Biomass	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	17.01	0.0019	461
		Degraded, Rehabilitated	0.04212	0.9732	462
		Natural, Rehabilitated	8.906	0.0026	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.7859	0.0217	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.7787	0.0217	462
		Degraded, Rehabilitated	5.0997	0.0021	461
		Natural, Rehabilitated	13.932	0.0012	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	16.14	0.0001	8063
		Degraded, Rehabilitated	0.10949	0.9055	8085
		Natural, Rehabilitated	15.275	0.0001	8061
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.8879	0.0287	462
		Degraded, Rehabilitated	1.4511	0.1823	462
		Natural, Rehabilitated	2.1234	0.00527	461

	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.883	0.0001	9805
		Degraded, Rehabilitated	2.5641	0.0171	9801
		Natural, Rehabilitated	6.3884	0.0001	9798
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.1451	0.0043	460
		Degraded, Rehabilitated	3.0755	0.0156	462
		Natural, Rehabilitated	0.43585	0.6832	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	17.177	0.0033	458
		Degraded, Rehabilitated	13.416	0.002	462
		Natural, Rehabilitated	4.6582	0.0043	461
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.4718	0.006	462
		Degraded, Rehabilitated	3.1751	0.0131	462
		Natural, Rehabilitated	0.44559	0.6987	462
Taxa Richness	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	14.259	0.0016	462
		Degraded, Rehabilitated	1.3148	0.2224	462
		Natural, Rehabilitated	17.174	0.0017	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.9013	0.0019	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	21.818	0.002	460
		Degraded, Rehabilitated	11.059	0.002	462
		Natural, Rehabilitated	5.7694	0.0021	460
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.149	0.0001	8088
		Degraded, Rehabilitated	8.607	0.0003	8082
		Natural, Rehabilitated	3.7819	0.0016	8131
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	13.324	0.0002	8071
		Degraded, Rehabilitated	6.5198	0.0002	8122
		Natural, Rehabilitated	2.8797	0.0121	8158
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	21.091	0.0001	9706
		Degraded, Rehabilitated	11.845	0.0001	9779
		Natural, Rehabilitated	2.6426	0.0164	9793
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	23.418	0.0017	439
		Degraded, Rehabilitated	14.321	0.0025	462
		Natural, Rehabilitated	4.0266	0.006	461
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.64	0.0022	461
		Degraded, Rehabilitated	16.324	0.0025	461
		Natural, Rehabilitated	0.06559	0.9477	459
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	10.212	0.0024	460
		Degraded, Rehabilitated	8.7602	0.0021	462
		Natural, Rehabilitated	0.23668	0.8103	461
Taxa Diversity	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.106	0.0015	462
		Degraded, Rehabilitated	0.10498	0.9458	461
		Natural, Rehabilitated	19.376	0.0024	460
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.9763	0.0015	462

	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	16.385	0.0029	460
		Degraded, Rehabilitated	4.4993	0.0059	461
		Natural, Rehabilitated	8.5993	0.0024	461
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.973	0.0002	8049
		Degraded, Rehabilitated	7.6256	0.0001	8099
		Natural, Rehabilitated	5.8207	0.0002	8067
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.0254	0.0001	4321
		Degraded, Rehabilitated	6.6449	0.0001	8086
		Natural, Rehabilitated	0.68931	0.4987	2881
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.1973	0.0001	9808
		Degraded, Rehabilitated	6.8162	0.0001	9793
		Natural, Rehabilitated	2.256	0.0285	9806
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	16.971	0.002	460
		Degraded, Rehabilitated	14.574	0.0018	460
		Natural, Rehabilitated	4.4046	0.0022	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	9.0647	0.0021	461
		Degraded, Rehabilitated	13.423	0.0021	462
		Natural, Rehabilitated	1.6262	0.1289	461
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.6331	0.0087	462
		Degraded, Rehabilitated	9.9079	0.0029	461
		Natural, Rehabilitated	6.8136	0.0016	462
Evenness	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.4796	0.0021	462
		Degraded, Rehabilitated	1.8349	0.0904	461
		Natural, Rehabilitated	14.731	0.0021	459
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.9225	0.00793	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	9.2775	0.0026	462
		Degraded, Rehabilitated	4.1809	0.0066	461
		Natural, Rehabilitated	4.0721	0.0018	461
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.8902	0.0001	8009
		Degraded, Rehabilitated	4.3065	0.0001	8075
		Natural, Rehabilitated	2.0725	0.0517	8098
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.7174	0.0035	4271
		Degraded, Rehabilitated	3.7587	0.0013	8019
		Natural, Rehabilitated	0.95119	0.3514	2891
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.42944	0.6703	9799
		Degraded, Rehabilitated	5.8181	0.0001	9786
		Natural, Rehabilitated	5.1981	0.0002	9788
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.6693	0.0019	462
		Degraded, Rehabilitated	5.8353	0.0026	462
		Natural, Rehabilitated	2.8158	0.0226	461
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.1426	0.0021	462

		Degraded, Rehabilitated	7.0026	0.0022	462
		Natural, Rehabilitated	4.0097	0.0016	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.2652	0.0509	462
		Degraded, Rehabilitated	11.884	0.0021	461
		Natural, Rehabilitated	9.252	0.0024	462
EPT Richness	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.8381	0.0033	462
		Degraded, Rehabilitated	0.77586	0.4434	462
		Natural, Rehabilitated	8.9786	0.0025	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.486	0.0028	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	9.6378	0.0012	462
		Degraded, Rehabilitated	6.6843	0.0024	462
		Natural, Rehabilitated	6.9159	0.0016	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.5191	0.0001	8077
		Degraded, Rehabilitated	5.4057	0.0002	8103
		Natural, Rehabilitated	0.97292	0.3465	8096
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.6794	0.0002	4344
		Degraded, Rehabilitated	2.3816	0.0169	462
		Natural, Rehabilitated	8.602	0.0001	4293
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.5973	0.0001	3429
		Degraded, Rehabilitated	4.0557	0.0003	3424
		Natural, Rehabilitated	7.9398	0.0001	9777
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	9.507	0.002	63
		Degraded, Rehabilitated	4.8204	0.0045	63
		Natural, Rehabilitated	3.6455	0.0019	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.1795	0.0013	462
		Degraded, Rehabilitated	7.959	0.0021	462
		Natural, Rehabilitated	0.20935	0.8384	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.8403	0.0028	462
		Degraded, Rehabilitated	4.3445	0.0019	461
		Natural, Rehabilitated	5.2321	0.0027	462
EPT Diversity	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.917	0.0027	462
		Degraded, Rehabilitated	0.52607	0.6056	462
		Natural, Rehabilitated	10.23	0.0024	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.7714	0.0012	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.856	0.002	462
		Degraded, Rehabilitated	5.9354	0.0018	462
		Natural, Rehabilitated	6.5588	0.002	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.6745	0.0001	8104
		Degraded, Rehabilitated	6.7983	0.0003	8073
		Natural, Rehabilitated	2.1447	0.0433	8037
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.129	0.0001	6227

		Degraded, Rehabilitated	5.0457	0.0002	6220
		Natural, Rehabilitated	5.3673	0.0004	8140
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	17.962	0.0001	3431
		Degraded, Rehabilitated	6.5707	0.0001	3419
		Natural, Rehabilitated	6.6839	0.0001	9785
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	9.3034	0.0023	63
		Degraded, Rehabilitated	7.4406	0.0024	63
		Natural, Rehabilitated	4.4497	0.002	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.4277	0.0022	462
		Degraded, Rehabilitated	14.522	0.0023	459
		Natural, Rehabilitated	2.9514	0.0207	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.4463	0.0022	462
		Degraded, Rehabilitated	4.5259	0.0027	462
		Natural, Rehabilitated	1.4341	0.1888	462
EPT Count%	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.629	0.0028	462
		Degraded, Rehabilitated	2.3385	0.0634	460
		Natural, Rehabilitated	17.183	0.0019	461
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	14.844	0.0022	461
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	22.006	0.0019	460
		Degraded, Rehabilitated	7.897	0.0025	462
		Natural, Rehabilitated	7.4811	0.0021	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.073	0.0002	8105
		Degraded, Rehabilitated	5.5662	0.0002	8088
		Natural, Rehabilitated	8.9976	0.0002	8084
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.6769	0.0003	4299
		Degraded, Rehabilitated	4.6466	0.0004	8096
		Natural, Rehabilitated	2.1647	0.0622	4305
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.924	0.0001	8122
		Degraded, Rehabilitated	11.763	0.0001	8106
		Natural, Rehabilitated	1.1356	0.2625	9766
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	10.414	0.0022	336
		Degraded, Rehabilitated	8.3182	0.0024	335
		Natural, Rehabilitated	4.2318	0.0043	460
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.5594	0.0023	462
		Degraded, Rehabilitated	6.7174	0.0028	460
		Natural, Rehabilitated	6.5368	0.0018	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.792	0.0025	461
		Degraded, Rehabilitated	10.675	0.0029	462
		Natural, Rehabilitated	3.328	0.0062	462
Chironomidae Count%	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.998	0.0024	459
		Degraded, Rehabilitated	0.4688	0.6815	462
		Natural, Rehabilitated	15.025	0.0029	462

	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.5434	0.1546	461
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.5138	0.0028	449
		Degraded, Rehabilitated	0.71685	0.4918	462
		Natural, Rehabilitated	3.8175	0.0047	451
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.961	0.0002	8067
		Degraded, Rehabilitated	6.5678	0.0001	8078
		Natural, Rehabilitated	4.0121	0.0014	8077
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.51754	0.6151	4272
		Degraded, Rehabilitated	2.0318	0.0683	4332
		Natural, Rehabilitated	1.9277	0.1306	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.388	0.0001	9806
		Degraded, Rehabilitated	10.698	0.0001	9784
		Natural, Rehabilitated	3.0526	0.0078	9789
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.3211	0.0041	461
		Degraded, Rehabilitated	2.6463	0.0245	462
		Natural, Rehabilitated	0.22318	0.826	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.566	0.0028	460
		Degraded, Rehabilitated	14.662	0.0021	459
		Natural, Rehabilitated	2.0982	0.0722	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.905	0.0136	462
		Degraded, Rehabilitated	9.2639	0.0033	461
		Natural, Rehabilitated	9.5517	0.0025	462
EPT Biomass%	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.533	0.0127	461
		Degraded, Rehabilitated	0.06119	0.9278	462
		Natural, Rehabilitated	6.8344	0.0012	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.2881	0.0013	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.1929	0.003	461
		Degraded, Rehabilitated	3.7032	0.009	462
		Natural, Rehabilitated	0.5811	0.6097	461
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.388	0.0007	8113
		Degraded, Rehabilitated	3.1513	0.0067	8133
		Natural, Rehabilitated	1.2791	0.2152	8157
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	10.76	0.0002	4287
		Degraded, Rehabilitated	9.2035	0.0003	4317
		Natural, Rehabilitated	1.1485	0.2832	461
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	13.457	0.0001	8117
		Degraded, Rehabilitated	6.3606	0.0001	8157
		Natural, Rehabilitated	2.1131	0.0502	9819
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.9518	0.0019	336
		Degraded, Rehabilitated	4.3202	0.002	336
		Natural, Rehabilitated	2.3247	0.0507	462

	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.8012	0.0139	462
		Degraded, Rehabilitated	5.0864	0.0025	462
		Natural, Rehabilitated	1.7723	0.1263	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.8967	0.0023	462
		Degraded, Rehabilitated	6.8125	0.0029	460
		Natural, Rehabilitated	2.1448	0.0579	462
Chironomidae Biomass%	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.4562	0.0026	460
		Degraded, Rehabilitated	1.1464	0.2877	462
		Natural, Rehabilitated	5.7692	0.0025	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.6713	0.0137	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.0652	0.0017	462
		Degraded, Rehabilitated	1.3822	0.1918	462
		Natural, Rehabilitated	5.9237	0.0014	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.984	0.0001	8152
		Degraded, Rehabilitated	4.8848	0.0003	8081
		Natural, Rehabilitated	4.8976	0.0007	8014
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.3114	0.0014	4261
		Degraded, Rehabilitated	3.4745	0.0107	462
		Natural, Rehabilitated	0.3541	0.7315	4260
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.1146	0.0001	9798
		Degraded, Rehabilitated	6.4757	0.0001	9806
		Natural, Rehabilitated	1.0258	0.3128	9800
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	9.1986	0.0034	462
		Degraded, Rehabilitated	7.7419	0.002	462
		Natural, Rehabilitated	0.3271	0.6852	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	10.76	0.0013	462
		Degraded, Rehabilitated	11.921	0.0023	462
		Natural, Rehabilitated	2.1455	0.0561	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.6337	0.0022	462
		Degraded, Rehabilitated	8.3891	0.0032	462
		Natural, Rehabilitated	5.5704	0.0028	461

Appendix 4.9. Summary of PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate community structural and functional univariate metrics for each reach separately. Bold font indicates significant (P<0.05) differences.

Degraded reach seasonal differences				Natural reach seasonal differences				Rehabilitated reach seasonal differences			
Total Density (individual m^{-2})				**Total Density (individual m^{-2})**				**Total Density (individual m^{-2})**			
Seasons	t	*P*(perm)	Unique perms	Seasons	t	*P*(perm)	Unique perms	Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	1.0644	0.2814	461	Sp.14, Su.14	16.158	0.0028	461				
Sp.14, Wi.15	2.6825	0.0232	462	Sp.14, Wi.15	16.161	0.0024	459	Sp.14, Wi.15	7.5906	0.0023	462
Sp.14, Sp.15	1.5312	0.1489	4309	Sp.14, Sp.15	0.43179	0.6848	4208	Sp.14, Sp.15	2.6826	**0.0159**	4308
Sp.14, Su.15	5.6221	0.0008	4323	Sp.14, Su.15	17.943	0.0004	4330	Sp.14, Su.15	5.7991	0.0002	4309
Sp.14, Au.15	0.74924	0.4833	7661	Sp.14, Au.15	2.6307	0.0181	7624	Sp.14, Au.15	5.6962	0.0001	7656
Sp.14, Wi.16	1.0094	0.3098	462	Sp.14, Wi.16	17.465	0.0028	462	Sp.14, Wi.16	2.6755	0.0283	461
Sp.14, Sp.16	0.096512	0.9426	462	Sp.14, Sp.16	0.89428	0.386	462	Sp.14, Sp.16	8.3392	**0.0016**	462
Sp.14, Su.16	2.1053	0.0684	461	Sp.14, Su.16	19.1	0.0019	462	Sp.14, Su.16	7.1398	0.0023	462
Su.14, Wi.15	1.1592	0.2967	462	Su.14, Wi.15	29.894	0.0017	458				
Su.14, Sp.15	0.22962	0.8264	4295	Su.14, Sp.15	14.296	0.0002	4286				
Su.14, Su.15	1.5081	0.1595	4311	Su.14, Su.15	1.6887	0.1136	4316				
Su.14, Au.15	0.33206	0.7467	7627	Su.14, Au.15	1.3516	0.2051	7559				
Su.14, Wi.16	0.51956	0.5846	462	Su.14, Wi.16	32.341	0.0021	462				
Su.14, Sp.16	0.92072	0.3879	462	Su.14, Sp.16	12.92	0.0021	461				
Su.14, Su.16	0.32901	0.8148	461	Su.14, Su.16	0.070089	0.9305	458				
Wi.15, Sp.15	1.1389	0.2687	4314	Wi.15, Sp.15	13.655	0.0003	4306	Wi.15, Sp.15	8.0658	0.0003	4308
Wi.15, Su.15	1.1837	0.2571	4269	Wi.15, Su.15	32.521	0.0002	4283	Wi.15, Su.15	8.6094	0.0002	4241
Wi.15, Au.15	1.6502	0.1205	7680	Wi.15, Au.15	6.7002	0.0002	7590	Wi.15, Au.15	10.964	0.0001	7599
Wi.15, Wi.16	0.036648	0.9746	461	Wi.15, Wi.16	0.50963	0.6043	462	Wi.15, Wi.16	6.0068	**0.0017**	462
Wi.15, Sp.16	2.3814	0.028	462	Wi.15, Sp.16	14.692	0.0024	460	Wi.15, Sp.16	14.734	0.0023	462
Wi.15, Su.16	1.1607	0.2821	462	Wi.15, Su.16	34.264	0.003	460	Wi.15, Su.16	9.9438	0.0026	462
Sp.15, Su.15	2.8161	0.0107	8053	Sp.15, Su.15	17.45	0.0001	8151	Sp.15, Su.15	4.972	0.0002	8097
Sp.15, Au.15	0.6665	0.5183	9660	Sp.15, Au.15	3.3456	0.0037	9651	Sp.15, Au.15	3.1495	0.0074	9692
Sp.15, Wi.16	0.52052	0.5995	4255	Sp.15, Wi.16	13.893	0.0003	4312	Sp.15, Wi.16	1.0441	0.3016	4279
Sp.15, Sp.16	1.3532	0.19	4276	Sp.15, Sp.16	1.2047	0.2471	4320	Sp.15, Sp.16	4.7513	**0.0011**	4299
Sp.15, Su.16	0.10329	0.9179	4281	Sp.15, Su.16	15.33	0.0003	4327	Sp.15, Su.16	6.3656	0.0003	4270
Su.15, Au.15	3.3037	0.0046	9683	Su.15, Au.15	2.1895	0.0416	9658	Su.15, Au.15	3.3934	0.0004	9723
Su.15, Wi.16	0.5228	0.5956	4302	Su.15, Wi.16	34.103	0.0002	4308	Su.15, Wi.16	3.0168	0.0006	4285
Su.15, Sp.16	4.8423	0.0004	4299	Su.15, Sp.16	15.205	0.0001	4206	Su.15, Sp.16	1.507	0.1316	4314
Su.15, Su.16	1.8951	0.0797	4336	Su.15, Su.16	1.9221	0.081	4298	Su.15, Su.16	1.2363	0.2586	4264
Au.15, Wi.16	0.90575	0.3736	7665	Au.15, Wi.16	6.5915	0.0001	7569	Au.15, Wi.16	1.115	0.2847	7515
Au.15, Sp.16	0.64364	0.5413	7661	Au.15, Sp.16	2.3733	0.0331	7558	Au.15, Sp.16	1.9257	0.0747	7617
Au.15, Su.16	0.7232	0.4827	7593	Au.15, Su.16	1.3412	0.2148	7593	Au.15, Su.16	4.9911	0.0001	7614
Wi.16, Sp.16	0.96229	0.329	460	Wi.16, Sp.16	15.416	0.0015	461	Wi.16, Sp.16	2.1692	0.0628	462
Wi.16, Su.16	0.40576	0.7082	461	Wi.16, Su.16	38.366	0.0031	462	Wi.16, Su.16	3.9805	0.002	461
Sp.16, Su.16	1.7126	0.1285	462	Sp.16, Su.16	14.479	0.0023	462	Sp.16, Su.16	2.8874	0.0069	462

Total Biomass (mgDM m^{-2})			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	3.088	0.0068	460
Sp.14, Wi.15	0.81231	0.5882	462
Sp.14, Sp.15	0.50505	0.6376	4295
Sp.14, Su.15	9.735	0.0019	462
Sp.14, Au.15	3.4824	0.0034	7604
Sp.14, Wi.16	0.90767	0.3861	461
Sp.14, Sp.16	1.1844	0.289	461
Sp.14, Su.16	6.1054	0.0014	462
Su.14, Wi.15	2.1098	0.0556	462
Su.14, Sp.15	3.0532	0.0047	4276
Su.14, Su.15	1.131	0.2853	461
Su.14, Au.15	0.36528	0.721	7637
Su.14, Wi.16	3.2231	0.0099	462
Su.14, Sp.16	3.4758	0.0054	462
Su.14, Su.16	0.78587	0.4471	462
Wi.15, Sp.15	0.42891	0.6776	4299
Wi.15, Su.15	4.5273	0.0058	462
Wi.15, Au.15	2.3845	0.031	7613
Wi.15, Wi.16	1.2903	0.2471	462
Wi.15, Sp.16	1.4154	0.1751	462
Wi.15, Su.16	3.7271	0.0085	462
Sp.15, Su.15	6.6117	0.0003	1982
Sp.15, Au.15	3.4626	0.0029	9684
Sp.15, Wi.16	1.2332	0.2344	4292
Sp.15, Sp.16	1.3415	0.2025	4296
Sp.15, Su.16	5.341	0.0001	4262
Su.15, Au.15	1.8881	0.0794	4937
Su.15, Wi.16	6.6102	0.0043	461
Su.15, Sp.16	9.2425	0.0027	462
Su.15, Su.16	0.49866	0.6213	462
Au.15, Wi.16	3.8139	0.0025	7601
Au.15, Sp.16	4.0202	0.0017	7598
Au.15, Su.16	1.461	0.1616	7628
Wi.16, Sp.16	0.12383	0.9046	462
Wi.16, Su.16	5.3802	0.0019	462
Sp.16, Su.16	6.4128	0.0026	462

Total Biomass (mgDM m^{-2})			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	2.5849	0.0335	461
Sp.14, Wi.15	8.5722	0.0021	457
Sp.14, Sp.15	0.98966	0.3411	4278
Sp.14, Su.15	1.4287	0.1716	462
Sp.14, Au.15	2.6416	0.0187	7650
Sp.14, Wi.16	8.241	0.0016	461
Sp.14, Sp.16	1.7901	0.0995	461
Sp.14, Su.16	0.17874	0.8617	462
Su.14, Wi.15	6.9349	0.0022	461
Su.14, Sp.15	4.7169	0.0007	4282
Su.14, Su.15	0.55015	0.6029	462
Su.14, Au.15	3.7066	0.0032	7625
Su.14, Wi.16	6.552	0.0015	462
Su.14, Sp.16	4.5173	0.0047	462
Su.14, Su.16	1.115	0.2847	462
Wi.15, Sp.15	12.529	0.0002	4285
Wi.15, Su.15	5.8311	0.0027	461
Wi.15, Au.15	6.574	0.0001	7685
Wi.15, Wi.16	0.46448	0.6377	462
Wi.15, Sp.16	10.187	0.0024	461
Wi.15, Su.16	9.4154	0.0021	459
Sp.15, Su.15	2.6909	0.0206	4288
Sp.15, Au.15	2.8887	0.0106	9654
Sp.15, Wi.16	12.136	0.0003	4266
Sp.15, Sp.16	1.4591	0.1664	4300
Sp.15, Su.16	1.4009	0.1841	4311
Su.15, Au.15	3.334	0.0048	7607
Su.15, Wi.16	5.4987	0.0029	461
Su.15, Sp.16	2.909	0.0215	462
Su.15, Su.16	1.4079	0.183	462
Au.15, Wi.16	6.3661	0.0001	7656
Au.15, Sp.16	1.8379	0.081	7638
Au.15, Su.16	2.739	0.0151	7654
Wi.16, Sp.16	9.8858	0.0021	461
Wi.16, Su.16	9.0831	0.0025	462
Sp.16, Su.16	2.1936	0.0624	462

Total Biomass (mgDM m^{-2})			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Wi.15	4.161	0.0016	462
Sp.14, Sp.15	0.38985	0.6882	4315
Sp.14, Su.15	6.6376	0.0021	462
Sp.14, Au.15	5.7108	0.0001	7640
Sp.14, Wi.16	2.32	0.0456	461
Sp.14, Sp.16	7.3531	**0.0016**	462
Sp.14, Su.16	6.5543	0.002	462
Wi.15, Sp.15	6.1256	0.0004	4287
Wi.15, Su.15	24.69	0.0026	457
Wi.15, Au.15	12.083	0.0001	7604
Wi.15, Wi.16	6.512	**0.0023**	462
Wi.15, Sp.16	24.063	0.0021	460
Wi.15, Su.16	11.741	0.0024	462
Sp.15, Su.15	8.3189	0.0003	4258
Sp.15, Au.15	6.7637	0.0002	9678
Sp.15, Wi.16	2.6324	0.0211	4339
Sp.15, Sp.16	9.2572	**0.0002**	4269
Sp.15, Su.16	8.0799	0.0004	4260
Su.15, Au.15	0.94262	0.3654	7637
Su.15, Wi.16	2.8173	0.0155	452
Su.15, Sp.16	1.611	0.1282	462
Su.15, Su.16	2.5341	**0.027**	461
Au.15, Wi.16	2.2575	0.0357	7710
Au.15, Sp.16	1.9594	0.0717	7601
Au.15, Su.16	3.4112	0.0039	7700
Wi.16, Sp.16	3.5125	0.0064	462
Wi.16, Su.16	3.9643	0.005	462
Sp.16, Su.16	1.7752	0.1112	462

Taxa Richness

Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	2.3335	0.0401	462
Sp.14, Wi.15	5.2202	0.0033	462
Sp.14, Sp.15	0.17631	0.8584	4273
Sp.14, Su.15	0.68244	0.5154	4319
Sp.14, Au.15	3.5938	0.0036	7563
Sp.14, Wi.16	5.8387	0.0026	461
Sp.14, Sp.16	1.0126	0.3367	461
Sp.14, Su.16	2.1357	0.0415	462
Su.14, Wi.15	8.4978	0.0023	462
Su.14, Sp.15	2.7718	0.0176	4285
Su.14, Su.15	2.0103	0.0683	4287
Su.14, Au.15	5.9941	0.0002	7685
Su.14, Wi.16	8.724	0.0018	461
Su.14, Sp.16	3.7055	0.0067	462
Su.14, Su.16	0.40906	0.6793	461
Wi.15, Sp.15	5.5247	0.0003	4272
Wi.15, Su.15	6.8616	0.0002	4298
Wi.15, Au.15	1.1337	0.2706	7572
Wi.15, Wi.16	1.303	0.2208	461
Wi.15, Sp.16	4.6879	0.0047	462
Wi.15, Su.16	8.9281	0.0022	461
Sp.15, Su.15	0.97913	0.3441	8086
Sp.15, Au.15	4.0247	0.0012	9674
Sp.15, Wi.16	6.3631	0.0002	4310
Sp.15, Sp.16	0.92956	0.3613	4338
Sp.15, Su.16	2.5261	0.0259	4294
Su.15, Au.15	5.0292	0.0001	9656
Su.15, Wi.16	7.5988	0.0005	4303
Su.15, Sp.16	1.9269	0.0769	4310
Su.15, Su.16	1.7101	0.1182	4296
Au.15, Wi.16	2.2267	0.0419	7615
Au.15, Sp.16	2.7649	0.0176	7624
Au.15, Su.16	5.8329	0.0001	7676
Wi.16, Sp.16	5.3684	0.0024	460
Wi.16, Su.16	9.0151	0.0015	462
Sp.16, Su.16	3.6313	0.0068	462

Taxa Richness

Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	3.4738	0.0075	462
Sp.14, Wi.15	2.3819	0.0428	462
Sp.14, Sp.15	0.94525	0.3615	4288
Sp.14, Su.15	6.6387	0.0002	4271
Sp.14, Au.15	3.6956	0.0013	7634
Sp.14, Wi.16	1.9054	0.085	462
Sp.14, Sp.16	1.7213	0.1141	462
Sp.14, Su.16	4.5373	0.0054	462
Su.14, Wi.15	5.0581	0.0025	462
Su.14, Sp.15	1.5397	0.1482	4321
Su.14, Su.15	1.1406	0.274	4334
Su.14, Au.15	1.6729	0.1158	7652
Su.14, Wi.16	5.0615	0.0027	461
Su.14, Sp.16	1.2174	0.2505	462
Su.14, Su.16	0.31014	0.7695	460
Wi.15, Sp.15	2.5638	0.0266	4309
Wi.15, Su.15	8.3615	0.0004	4286
Wi.15, Au.15	6.359	0.0001	7674
Wi.15, Wi.16	0.88018	0.4061	462
Wi.15, Sp.16	3.411	0.0102	462
Wi.15, Su.16	6.0562	0.0027	461
Sp.15, Su.15	2.8576	0.0076	8148
Sp.15, Au.15	1.0248	0.315	9709
Sp.15, Wi.16	2.0796	0.0637	4296
Sp.15, Sp.16	0.44302	0.6564	4240
Sp.15, Su.16	1.851	0.0872	4311
Su.15, Au.15	4.2778	0.0013	9679
Su.15, Wi.16	9.1154	0.0003	4321
Su.15, Sp.16	2.7147	0.0144	4314
Su.15, Su.16	0.89468	0.3905	4276
Au.15, Wi.16	6.2927	0.0003	7671
Au.15, Sp.16	0.39729	0.6966	7648
Au.15, Su.16	2.4601	0.0258	7653
Wi.16, Sp.16	3.1061	0.0138	458
Wi.16, Su.16	6.4838	0.0022	461
Sp.16, Su.16	1.6289	0.134	462

Taxa Richness

Seasons	t	*P*(perm)	Unique perms
Sp.14, Wi.15	6.041	0.0024	461
Sp.14, Sp.15	6.9633	**0.0004**	4296
Sp.14, Su.15	5.4509	0.0002	4278
Sp.14, Au.15	6.0477	0.0001	7646
Sp.14, Wi.16	9.1034	0.0025	462
Sp.14, Sp.16	16.108	**0.0019**	460
Sp.14, Su.16	10.151	0.0024	462
Wi.15, Sp.15	0.27178	0.7866	4259
Wi.15, Su.15	0.96364	0.3495	4302
Wi.15, Au.15	0.54918	0.5865	7643
Wi.15, Wi.16	1.7522	0.1131	462
Wi.15, Sp.16	3.0227	0.0166	462
Wi.15, Su.16	1.2631	0.2234	462
Sp.15, Su.15	0.86403	0.3969	8084
Sp.15, Au.15	0.95297	0.3516	9688
Sp.15, Wi.16	2.4295	0.0275	4290
Sp.15, Sp.16	4.0037	**0.003**	4309
Sp.15, Su.16	1.854	0.0877	4332
Su.15, Au.15	1.6765	0.111	9689
Su.15, Wi.16	3.0127	0.0128	4315
Su.15, Sp.16	4.5035	0.0017	4274
Su.15, Su.16	2.5173	**0.0277**	4288
Au.15, Wi.16	1.1894	0.25	7642
Au.15, Sp.16	2.0723	0.0545	7672
Au.15, Su.16	0.60339	0.5646	7638
Wi.16, Sp.16	0.97754	0.3426	462
Wi.16, Su.16	0.74174	0.4705	461
Sp.16, Su.16	2.2556	0.0708	462

Taxa Diversity			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	1.7371	0.0623	462
Sp.14, Wi.15	2.8131	0.0231	462
Sp.14, Sp.15	0.51713	0.6151	4309
Sp.14, Su.15	0.78775	0.4895	4293
Sp.14, Au.15	0.35269	0.7386	7581
Sp.14, Wi.16	3.3567	0.0078	462
Sp.14, Sp.16	0.27596	0.7119	462
Sp.14, Su.16	2.0767	0.0352	462
Su.14, Wi.15	5.7145	0.0021	461
Su.14, Sp.15	2.8711	0.0105	4285
Su.14, Su.15	1.5075	0.1515	4292
Su.14, Au.15	2.2871	0.0369	7556
Su.14, Wi.16	6.8816	0.0019	462
Su.14, Sp.16	2.1254	0.0401	462
Su.14, Su.16	0.72948	0.5049	462
Wi.15, Sp.15	3.001	0.0133	4284
Wi.15, Su.15	4.8103	0.0005	4309
Wi.15, Au.15	4.7239	0.0004	7598
Wi.15, Wi.16	0.41812	0.6756	461
Wi.15, Sp.16	2.5548	0.0332	462
Wi.15, Su.16	5.5997	0.0016	462
Sp.15, Su.15	1.7011	0.1062	7983
Sp.15, Au.15	1.2258	0.2366	9658
Sp.15, Wi.16	3.6614	0.0049	4263
Sp.15, Sp.16	0.17495	0.8625	4282
Sp.15, Su.16	3.2279	0.0042	4313
Su.15, Au.15	0.72052	0.4808	9639
Su.15, Wi.16	5.7133	0.0004	4325
Su.15, Sp.16	1.1816	0.2688	4288
Su.15, Su.16	2.0406	0.0607	4289
Au.15, Wi.16	5.6241	0.0003	7610
Au.15, Sp.16	0.78074	0.4637	7620
Au.15, Su.16	2.8246	0.0103	7617
Wi.16, Sp.16	3.0937	0.0196	462
Wi.16, Su.16	6.5258	0.002	460
Sp.16, Su.16	2.4284	0.0224	462

Taxa Diversity			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	11.76	0.0026	461
Sp.14, Wi.15	0.66655	0.5074	462
Sp.14, Sp.15	0.70548	0.495	4294
Sp.14, Su.15	12.717	0.002	462
Sp.14, Au.15	8.2393	0.0001	7661
Sp.14, Wi.16	2.0424	0.0753	462
Sp.14, Sp.16	0.12355	0.9085	462
Sp.14, Su.16	8.3648	0.0021	461
Su.14, Wi.15	11.595	0.0026	462
Su.14, Sp.15	6.0625	0.0002	4266
Su.14, Su.15	0.46232	0.633	462
Su.14, Au.15	0.66094	0.5355	7630
Su.14, Wi.16	9.65	0.0024	462
Su.14, Sp.16	5.8598	0.0017	462
Su.14, Su.16	0.44898	0.6633	462
Wi.15, Sp.15	1.1603	0.2641	4317
Wi.15, Su.15	12.408	0.0019	461
Wi.15, Au.15	8.6427	0.0001	7632
Wi.15, Wi.16	1.4988	0.1679	461
Wi.15, Sp.16	0.52693	0.6138	462
Wi.15, Su.16	8.592	0.0023	461
Sp.15, Su.15	6.3012	0.0006	4300
Sp.15, Au.15	6.9835	0.0001	9650
Sp.15, Wi.16	2.3342	0.037	4284
Sp.15, Sp.16	0.45231	0.6659	4298
Sp.15, Su.16	5.7177	0.0002	4256
Su.15, Au.15	0.46649	0.6802	7633
Su.15, Wi.16	10.04	0.002	461
Su.15, Sp.16	6.09	0.0028	462
Su.15, Su.16	0.23001	0.8027	462
Au.15, Wi.16	9.2471	0.0002	7610
Au.15, Sp.16	6.4627	0.0002	7624
Au.15, Su.16	0.23591	0.8186	7696
Wi.16, Sp.16	1.57	0.1418	462
Wi.16, Su.16	8.2675	0.0023	462
Sp.16, Su.16	5.3881	0.0023	462

Taxa Diversity			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	2.0326	0.0788	461
Sp.14, Sp.15	7.1819	**0.0005**	4269
Sp.14, Su.15	6.9731	0.0007	2865
Sp.14, Au.15	5.128	0.0002	7607
Sp.14, Wi.16	13.069	0.0015	461
Sp.14, Sp.16	23.478	**0.0031**	461
Sp.14, Su.16	15.891	0.0019	462
Wi.15, Sp.15	3.2129	0.0069	4271
Wi.15, Su.15	3.3548	0.0072	2891
Wi.15, Au.15	3.4163	0.0027	7625
Wi.15, Wi.16	5.9354	**0.0022**	462
Wi.15, Sp.16	9.8952	0.0024	462
Wi.15, Su.16	7.5128	0.003	462
Sp.15, Su.15	0.5574	0.5829	8115
Sp.15, Au.15	1.6746	0.1125	9682
Sp.15, Wi.16	3.9721	0.0014	4330
Sp.15, Sp.16	9.1928	**0.0005**	4325
Sp.15, Su.16	6.103	0.0002	4338
Su.15, Au.15	1.2077	0.2576	9501
Su.15, Wi.16	3.0309	0.0136	2887
Su.15, Sp.16	7.6028	0.0008	2889
Su.15, Su.16	4.9357	**0.001**	2876
Au.15, Wi.16	0.72654	0.477	7585
Au.15, Sp.16	3.1766	0.0069	7561
Au.15, Su.16	1.8556	0.0835	7680
Wi.16, Sp.16	5.7228	0.0016	462
Wi.16, Su.16	2.2848	0.0532	462
Sp.16, Su.16	3.0921	0.0137	462

Evenness			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	0.4274	0.8817	462
Sp.14, Wi.15	2.9766	0.011	462
Sp.14, Sp.15	0.77176	0.4183	4280
Sp.14, Su.15	0.10848	0.9055	4300
Sp.14, Au.15	0.10169	0.9172	7594
Sp.14, Wi.16	1.4897	0.1648	461
Sp.14, Sp.16	0.2274	0.6661	462
Sp.14, Su.16	0.49178	0.8289	462
Su.14, Wi.15	4.7087	0.0018	462
Su.14, Sp.15	1.5224	0.16	4209
Su.14, Su.15	0.77316	0.5276	4305
Su.14, Au.15	0.58788	0.5836	7630
Su.14, Wi.16	2.2644	0.0566	462
Su.14, Sp.16	0.75435	0.6295	462
Su.14, Su.16	0.16015	0.8881	462
Wi.15, Sp.15	2.775	0.0168	4303
Wi.15, Su.15	3.9186	0.0023	4241
Wi.15, Au.15	4.8864	0.0005	7594
Wi.15, Wi.16	1.1489	0.2952	462
Wi.15, Sp.16	2.7956	0.0177	462
Wi.15, Su.16	4.7314	0.0025	461
Sp.15, Su.15	0.89481	0.3906	8066
Sp.15, Au.15	1.3269	0.2097	9664
Sp.15, Wi.16	1.0987	0.29	4252
Sp.15, Sp.16	0.51002	0.6289	4267
Sp.15, Su.16	1.5905	0.1394	4278
Su.15, Au.15	0.31007	0.7655	9693
Su.15, Wi.16	1.8783	0.0859	4293
Su.15, Sp.16	0.19558	0.8377	4314
Su.15, Su.16	0.86185	0.4605	4290
Au.15, Wi.16	2.4249	0.0282	7640
Au.15, Sp.16	0.46627	0.6636	7629
Au.15, Su.16	0.69781	0.5205	7673
Wi.16, Sp.16	1.304	0.2127	461
Wi.16, Su.16	2.308	0.0468	462
Sp.16, Su.16	0.81751	0.5722	462

Evenness			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	7.5389	0.0025	462
Sp.14, Wi.15	1.119	0.2986	462
Sp.14, Sp.15	0.10024	0.9107	4262
Sp.14, Su.15	4.0834	0.0089	462
Sp.14, Au.15	5.5002	0.0002	7643
Sp.14, Wi.16	2.7427	0.0268	459
Sp.14, Sp.16	0.71059	0.4974	462
Sp.14, Su.16	7.1106	0.0019	462
Su.14, Wi.15	7.0244	0.0028	462
Su.14, Sp.15	5.7101	0.0002	4303
Su.14, Su.15	1.1883	0.2927	461
Su.14, Au.15	1.7249	0.1046	7677
Su.14, Wi.16	8.0052	0.0025	461
Su.14, Sp.16	7.4015	0.0023	462
Su.14, Su.16	0.53903	0.5915	462
Wi.15, Sp.15	1.033	0.3082	4294
Wi.15, Su.15	4.4035	0.0082	460
Wi.15, Au.15	5.9514	0.0001	7664
Wi.15, Wi.16	1.5043	0.1553	461
Wi.15, Sp.16	0.46376	0.6509	462
Wi.15, Su.16	6.6519	0.002	459
Sp.15, Su.15	3.7022	0.005	4311
Sp.15, Au.15	6.1614	0.0003	9662
Sp.15, Wi.16	2.5355	0.0259	4290
Sp.15, Sp.16	0.64642	0.5164	4282
Sp.15, Su.16	5.3036	0.0004	4248
Su.15, Au.15	2.4598	0.0265	7659
Su.15, Wi.16	5.4674	0.0024	461
Su.15, Sp.16	4.3339	0.0092	462
Su.15, Su.16	0.8033	0.503	462
Au.15, Wi.16	6.9201	0.0002	7643
Au.15, Sp.16	5.7763	0.0002	7628
Au.15, Su.16	2.0176	0.061	7720
Wi.16, Sp.16	2.0511	0.0703	462
Wi.16, Su.16	7.6713	0.0027	462
Sp.16, Su.16	7.0008	0.0025	461

Evenness			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Wi.15	3.3719	0.0164	462
Sp.14, Sp.15	6.1692	**0.0003**	4288
Sp.14, Su.15	6.543	0.0006	2900
Sp.14, Au.15	7.3232	0.0001	7604
Sp.14, Wi.16	15.872	0.0024	462
Sp.14, Sp.16	20.882	**0.0024**	461
Sp.14, Su.16	17.325	0.0025	460
Wi.15, Sp.15	1.7658	0.1	4344
Wi.15, Su.15	1.6404	0.13	2776
Wi.15, Au.15	2.7992	0.0096	7593
Wi.15, Wi.16	3.7975	**0.0023**	462
Wi.15, Sp.16	5.9479	0.0029	462
Wi.15, Su.16	4.4608	0.0013	461
Sp.15, Su.15	0.20676	0.8366	8091
Sp.15, Au.15	1.1095	0.2881	9681
Sp.15, Wi.16	2.0487	0.0633	4297
Sp.15, Sp.16	4.5205	**0.0009**	4315
Sp.15, Su.16	2.8143	0.0158	4288
Su.15, Au.15	1.3346	0.1966	9501
Su.15, Wi.16	2.5369	0.0245	2879
Su.15, Sp.16	5.3038	0.0009	2888
Su.15, Su.16	3.3915	**0.0041**	2882
Au.15, Wi.16	0.88517	0.3891	7643
Au.15, Sp.16	3.3374	0.0051	7588
Au.15, Su.16	1.6466	0.1178	7636
Wi.16, Sp.16	6.3644	0.0023	462
Wi.16, Su.16	1.9177	0.0843	458
Sp.16, Su.16	4.3904	0.0024	460

EPT Richness			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	1.9297	0.0783	461
Sp.14, Wi.15	2.6745	0.0191	462
Sp.14, Sp.15	1.1631	0.2885	4281
Sp.14, Su.15	0.79232	0.505	462
Sp.14, Au.15	2.4063	0.0193	122
Sp.14, Wi.16	4.0991	0.008	63
Sp.14, Sp.16	0.49866	0.6213	461
Sp.14, Su.16	1.6907	0.1166	461
Su.14, Wi.15	0.37751	0.6875	336
Su.14, Sp.15	0.89041	0.3872	3359
Su.14, Su.15	0.80767	0.4365	335
Su.14, Au.15	1.2649	0.1938	64
Su.14, Wi.16	2.0529	0.0731	32
Su.14, Sp.16	0.5312	0.6042	336
Su.14, Su.16	0.18213	0.8653	336
Wi.15, Sp.15	1.3962	0.1991	3347
Wi.15, Su.15	1.2117	0.2623	336
Wi.15, Au.15	1.0643	0.3503	64
Wi.15, Wi.16	1.8951	0.0797	32
Wi.15, Sp.16	0.1803	0.8681	336
Wi.15, Su.16	0.57335	0.5631	336
Sp.15, Su.15	0.12436	0.9023	3360
Sp.15, Au.15	2.1439	0.0403	503
Sp.15, Wi.16	3.2246	0.0163	459
Sp.15, Sp.16	1.56	0.1401	3360
Sp.15, Su.16	0.67182	0.5091	3337
Su.15, Au.15	1.803	0.1011	63
Su.15, Wi.16	2.6442	0.0542	32
Su.15, Sp.16	1.3395	0.2091	336
Su.15, Su.16	0.63473	0.5178	336
Au.15, Wi.16	0.14533	1	4
Au.15, Sp.16	0.96608	0.4033	64
Au.15, Su.16	1.3807	0.1751	63
Wi.16, Sp.16	1.7241	0.113	32
Wi.16, Su.16	2.2028	0.0667	32
Sp.16, Su.16	0.72224	0.4782	336

EPT Richness			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	0.44724	0.6682	462
Sp.14, Wi.15	1.8337	0.0962	462
Sp.14, Sp.15	1.115	0.2847	4277
Sp.14, Su.15	0.054068	0.9612	4334
Sp.14, Au.15	0.002384	0.9976	7639
Sp.14, Wi.16	2.8458	0.0227	462
Sp.14, Sp.16	1.5081	0.1595	462
Sp.14, Su.16	1.3007	0.2376	462
Su.14, Wi.15	2.4707	0.0433	461
Su.14, Sp.15	1.6738	0.1146	4338
Su.14, Su.15	0.58023	0.5691	4313
Su.14, Au.15	0.63445	0.5281	7692
Su.14, Wi.16	3.8006	0.0082	462
Su.14, Sp.16	1.9456	0.0721	462
Su.14, Su.16	0.91048	0.3861	462
Wi.15, Sp.15	4.4167	0.0004	4310
Wi.15, Su.15	2.6865	0.0197	4296
Wi.15, Au.15	2.6132	0.0197	7612
Wi.15, Wi.16	0.74642	0.4649	462
Wi.15, Sp.16	3.8027	0.0062	462
Wi.15, Su.16	3.4925	0.0085	462
Sp.15, Su.15	2.8011	0.0116	8081
Sp.15, Au.15	2.9373	0.0078	9676
Sp.15, Wi.16	5.9535	0.0001	4271
Sp.15, Sp.16	0.94328	0.3739	4256
Sp.15, Su.16	0.72693	0.48	4260
Su.15, Au.15	0.072702	0.944	9642
Su.15, Wi.16	4.4597	0.0013	4262
Su.15, Sp.16	2.9325	0.0059	4333
Su.15, Su.16	1.8176	0.0908	4278
Au.15, Wi.16	4.012	0.0006	7561
Au.15, Sp.16	3.1725	0.0036	7605
Au.15, Su.16	1.8467	0.0837	7628
Wi.16, Sp.16	4.7345	0.0024	462
Wi.16, Su.16	5.2186	0.0023	461
Sp.16, Su.16	1.3174	0.2243	462

EPT Richness			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Wi.15	6.0145	0.0029	462
Sp.14, Sp.15	6.249	**0.0002**	4303
Sp.14, Su.15	4.2668	0.0033	462
Sp.14, Au.15	2.3853	0.0279	7608
Sp.14, Wi.16	2.1823	0.0629	462
Sp.14, Sp.16	8.2456	**0.002**	462
Sp.14, Su.16	5.7073	0.0019	462
Wi.15, Sp.15	1.1673	0.2775	4286
Wi.15, Su.15	2.145	0.0567	462
Wi.15, Au.15	2.7994	0.0116	7652
Wi.15, Wi.16	0.99277	0.4312	462
Wi.15, Sp.16	2.9711	0.0116	462
Wi.15, Su.16	0.87405	0.3864	461
Sp.15, Su.15	2.6716	0.0171	4292
Sp.15, Au.15	3.99	0.0008	9640
Sp.15, Wi.16	1.761	0.0854	4324
Sp.15, Sp.16	0.30892	0.7826	4295
Sp.15, Su.16	1.7412	0.108	4305
Su.15, Au.15	1.3819	0.1831	7584
Su.15, Wi.16	0.12956	0.9561	462
Su.15, Sp.16	5.171	0.0023	459
Su.15, Su.16	1.5405	0.1452	462
Au.15, Wi.16	0.83216	0.413	7615
Au.15, Sp.16	4.2257	0.0013	7416
Au.15, Su.16	2.3685	0.028	7575
Wi.16, Sp.16	1.8339	0.0062	462
Wi.16, Su.16	0.71403	0.7254	462
Sp.16, Su.16	4.9043	0.0029	462

EPT Diversity			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	0.469	0.6724	462
Sp.14, Wi.15	2.281	0.0419	462
Sp.14, Sp.15	0.20744	0.8375	4302
Sp.14, Su.15	1.1829	0.2586	2245
Sp.14, Au.15	8.0933	0.0001	122
Sp.14, Wi.16	2.4956	0.0384	63
Sp.14, Sp.16	0.83783	0.4321	462
Sp.14, Su.16	0.32769	0.7759	462
Su.14, Wi.15	1.9353	0.0907	336
Su.14, Sp.15	0.25927	0.7896	3340
Su.14, Su.15	1.3943	0.1782	1414
Su.14, Au.15	5.7688	0.0008	63
Su.14, Wi.16	2.3742	0.0763	32
Su.14, Sp.16	1.0176	0.3335	336
Su.14, Su.16	0.11809	0.8373	336
Wi.15, Sp.15	1.8802	0.0857	3360
Wi.15, Su.15	0.41322	0.6783	1391
Wi.15, Au.15	4.1232	0.0026	47
Wi.15, Wi.16	1.0554	0.3082	32
Wi.15, Sp.16	0.89809	0.3862	336
Wi.15, Su.16	1.8305	0.1076	336
Sp.15, Su.15	1.3486	0.1937	4626
Sp.15, Au.15	5.9693	0.0002	501
Sp.15, Wi.16	2.5448	0.0289	450
Sp.15, Sp.16	0.89431	0.3885	3329
Sp.15, Su.16	0.12502	0.8986	3323
Su.15, Au.15	3.5697	0.0029	128
Su.15, Wi.16	1.3347	0.2029	126
Su.15, Sp.16	0.38223	0.7102	1401
Su.15, Su.16	1.2793	0.2062	1391
Au.15, Wi.16	1.0289	0.3302	4
Au.15, Sp.16	4.6409	0.0012	63
Au.15, Su.16	5.678	0.0008	63
Wi.16, Sp.16	1.6066	0.1493	32
Wi.16, Su.16	2.2927	0.0795	32
Sp.16, Su.16	0.90578	0.3771	336

EPT Diversity			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	0.11791	0.8929	461
Sp.14, Wi.15	1.4475	0.1813	462
Sp.14, Sp.15	0.11544	0.9091	4329
Sp.14, Su.15	0.27031	0.7898	4311
Sp.14, Au.15	1.5059	0.156	7600
Sp.14, Wi.16	1.8709	0.0816	462
Sp.14, Sp.16	0.67687	0.5132	462
Sp.14, Su.16	0.00054	1	462
Su.14, Wi.15	1.3348	0.216	462
Su.14, Sp.15	0.21387	0.8309	4281
Su.14, Su.15	0.39837	0.6932	4278
Su.14, Au.15	1.4159	0.177	7641
Su.14, Wi.16	1.7842	0.107	462
Su.14, Sp.16	0.74242	0.4785	460
Su.14, Su.16	0.0878	0.9105	462
Wi.15, Sp.15	1.3953	0.1911	4311
Wi.15, Su.15	1.8734	0.0845	4299
Wi.15, Au.15	0.29367	0.7754	7556
Wi.15, Wi.16	0.71487	0.4841	462
Wi.15, Sp.16	1.5354	0.1535	462
Wi.15, Su.16	1.1237	0.2783	461
Sp.15, Su.15	0.10522	0.9166	8109
Sp.15, Au.15	1.7321	0.1013	9661
Sp.15, Wi.16	1.9551	0.0658	4185
Sp.15, Sp.16	0.63243	0.5375	4293
Sp.15, Su.16	0.0979	0.9178	4242
Su.15, Au.15	2.0105	0.0578	9669
Su.15, Wi.16	2.3871	0.0314	4295
Su.15, Sp.16	0.64124	0.5323	4310
Su.15, Su.16	0.21	0.8334	4303
Au.15, Wi.16	0.4539	0.6576	7685
Au.15, Sp.16	1.9237	0.0753	7612
Au.15, Su.16	1.3674	0.1944	7606
Wi.16, Sp.16	1.9063	0.0915	462
Wi.16, Su.16	1.5872	0.1404	462
Sp.16, Su.16	0.60047	0.5605	460

EPT Diversity			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	4.1592	0.0077	460
Sp.14, Sp.15	7.0748	**0.0006**	4321
Sp.14, Su.15	4.2648	0.0009	4286
Sp.14, Au.15	2.1989	0.0319	7653
Sp.14, Wi.16	7.2577	0.002	462
Sp.14, Sp.16	15.327	**0.003**	462
Sp.14, Su.16	5.5034	0.0017	462
Wi.15, Sp.15	3.0343	0.0122	4282
Wi.15, Su.15	0.39798	0.7093	4335
Wi.15, Au.15	0.66268	0.5151	7604
Wi.15, Wi.16	2.5519	**0.0296**	462
Wi.15, Sp.16	10.34	0.0018	462
Wi.15, Su.16	2.4102	0.0443	462
Sp.15, Su.15	2.6706	0.0165	8042
Sp.15, Au.15	3.26	0.0065	9674
Sp.15, Wi.16	0.88627	0.3933	4345
Sp.15, Sp.16	6.059	**0.0003**	4290
Sp.15, Su.16	0.092029	0.9251	4303
Su.15, Au.15	1.0906	0.292	9667
Su.15, Wi.16	1.8287	0.0871	4367
Su.15, Sp.16	8.5025	0.0001	4280
Su.15, Su.16	2.1783	**0.0471**	4293
Au.15, Wi.16	2.2889	0.0382	7642
Au.15, Sp.16	6.9911	0.0001	7607
Au.15, Su.16	2.6732	0.0168	7613
Wi.16, Sp.16	9.0832	0.0032	462
Wi.16, Su.16	0.76617	0.4494	462
Sp.16, Su.16	4.5098	0.0023	462

EPT Count%

Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	1.6543	0.1261	462
Sp.14, Wi.15	1.2628	0.2288	461
Sp.14, Sp.15	0.14464	0.8893	4296
Sp.14, Su.15	1.6922	0.1183	4307
Sp.14, Au.15	4.6744	0.0005	717
Sp.14, Wi.16	2.5747	0.0222	336
Sp.14, Sp.16	0.45726	0.6424	462
Sp.14, Su.16	1.9233	0.0886	462
Su.14, Wi.15	0.7586	0.4679	462
Su.14, Sp.15	1.3838	0.1916	4315
Su.14, Su.15	0.37119	0.7413	4309
Su.14, Au.15	3.4983	0.0044	723
Su.14, Wi.16	1.6274	0.1395	336
Su.14, Sp.16	0.8321	0.4246	462
Su.14, Su.16	0.35558	0.7284	462
Wi.15, Sp.15	0.94199	0.3713	4285
Wi.15, Su.15	0.88421	0.4417	4327
Wi.15, Au.15	4.0988	0.0027	716
Wi.15, Wi.16	2.0895	0.0784	336
Wi.15, Sp.16	0.43134	0.6916	462
Wi.15, Su.16	1.1476	0.2952	461
Sp.15, Su.15	1.6685	0.1154	8099
Sp.15, Au.15	5.036	0.0004	4807
Sp.15, Wi.16	2.6888	0.0192	3343
Sp.15, Sp.16	0.34751	0.7269	4252
Sp.15, Su.16	1.6533	0.1227	4297
Su.15, Au.15	3.2232	0.0062	3078
Su.15, Wi.16	1.3229	0.2087	2259
Su.15, Sp.16	1.072	0.3067	4272
Su.15, Su.16	0.10085	0.9295	4296
Au.15, Wi.16	1.184	0.2567	232
Au.15, Sp.16	3.871	0.003	708
Au.15, Su.16	3.2141	0.0061	723
Wi.16, Sp.16	1.9819	0.0755	336
Wi.16, Su.16	1.4062	0.185	336
Sp.16, Su.16	1.067	0.3084	462

EPT Count%

Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	7.9973	0.0028	462
Sp.14, Wi.15	0.39371	0.7035	461
Sp.14, Sp.15	1.1038	0.2831	4289
Sp.14, Su.15	7.9279	0.0025	462
Sp.14, Au.15	4.1635	0.0013	7582
Sp.14, Wi.16	0.60357	0.6304	462
Sp.14, Sp.16	1.6572	0.1251	462
Sp.14, Su.16	8.4458	0.0022	462
Su.14, Wi.15	8.2196	0.0024	462
Su.14, Sp.15	7.4783	0.0003	4302
Su.14, Su.15	1.2078	0.2536	460
Su.14, Au.15	0.88696	0.3742	7638
Su.14, Wi.16	18.072	0.0022	459
Su.14, Sp.16	5.0461	0.0021	460
Su.14, Su.16	2.8374	0.0117	462
Wi.15, Sp.15	1.547	0.1438	4273
Wi.15, Su.15	8.1584	0.0017	462
Wi.15, Au.15	4.38	0.0011	7591
Wi.15, Wi.16	0.081487	0.922	461
Wi.15, Sp.16	1.9998	0.0767	462
Wi.15, Su.16	8.6629	0.0019	462
Sp.15, Su.15	7.6303	0.0003	4331
Sp.15, Au.15	4.4335	0.0003	9675
Sp.15, Wi.16	2.0571	0.0567	4247
Sp.15, Sp.16	0.90675	0.371	4295
Sp.15, Su.16	8.4217	0.0005	4212
Su.15, Au.15	0.62259	0.5596	7635
Su.15, Wi.16	14.52	0.0019	461
Su.15, Sp.16	5.2262	0.002	462
Su.15, Su.16	1.6314	0.133	461
Au.15, Wi.16	4.5761	0.0004	7496
Au.15, Sp.16	3.1314	0.0096	7649
Au.15, Su.16	0.073777	0.9392	7650
Wi.16, Sp.16	2.6241	0.0318	462
Wi.16, Su.16	13.614	0.002	460
Sp.16, Su.16	5.9174	0.0012	462

EPT Count%

Seasons	t	*P*(perm)	Unique perms
Sp.14, Wi.15	3.837	0.0038	462
Sp.14, Sp.15	4.4845	**0.0017**	4294
Sp.14, Su.15	1.6532	0.1284	4276
Sp.14, Au.15	4.6216	0.0009	7554
Sp.14, Wi.16	10.152	0.0028	462
Sp.14, Sp.16	14.084	**0.0027**	460
Sp.14, Su.16	8.0511	0.0025	462
Wi.15, Sp.15	0.11458	0.9095	4280
Wi.15, Su.15	0.38483	0.7172	4278
Wi.15, Au.15	2.2888	0.0406	7620
Wi.15, Wi.16	4.0477	**0.0067**	462
Wi.15, Sp.16	2.9841	0.0165	462
Wi.15, Su.16	0.97456	0.362	462
Sp.15, Su.15	0.54562	0.6065	8117
Sp.15, Au.15	2.7015	0.0191	9671
Sp.15, Wi.16	4.551	0.0002	4273
Sp.15, Sp.16	3.1591	**0.0046**	4281
Sp.15, Su.16	0.95564	0.3709	4316
Su.15, Au.15	2.6148	0.0176	9678
Su.15, Wi.16	2.7959	0.0165	4289
Su.15, Sp.16	1.8812	0.0842	4267
Su.15, Su.16	0.91957	0.38	4263
Au.15, Wi.16	0.2648	0.7773	7540
Au.15, Sp.16	0.84606	0.4192	7584
Au.15, Su.16	1.8499	0.0839	7600
Wi.16, Sp.16	2.6863	0.0049	462
Wi.16, Su.16	4.5503	0.0018	462
Sp.16, Su.16	4.2714	0.0014	462

Chironomidae Count%			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	1.1689	0.2824	462
Sp.14, Wi.15	3.0347	0.0185	462
Sp.14, Sp.15	0.28199	0.7839	4299
Sp.14, Su.15	1.3503	0.1983	4287
Sp.14, Au.15	3.4839	0.002	7614
Sp.14, Wi.16	4.5279	0.0048	462
Sp.14, Sp.16	1.0015	0.3361	462
Sp.14, Su.16	2.3116	0.0418	462
Su.14, Wi.15	2.1955	0.0565	462
Su.14, Sp.15	1.2451	0.2353	4332
Su.14, Su.15	0.34951	0.7299	4319
Su.14, Au.15	2.0279	0.0563	7645
Su.14, Wi.16	3.5012	0.011	461
Su.14, Sp.16	2.2419	0.0508	462
Su.14, Su.16	0.72202	0.4833	461
Wi.15, Sp.15	3.6739	0.0024	4301
Wi.15, Su.15	1.9438	0.0744	4318
Wi.15, Au.15	1.3644	0.19	7630
Wi.15, Wi.16	0.72864	0.4659	462
Wi.15, Sp.16	3.7821	0.0069	462
Wi.15, Su.16	1.9998	0.0739	462
Sp.15, Su.15	1.4803	0.1546	8085
Sp.15, Au.15	4.0952	0.0008	9668
Sp.15, Wi.16	5.5736	0.0006	4282
Sp.15, Sp.16	1.6349	0.1295	4283
Sp.15, Su.16	2.7153	0.0193	4273
Su.15, Au.15	1.446	0.1672	9655
Su.15, Wi.16	3.0459	0.0084	4284
Su.15, Sp.16	2.1717	0.0476	4284
Su.15, Su.16	0.15702	0.8799	4299
Au.15, Wi.16	2.7561	0.0153	7662
Au.15, Sp.16	4.8147	0.0003	7559
Au.15, Su.16	1.5689	0.1326	7637
Wi.16, Sp.16	5.5457	0.0024	462
Wi.16, Su.16	3.5235	0.0121	462
Sp.16, Su.16	4.1704	0.0042	462

Chironomidae Count%			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	17.138	0.002	459
Sp.14, Wi.15	2.182	0.0563	459
Sp.14, Sp.15	0.63918	0.5251	4310
Sp.14, Su.15	17.835	0.0019	460
Sp.14, Au.15	1.952	0.07	7662
Sp.14, Wi.16	0.15771	0.8666	462
Sp.14, Sp.16	0.39261	0.7189	462
Sp.14, Su.16	16.046	0.0019	460
Su.14, Wi.15	23.829	0.0026	429
Su.14, Sp.15	9.7787	0.0003	4305
Su.14, Su.15	1.3331	0.2064	462
Su.14, Au.15	8.1206	0.0002	7665
Su.14, Wi.16	22.342	0.0017	462
Su.14, Sp.16	9.7563	0.0025	462
Su.14, Su.16	3.2895	0.0209	462
Wi.15, Sp.15	2.2208	0.0402	4219
Wi.15, Su.15	24.86	0.0023	426
Wi.15, Au.15	3.5453	0.0033	7633
Wi.15, Wi.16	0.49866	0.6213	458
Wi.15, Sp.16	1.8895	0.0829	458
Wi.15, Su.16	22.605	0.0023	433
Sp.15, Su.15	10.091	0.0001	4284
Sp.15, Au.15	1.3415	0.1944	9659
Sp.15, Wi.16	0.55819	0.5835	4287
Sp.15, Sp.16	0.18837	0.8518	4353
Sp.15, Su.16	9.0616	0.0003	4281
Su.15, Au.15	8.4124	0.0002	7563
Su.15, Wi.16	23.496	0.0021	462
Su.15, Sp.16	10.077	0.0019	461
Su.15, Su.16	1.5081	0.1595	462
Au.15, Wi.16	1.9067	0.0788	7562
Au.15, Sp.16	1.3626	0.19	7593
Au.15, Su.16	7.4164	0.0003	7647
Wi.16, Sp.16	0.31284	0.7517	462
Wi.16, Su.16	21.003	0.0016	461
Sp.16, Su.16	9.0651	0.0023	462

Chironomidae Count%			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Wi.15	4.1404	0.0029	461
Sp.14, Sp.15	5.4619	**0.0003**	4300
Sp.14, Su.15	3.1532	0.0158	462
Sp.14, Au.15	13.491	0.0001	7634
Sp.14, Wi.16	8.264	0.0022	462
Sp.14, Sp.16	14.035	**0.003**	461
Sp.14, Su.16	10.457	0.0024	462
Wi.15, Sp.15	0.23852	0.8116	4291
Wi.15, Su.15	0.71634	0.4907	462
Wi.15, Au.15	4.0286	0.0019	7717
Wi.15, Wi.16	2.4199	**0.0454**	459
Wi.15, Sp.16	1.4808	0.168	462
Wi.15, Su.16	0.56711	0.6062	461
Sp.15, Su.15	0.71384	0.4813	4314
Sp.15, Au.15	5.7775	0.0001	9651
Sp.15, Wi.16	3.5135	0.0057	4333
Sp.15, Sp.16	2.4504	**0.0282**	4318
Sp.15, Su.16	1.14	0.2681	4305
Su.15, Au.15	5.1702	0.0003	7598
Su.15, Wi.16	3.1793	0.023	462
Su.15, Sp.16	2.4525	0.0368	462
Su.15, Su.16	1.5261	0.1652	462
Au.15, Wi.16	0.41643	0.6744	7696
Au.15, Sp.16	3.6149	0.0027	7631
Au.15, Su.16	5.0973	0.0006	7636
Wi.16, Sp.16	1.9102	0.0947	462
Wi.16, Su.16	2.878	0.0222	462
Sp.16, Su.16	2.5209	0.0323	462

EPT Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.70345	0.56	462
Sp.14, Wi.15	0.91044	0.4558	461
Sp.14, Sp.15	0.19693	0.824	4237
Sp.14, Su.15	2.4046	0.0136	4290
Sp.14, Au.15	5.087	0.0003	721
Sp.14, Wi.16	2.2737	0.0378	335
Sp.14, Sp.16	0.069035	0.846	461
Sp.14, Su.16	1.2299	0.2641	462
Su.14, Wi.15	0.31169	0.7707	462
Su.14, Sp.15	1.0584	0.3451	4343
Su.14, Su.15	2.1354	0.0522	4321
Su.14, Au.15	5.63	0.0006	724
Su.14, Wi.16	2.1504	0.0633	336
Su.14, Sp.16	0.7424	0.5603	462
Su.14, Su.16	0.73649	0.4716	462
Wi.15, Sp.15	1.2983	0.2331	4278
Wi.15, Su.15	1.679	0.1184	4304
Wi.15, Au.15	4.9526	0.0004	725
Wi.15, Wi.16	1.7981	0.1015	336
Wi.15, Sp.16	0.9372	0.4556	462
Wi.15, Su.16	0.34703	0.755	462
Sp.15, Su.15	3.0867	0.0021	8068
Sp.15, Au.15	6.2359	0.0001	4720
Sp.15, Wi.16	2.9019	0.0078	3363
Sp.15, Sp.16	0.10646	0.8832	4289
Sp.15, Su.16	1.6747	0.0951	4303
Su.15, Au.15	3.5979	0.003	3068
Su.15, Wi.16	0.66879	0.518	2263
Su.15, Sp.16	2.3646	0.0112	4308
Su.15, Su.16	1.5081	0.1595	4251
Au.15, Wi.16	1.9311	0.082	232
Au.15, Sp.16	4.9054	0.0001	726
Au.15, Su.16	5.2083	0.0004	719
Wi.16, Sp.16	2.2283	0.0349	336
Wi.16, Su.16	1.7162	0.1162	336
Sp.16, Su.16	1.2322	0.2582	462

EPT Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.75562	0.4813	462
Sp.14, Wi.15	0.47948	0.64	462
Sp.14, Sp.15	0.59512	0.5466	4291
Sp.14, Su.15	0.05617	0.9627	462
Sp.14, Au.15	9.8446	0.0003	7688
Sp.14, Wi.16	1.0841	0.3117	462
Sp.14, Sp.16	1.5437	0.1424	460
Sp.14, Su.16	1.8291	0.1158	461
Su.14, Wi.15	1.4005	0.1889	460
Su.14, Sp.15	1.7008	0.1065	4279
Su.14, Su.15	0.95442	0.3634	462
Su.14, Au.15	15.866	0.0001	7495
Su.14, Wi.16	0.63102	0.5337	462
Su.14, Sp.16	4.9509	0.0021	462
Su.14, Su.16	0.15771	0.8666	462
Wi.15, Sp.15	0.008129	0.994	4325
Wi.15, Su.15	0.62186	0.5441	461
Wi.15, Au.15	9.1631	0.0001	7594
Wi.15, Wi.16	1.651	0.124	462
Wi.15, Sp.16	0.91081	0.4769	462
Wi.15, Su.16	1.2451	0.2452	462
Sp.15, Su.15	0.7651	0.4533	4319
Sp.15, Au.15	11.024	0.0001	9671
Sp.15, Wi.16	2.0176	0.0611	4312
Sp.15, Sp.16	1.0854	0.2894	4282
Sp.15, Su.16	1.4962	0.1564	4284
Su.15, Au.15	12.33	0.0001	7532
Su.15, Wi.16	1.2911	0.2088	462
Su.15, Sp.16	2.3005	0.0366	462
Su.15, Su.16	0.41499	0.6859	462
Au.15, Wi.16	13.785	0.0001	7636
Au.15, Sp.16	12.485	0.0001	7528
Au.15, Su.16	10.361	0.0001	7560
Wi.16, Sp.16	3.8408	0.0023	461
Wi.16, Su.16	3.8841	0.0019	462
Sp.16, Su.16	0.77681	0.4575	462

EPT Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	3.0067	0.0249	462
Sp.14, Sp.15	4.426	**0.0026**	4322
Sp.14, Su.15	6.085	0.0023	462
Sp.14, Au.15	0.91904	0.3653	7653
Sp.14, Wi.16	2.1919	0.0392	461
Sp.14, Sp.16	4.7702	**0.0053**	461
Sp.14, Su.16	4.6515	0.0052	461
Wi.15, Sp.15	0.11549	0.9084	4281
Wi.15, Su.15	0.33996	0.7466	458
Wi.15, Au.15	3.9343	0.0016	7659
Wi.15, Wi.16	0.63413	0.527	461
Wi.15, Sp.16	1.0016	0.3283	461
Wi.15, Su.16	0.77547	0.4625	462
Sp.15, Su.15	0.68341	0.5141	4280
Sp.15, Au.15	5.1998	0.0001	9703
Sp.15, Wi.16	0.76721	0.4441	4253
Sp.15, Sp.16	1.3982	0.1794	4294
Sp.15, Su.16	1.0308	0.319	4304
Su.15, Au.15	5.4228	0.0001	7643
Su.15, Wi.16	1.1686	0.2625	462
Su.15, Sp.16	2.9398	0.0214	462
Su.15, Su.16	2.2308	0.0569	462
Au.15, Wi.16	3.0619	0.0074	7631
Au.15, Sp.16	3.8896	0.0018	7601
Au.15, Su.16	4.0723	0.001	7542
Wi.16, Sp.16	0.12702	0.8867	462
Wi.16, Su.16	0.077253	0.9484	460
Sp.16, Su.16	0.55034	0.5851	462

Chironomidae Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	1.5438	0.1588	462
Sp.14, Wi.15	1.4881	0.1852	460
Sp.14, Sp.15	0.1363	0.8949	4253
Sp.14, Su.15	1.038	0.3211	462
Sp.14, Au.15	2.2362	0.0438	7678
Sp.14, Wi.16	0.6398	0.5409	462
Sp.14, Sp.16	0.84159	0.4182	462
Sp.14, Su.16	1.9509	0.0801	462
Su.14, Wi.15	0.22733	0.8353	462
Su.14, Sp.15	2.638	0.0161	4226
Su.14, Su.15	0.34539	0.7431	462
Su.14, Au.15	1.0928	0.2978	7655
Su.14, Wi.16	2.4641	0.0348	462
Su.14, Sp.16	2.8552	0.015	462
Su.14, Su.16	0.31241	0.7379	460
Wi.15, Sp.15	2.2985	0.0323	4282
Wi.15, Su.15	0.49252	0.6199	462
Wi.15, Au.15	0.8405	0.3947	7631
Wi.15, Wi.16	2.189	0.0518	461
Wi.15, Sp.16	2.4443	0.0274	462
Wi.15, Su.16	0.0084292	0.9919	462
Sp.15, Su.15	1.6824	0.1087	4272
Sp.15, Au.15	3.0255	0.0089	9664
Sp.15, Wi.16	0.86018	0.4169	4314
Sp.15, Sp.16	1.2202	0.2374	4311
Sp.15, Su.16	3.5358	0.0032	4330
Su.15, Au.15	1.3171	0.1991	7642
Su.15, Wi.16	1.7513	0.1225	462
Su.15, Sp.16	2.008	0.0575	461
Su.15, Su.16	0.62912	0.5471	462
Au.15, Wi.16	2.8133	0.0143	7636
Au.15, Sp.16	2.9861	0.0115	7645
Au.15, Su.16	0.92362	0.3702	7678
Wi.16, Sp.16	0.18495	0.8283	461
Wi.16, Su.16	3.0678	0.0062	462
Sp.16, Su.16	3.6116	0.0045	461

Chironomidae Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	6.9136	0.0014	462
Sp.14, Wi.15	0.10167	0.9127	462
Sp.14, Sp.15	0.33572	0.7304	4239
Sp.14, Su.15	6.1662	0.0002	4259
Sp.14, Au.15	1.4005	0.1732	7550
Sp.14, Wi.16	1.6366	0.1249	462
Sp.14, Sp.16	0.41499	0.6859	462
Sp.14, Su.16	6.018	0.0028	461
Su.14, Wi.15	8.9912	0.0024	462
Su.14, Sp.15	6.3198	0.0006	4329
Su.14, Su.15	1.7373	0.0952	4304
Su.14, Au.15	7.9432	0.0001	7603
Su.14, Wi.16	5.9178	0.0019	462
Su.14, Sp.16	7.0052	0.0023	462
Su.14, Su.16	0.41499	0.6859	462
Wi.15, Sp.15	0.45812	0.6572	4266
Wi.15, Su.15	7.1995	0.0006	4303
Wi.15, Au.15	1.4342	0.1697	7679
Wi.15, Wi.16	1.794	0.1067	462
Wi.15, Sp.16	0.3684	0.7086	461
Wi.15, Su.16	7.762	0.002	462
Sp.15, Su.15	6.1863	0.0001	8008
Sp.15, Au.15	1.8649	0.0825	9665
Sp.15, Wi.16	1.9247	0.073	4278
Sp.15, Sp.16	0.75107	0.4494	4297
Sp.15, Su.16	5.5727	0.0007	4311
Su.15, Au.15	6.7726	0.0002	9659
Su.15, Wi.16	4.5633	0.0016	4297
Su.15, Sp.16	5.9652	0.0004	4318
Su.15, Su.16	0.21884	0.8464	4288
Au.15, Wi.16	0.824	0.4181	7613
Au.15, Sp.16	0.86763	0.3912	7558
Au.15, Su.16	6.6798	0.0001	7685
Wi.16, Sp.16	1.2727	0.231	462
Wi.16, Su.16	4.8214	0.0029	456
Sp.16, Su.16	6.0136	0.0021	461

Chironomidae Biomass%			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	1.361	0.2092	462
Sp.14, Sp.15	1.9887	0.0697	4291
Sp.14, Su.15	2.5227	0.0408	462
Sp.14, Au.15	7.1279	0.0001	7625
Sp.14, Wi.16	4.5318	0.0066	462
Sp.14, Sp.16	4.798	**0.0024**	462
Sp.14, Su.16	4.7001	0.0068	462
Wi.15, Sp.15	0.70489	0.5009	4295
Wi.15, Su.15	1.3455	0.206	460
Wi.15, Au.15	6.1738	0.0002	7697
Wi.15, Wi.16	3.8202	**0.0084**	461
Wi.15, Sp.16	4.2213	0.0047	462
Wi.15, Su.16	4.0807	0.0067	462
Sp.15, Su.15	0.46441	0.6504	4304
Sp.15, Au.15	5.1058	0.0002	9660
Sp.15, Wi.16	3.0008	0.0154	4281
Sp.15, Sp.16	2.684	**0.0215**	4306
Sp.15, Su.16	2.6257	0.0246	4273
Su.15, Au.15	4.8897	0.0001	7663
Su.15, Wi.16	2.8614	0.0225	462
Su.15, Sp.16	3.0258	0.0143	461
Su.15, Su.16	2.8894	**0.0198**	462
Au.15, Wi.16	0.9118	0.371	7682
Au.15, Sp.16	2.3328	0.0347	7615
Au.15, Su.16	2.3347	0.0335	7617
Wi.16, Sp.16	0.9029	0.3521	462
Wi.16, Su.16	0.91498	0.3812	462
Sp.16, Su.16	0.050521	0.9507	462

Appendix 4.10. Summary of the PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate community taxonomical composition (Count m^{-2}, and Biomass m^{-2}) between the study reaches. Reaches compared seasonally. Bold font indicates significant (P<0.05) differences.

Community metrics	Seasons	PERMANOVA results			
Taxa Count m^{-2}	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.2933	0.0015	462
		Degraded, Rehabilitated	3.6526	0.002	462
		Natural, Rehabilitated	5.6306	0.0018	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.067	0.0027	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.3609	0.0026	462
		Degraded, Rehabilitated	2.7911	0.0015	462
		Natural, Rehabilitated	4.0451	0.0026	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.7062	0.0001	8153
		Degraded, Rehabilitated	3.3293	0.0001	8214
		Natural, Rehabilitated	4.0135	0.0002	8128
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.4775	0.0001	8161
		Degraded, Rehabilitated	3.3379	0.0003	8128
		Natural, Rehabilitated	4.3659	0.0001	8119
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.8264	0.0001	9915
		Degraded, Rehabilitated	4.9455	0.0001	9913
		Natural, Rehabilitated	4.2926	0.0001	9907
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.4661	0.0022	462
		Degraded, Rehabilitated	3.8402	0.0014	462
		Natural, Rehabilitated	2.7532	0.0025	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.1486	0.0028	462
		Degraded, Rehabilitated	5.2744	0.0024	462
		Natural, Rehabilitated	3.9396	0.002	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.003	0.0028	462
		Degraded, Rehabilitated	3.8631	0.0023	461
		Natural, Rehabilitated	6.191	0.0016	462
Taxa Biomass m^{-2}	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.5539	0.0027	462
		Degraded, Rehabilitated	3.0043	0.0018	462
		Natural, Rehabilitated	4.6591	0.0021	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.5461	0.002	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.6717	0.0023	462
		Degraded, Rehabilitated	2.4659	0.0016	462
		Natural, Rehabilitated	3.7776	0.002	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.2466	0.0001	8192
		Degraded, Rehabilitated	2.967	0.0001	8183
		Natural, Rehabilitated	4.0035	0.0001	8167
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.1712	0.0001	8186

		Degraded, Rehabilitated	3.4947	0.0001	8198
		Natural, Rehabilitated	4.0487	0.0002	8166
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.956	0.0001	9894
		Degraded, Rehabilitated	4.1687	0.0001	9893
		Natural, Rehabilitated	4.157	0.0001	9899
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.0015	0.0021	462
		Degraded, Rehabilitated	3.5643	0.0021	462
		Natural, Rehabilitated	2.9273	0.0027	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.508	0.0027	462
		Degraded, Rehabilitated	4.4887	0.0022	462
		Natural, Rehabilitated	3.8234	0.0028	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.1794	0.0025	462
		Degraded, Rehabilitated	3.5467	0.0025	462
		Natural, Rehabilitated	5.2652	0.0022	462

Appendix 4.11. Summary of PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate community taxonomical composition (Count m^{-2}, and Biomass m^{-2}) for each reach separately. Bold font indicates significant (P<0.05) differences.

Degraded reach seasonal differences

Taxa Count m^{-2}

Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	2.3525	0.0021	462
Sp.14, Wi.15	1.76	0.0091	462
Sp.14, Sp.15	0.64995	0.7946	4346
Sp.14, Su.15	2.9162	0.0002	4279
Sp.14, Au.15	2.4328	0.0012	7735
Sp.14, Wi.16	2.7096	0.0015	461
Sp.14, Sp.16	0.4098	0.9183	462
Sp.14, Su.16	2.273	0.002	462
Su.14, Wi.15	2.658	0.0023	462
Su.14, Sp.15	2.2656	0.0001	4359
Su.14, Su.15	1.2834	0.1456	4295
Su.14, Au.15	2.4013	0.0002	7641
Su.14, Wi.16	3.3184	0.0016	462
Su.14, Sp.16	2.4345	0.0016	462
Su.14, Su.16	0.57461	0.7821	462
Wi.15, Sp.15	2.1803	0.0023	4285
Wi.15, Su.15	3.2749	0.0004	4293
Wi.15, Au.15	2.5303	0.0008	7685
Wi.15, Wi.16	0.41499	0.6859	461
Wi.15, Sp.16	1.7441	0.0066	462
Wi.15, Su.16	2.5482	0.0028	462
Sp.15, Su.15	2.8019	0.0004	8152
Sp.15, Au.15	2.664	0.0002	9776
Sp.15, Wi.16	3.2543	0.0002	4316
Sp.15, Sp.16	0.82478	0.555	4288
Sp.15, Su.16	2.1221	0.0004	4300
Su.15, Au.15	2.4186	0.0002	9758
Su.15, Wi.16	3.9153	0.0001	4341
Su.15, Sp.16	3.0301	0.0004	4352
Su.15, Su.16	1.2837	0.1481	4299
Au.15, Wi.16	2.8322	0.0002	7650
Au.15, Sp.16	2.3968	0.0015	7675
Au.15, Su.16	2.2638	0.0003	7653
Wi.16, Sp.16	2.6586	0.0017	462
Wi.16, Su.16	3.3138	0.0026	462
Sp.16, Su.16	2.283	0.0023	462

Natural reach seasonal differences

Taxa Count m^{-2}

Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	3.3428	0.0018	462
Sp.14, Wi.15	2.7518	0.0021	462
Sp.14, Sp.15	1.0723	0.3367	4313
Sp.14, Su.15	2.8713	0.0002	4325
Sp.14, Au.15	2.5582	0.0001	7712
Sp.14, Wi.16	2.2801	0.0019	462
Sp.14, Sp.16	1.5316	0.0663	462
Sp.14, Su.16	3.5042	0.0015	462
Su.14, Wi.15	4.0325	0.002	462
Su.14, Sp.15	3.1243	0.0003	4297
Su.14, Su.15	1.3177	0.1935	4344
Su.14, Au.15	3.3296	0.0002	7687
Su.14, Wi.16	3.5118	0.0026	461
Su.14, Sp.16	3.4879	0.0015	462
Su.14, Su.16	1.4438	0.0806	462
Wi.15, Sp.15	2.9991	0.0003	4296
Wi.15, Su.15	3.3777	0.0002	4344
Wi.15, Au.15	3.3558	0.0002	7698
Wi.15, Wi.16	1.6324	0.0887	462
Wi.15, Sp.16	3.3305	0.0019	462
Wi.15, Su.16	4.2546	0.0024	462
Sp.15, Su.15	2.8779	0.0001	8099
Sp.15, Au.15	2.7934	0.0001	9763
Sp.15, Wi.16	2.5589	0.0002	4286
Sp.15, Sp.16	1.0423	0.3641	4295
Sp.15, Su.16	3.1777	0.0002	4291
Su.15, Au.15	2.4811	0.0003	9766
Su.15, Wi.16	2.9441	0.0003	4312
Su.15, Sp.16	2.9408	0.0002	4278
Su.15, Su.16	1.2409	0.2123	4321
Au.15, Wi.16	2.6238	0.0002	7647
Au.15, Sp.16	2.9619	0.0001	7740
Au.15, Su.16	3.3105	0.0002	7727
Wi.16, Sp.16	2.7732	0.0029	462
Wi.16, Su.16	3.8413	0.0021	461
Sp.16, Su.16	3.5202	0.0033	462

Rehabilitated reach seasonal differences

Taxa Count m^{-2}

Seasons	t	*P*(perm)	Unique perms
Sp.14, Wi.15	2.9627	0.0021	462
Sp.14, Sp.15	3.316	**0.0005**	4297
Sp.14, Su.15	4.832	0.0003	4307
Sp.14, Au.15	4.5876	0.0004	7752
Sp.14, Wi.16	3.2934	0.0025	462
Sp.14, Sp.16	5.6185	**0.0022**	462
Sp.14, Su.16	6.502	0.0024	462
Wi.15, Sp.15	2.5696	0.0002	4306
Wi.15, Su.15	4.0419	0.0002	4327
Wi.15, Au.15	4.0425	0.0001	7717
Wi.15, Wi.16	2.5719	**0.0018**	462
Wi.15, Sp.16	4.4535	0.0028	462
Wi.15, Su.16	4.8121	0.0027	462
Sp.15, Su.15	3.6252	0.0001	8208
Sp.15, Au.15	3.5463	0.0001	9742
Sp.15, Wi.16	2.2027	0.0004	4310
Sp.15, Sp.16	3.1894	**0.0004**	4329
Sp.15, Su.16	3.8954	0.0003	4285
Su.15, Au.15	2.821	0.0001	9724
Su.15, Wi.16	2.9042	0.0004	4335
Su.15, Sp.16	3.6905	0.0002	4319
Su.15, Su.16	2.1378	**0.0016**	4326
Au.15, Wi.16	2.1971	0.0006	7670
Au.15, Sp.16	3.1073	0.0001	7679
Au.15, Su.16	3.308	0.0001	7703
Wi.16, Sp.16	2.3952	0.0023	462
Wi.16, Su.16	3.2995	0.0012	462
Sp.16, Su.16	5.4539	0.002	461

Taxa Biomass m^{-2}			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	2.1017	0.0032	462
Sp.14, Wi.15	1.557	0.0159	462
Sp.14, Sp.15	0.52225	0.9197	4325
Sp.14, Su.15	2.7371	0.0004	4318
Sp.14, Au.15	2.3103	0.0003	7748
Sp.14, Wi.16	2.405	0.0024	461
Sp.14, Sp.16	0.38736	0.9353	462
Sp.14, Su.16	2.0876	0.0019	462
Su.14, Wi.15	2.436	0.0024	462
Su.14, Sp.15	2.0457	0.0003	4365
Su.14, Su.15	1.3737	0.096	4353
Su.14, Au.15	2.292	0.0005	7692
Su.14, Wi.16	3.3272	0.0017	462
Su.14, Sp.16	2.2197	0.0031	462
Su.14, Su.16	0.80288	0.6741	462
Wi.15, Sp.15	1.9305	0.0025	4270
Wi.15, Su.15	3.1201	0.0002	4316
Wi.15, Au.15	2.4358	0.0004	7769
Wi.15, Wi.16	0.676	0.0624	462
Wi.15, Sp.16	1.5311	0.0246	461
Wi.15, Su.16	2.2915	0.0025	462
Sp.15, Su.15	2.6599	0.0002	8132
Sp.15, Au.15	2.5127	0.0002	9767
Sp.15, Wi.16	2.887	0.0002	4354
Sp.15, Sp.16	0.69655	0.7275	4346
Sp.15, Su.16	1.9294	0.0008	4305
Su.15, Au.15	2.4942	0.0001	9778
Su.15, Wi.16	4.0213	0.0004	4328
Su.15, Sp.16	2.9204	0.0004	4355
Su.15, Su.16	1.4862	0.059	4300
Au.15, Wi.16	2.8729	0.0003	7679
Au.15, Sp.16	2.2945	0.0012	7722
Au.15, Su.16	2.0718	0.0004	7699
Wi.16, Sp.16	2.2515	0.0023	462
Wi.16, Su.16	3.1153	0.0035	462
Sp.16, Su.16	2.0727	0.0021	462

Taxa Biomass m^{-2}			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	2.8433	0.0031	462
Sp.14, Wi.15	2.7612	0.0023	462
Sp.14, Sp.15	1.0168	0.3697	4342
Sp.14, Su.15	2.5489	0.0003	4322
Sp.14, Au.15	2.5243	0.0001	7689
Sp.14, Wi.16	2.4292	0.0027	462
Sp.14, Sp.16	1.5861	0.0521	462
Sp.14, Su.16	2.9354	0.0025	462
Su.14, Wi.15	3.5707	0.0026	462
Su.14, Sp.15	2.9989	0.0003	4293
Su.14, Su.15	1.2142	0.2154	4309
Su.14, Au.15	3.2511	0.0002	7677
Su.14, Wi.16	3.2491	0.0025	462
Su.14, Sp.16	3.3144	0.0026	462
Su.14, Su.16	1.4458	0.0838	462
Wi.15, Sp.15	3.1582	0.0002	4298
Wi.15, Su.15	3.2209	0.0002	4318
Wi.15, Au.15	3.3968	0.0003	7735
Wi.15, Wi.16	1.6628	0.0642	461
Wi.15, Sp.16	3.35	0.0017	462
Wi.15, Su.16	3.9085	0.002	462
Sp.15, Su.15	2.7561	0.0001	8149
Sp.15, Au.15	2.7884	0.0001	9746
Sp.15, Wi.16	2.834	0.0001	4309
Sp.15, Sp.16	1.0982	0.2865	4308
Sp.15, Su.16	2.9629	0.0002	4315
Su.15, Au.15	2.4338	0.0002	9767
Su.15, Wi.16	2.8748	0.0005	4299
Su.15, Sp.16	2.7978	0.0005	4307
Su.15, Su.16	1.2594	0.1655	4357
Au.15, Wi.16	2.7733	0.0002	7717
Au.15, Sp.16	2.8745	0.0001	7648
Au.15, Su.16	3.1484	0.0002	7723
Wi.16, Sp.16	2.9481	0.0018	462
Wi.16, Su.16	3.63	0.0023	462
Sp.16, Su.16	3.2807	0.0016	461

Taxa Biomass m^{-2}			
Seasons	t	*P*(perm)	Unique perms
Sp.14, Wi.15	2.8641	0.0021	462
Sp.14, Sp.15	2.9509	**0.0001**	4304
Sp.14, Su.15	4.4306	0.0004	4294
Sp.14, Au.15	4.0184	0.0003	7738
Sp.14, Wi.16	3.0103	0.003	461
Sp.14, Sp.16	4.5741	**0.002**	462
Sp.14, Su.16	5.3268	0.0022	462
Wi.15, Sp.15	2.2468	0.0003	4295
Wi.15, Su.15	4.1507	0.0003	4335
Wi.15, Au.15	3.9286	0.0002	7709
Wi.15, Wi.16	2.4171	**0.0022**	462
Wi.15, Sp.16	4.3906	0.0026	462
Wi.15, Su.16	4.7001	0.0023	462
Sp.15, Su.15	3.4984	0.0002	8204
Sp.15, Au.15	3.3231	0.0001	9774
Sp.15, Wi.16	2.0822	0.0001	4291
Sp.15, Sp.16	3.2293	**0.0001**	4336
Sp.15, Su.16	3.768	0.0003	4268
Su.15, Au.15	2.6572	0.0002	9785
Su.15, Wi.16	2.7266	0.0004	4348
Su.15, Sp.16	3.6071	0.0003	4330
Su.15, Su.16	2.0435	**0.0027**	4341
Au.15, Wi.16	2.1549	0.0005	7733
Au.15, Sp.16	3.0403	0.0003	7688
Au.15, Su.16	3.329	0.0001	7743
Wi.16, Sp.16	2.6286	0.0022	462
Wi.16, Su.16	3.3281	0.0022	462
Sp.16, Su.16	4.9538	0.0025	461

Appendix 4.12. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomical composition (Count m^{-2}) 4th root transformed data, identifying Taxa contributing at least 70% of the spatial dissimilarity in community composition between the study reaches, reaches were compared seasonally before and after the rehabilitation. Average abundances presented in individuals m^{-2} (4th root transformed).

Spring 2014 (before rehabilitation)

Average dissimilarity between both reaches = 58.55

Taxa	Average Abundance Degraded	Average Abundance Natural	Contribution%	Cumulative%
Baetis rhodani	0.67	4.24	4.13	4.13
Potamopyrgus antipodarum	1.17	4.31	3.65	7.78
Simuliidae	0.14	3.07	3.40	11.18
Beraea pullata	0.00	2.56	2.96	14.14
Hydropsyche siltatay	0.00	2.26	2.63	16.77
Ancylus fluviatilis	0.55	2.77	2.57	19.34
Crunoecia irrorata	0.00	2.07	2.40	21.75
Agapetus fuscipes	0.00	2.01	2.33	24.08
Ceraclea sp.	0.00	2.00	2.32	26.40
Lasiocephala basalis	0.00	1.98	2.30	28.70
Micropterna sp.	0.00	1.96	2.28	30.97
Ephemera danica	0.00	1.96	2.27	33.25
Limnephilus lunatus.	0.15	2.10	2.26	35.51
Lymnaea (Radix) peregra	0.00	1.91	2.21	37.72
Lepidostoma hirtum	0.00	1.80	2.08	39.80
Elmidae	0.00	1.71	1.99	41.78
Ceratopogonidae	0.61	2.19	1.97	43.75
Glyphotaelius pellucidus	0.00	1.68	1.96	45.71
Sericostoma personatum	0.28	1.91	1.90	47.61
Lymnaea truncatula	0.46	2.05	1.85	49.46
Lumbriculidae	0.00	1.58	1.82	51.28
Serratella ignita	0.00	1.57	1.82	53.10
Sphaerium sp.	0.70	2.24	1.80	54.90
Mystacides longicornis (azurea)	0.00	1.46	1.68	56.58
Limnesia sp	0.15	1.48	1.62	58.20
Chironominae	4.04	2.66	1.61	59.81
Habrophlebia fusca	1.06	2.34	1.50	61.31
Gammarus pulex	1.73	2.96	1.43	62.74
Limnephilus nigriceps	0.15	1.29	1.39	64.13
Paraleptophlebia werneri	0.00	1.17	1.36	65.49
Prodiamesinae	2.39	1.25	1.32	66.80
Polycentropus flavomaculatus	0.00	1.11	1.27	68.08
Silo pallipes	0.00	1.11	1.27	69.34
Hydropsyche instabilus	0.00	1.07	1.25	70.59

Spring 2015

Average dissimilarity between both reaches = 56.83

Taxa	Average Abundance Degraded	Average Abundance Natural	Contribution%	Cumulative%
Baetis rhodani	0.33	4.09	4.50	4.50
Potamopyrgus antipodarum	1.51	4.38	3.47	7.97
Simuliidae	0.10	2.89	3.33	11.31
Hydropsyche siltatay	0.00	2.23	2.68	13.98
Beraea pullata	0.00	2.21	2.63	16.62
Crunoecia irrorata	0.00	2.14	2.58	19.19
Agapetus fuscipes	0.00	2.09	2.51	21.70
Ancylus fluviatilis	0.74	2.80	2.48	24.18

Micropterna sp.	0.00	2.01	2.40	26.58
Lasiocephala basalis	0.00	1.95	2.35	28.93
Lymnaea (Radix) peregra	0.09	2.01	2.33	31.26
Bithynia leachii	0.16	1.86	2.12	33.38
Limnephilus lunatus.	0.26	1.94	2.02	35.40
Lepidostoma hirtum	0.00	1.67	2.00	37.40
Ceraclea sp.	0.18	1.77	1.96	39.36
Pisidium sp.	0.09	1.67	1.94	41.30
Serratella ignita	0.00	1.60	1.91	43.20
Ceratopogonidae	0.80	2.19	1.83	45.04
Gammarus pulex	1.57	3.05	1.78	46.82
Sericostoma personatum	0.19	1.63	1.76	48.58
Ephemera danica	0.00	1.48	1.76	50.34
Paraleptophlebia werneri	0.00	1.43	1.69	52.03
Nais sp.	3.94	2.57	1.64	53.68
Chironominae	4.33	3.01	1.57	55.25
Habrophlebia fusca	1.12	2.34	1.50	56.74
Lymnaea truncatula	0.36	1.60	1.49	58.24
Diplodontus despiciens	0.00	1.20	1.46	59.69
Polycentropus flavomaculatus	0.00	1.17	1.44	61.14
Elmidae	0.00	1.16	1.36	62.50
Planorbis contortus	1.92	0.98	1.36	63.86
Pediciidae	0.00	1.12	1.33	65.19
Lumbriculidae	0.00	1.14	1.32	66.51
Chaetopteryx villosa	0.13	1.19	1.32	67.83
Glyphotaelius pellucidus	0.00	1.14	1.31	69.14
Caenis luctuosa	1.46	1.34	1.26	70.41
Spring 2016				
Average dissimilarity between both reaches = 58.99				
	Average Abundance			
Taxa	Degraded	Natural	Contribution%	Cumulative%
Baetis rhodani	0.49	4.13	4.35	4.35
Potamopyrgus antipodarum	1.29	4.40	3.74	8.09
Simuliidae	0.13	3.18	3.64	11.74
Pisidium sp.	0.00	2.38	2.86	14.59
Ancylus fluviatilis	0.53	2.87	2.80	17.39
Crunoecia irrorata	0.00	2.28	2.73	20.12
Hydropsyche siltatay	0.00	2.22	2.65	22.77
Agapetus fuscipes	0.00	2.23	2.64	25.42
Bithynia leachii	0.20	2.24	2.47	27.89
Serratella ignita	0.00	2.02	2.43	30.32
Micropterna sp.	0.00	2.04	2.42	32.75
Lymnaea (Radix) peregra	0.00	2.04	2.42	35.17
Lasiocephala basalis	0.00	1.89	2.26	37.43
Sphaerium sp.	0.86	2.71	2.23	39.66
Lymnaea truncatula	0.60	2.33	2.07	41.73
Ancylus lacustris	0.00	1.72	2.04	43.77
Lepidostoma hirtum	0.00	1.67	1.97	45.74
Lumbriculidae	0.00	1.63	1.91	47.65
Ceratopogonidae	0.61	1.98	1.84	49.49
Gammarus pulex	1.46	2.97	1.83	51.32
Beraea pullata	0.00	1.61	1.82	53.14
Diplodontus despiciens	0.00	1.50	1.78	54.92
Ceraclea sp.	0.00	1.51	1.76	56.68
Habrophlebia fusca	0.89	2.31	1.72	58.40
Paraleptophlebia werneri	0.00	1.41	1.71	60.11
Chaetopteryx villosa	0.00	1.42	1.65	61.76

Prodiamesinae	2.61	1.23	1.65	63.41
Sericostoma personatum	0.28	1.56	1.61	65.02
Pediciidae	0.00	1.28	1.56	66.58
Ephemera danica	0.00	1.31	1.52	68.10
Caenis luctuosa	1.27	1.13	1.37	69.47
Limnephilus lunatus.	0.00	1.16	1.31	70.79
Spring 2014				
Average dissimilarity between both reaches = 45.23				
	Average Abundance			
Taxa	Degraded	Rehabilitated	Contribution%	Cumulative%
Lumbriculidae	0.00	2.07	5.25	5.25
Planorbis contortus	1.56	0.00	3.96	9.21
Orthocladiinae	2.80	1.40	3.56	12.77
Nais sp.	3.49	2.11	3.51	16.28
Agapetus fuscipes	0.00	1.21	3.06	19.34
Potamopyrgus antipodarum	1.17	0.00	2.95	22.28
Habrophlebia fusca	1.06	0.00	2.66	24.94
Tanypodinae	2.38	1.34	2.63	27.57
Ceratopogonidae	0.61	1.05	2.44	30.01
Lebirtia porosa	1.33	1.34	2.39	32.40
Hydropsyche siltatay	0.00	0.93	2.30	34.70
Hygrobates sp (longu)	2.65	1.76	2.27	36.97
Baetis rhodani	0.67	1.53	2.27	39.24
Simuliidae	0.14	1.03	2.25	41.49
Bithynia tentaculata	0.87	0.74	2.20	43.69
Pisidium sp.	0.00	0.90	2.20	45.89
Tubificidae	2.93	3.20	2.04	47.93
Sialis lutaria	0.15	0.88	2.03	49.96
Sericostoma personatum	0.28	0.72	1.95	51.91
Mystacides longicornis (azurea)	0.00	0.73	1.85	53.77
Lymnaea (Radix) peregra	0.00	0.76	1.84	55.61
Limnephilus lunatus.	0.15	0.84	1.81	57.42
Bithynia leachii	0.21	0.76	1.77	59.18
Velia caprai	0.00	0.68	1.76	60.95
Sperchon sp.	0.64	0.13	1.69	62.64
Gammarus pulex	1.73	1.08	1.67	64.31
Coenagrion sp.	0.25	0.90	1.66	65.98
Caenis luctuosa	1.30	1.10	1.59	67.57
Sphaerium sp.	0.70	0.33	1.54	69.11
Psychodidae	0.43	0.44	1.52	70.63
Spring 2015				
Average dissimilarity between both reaches = 43.48				
	Average Abundance			
Taxa	Degraded	Rehabilitated	Contribution%	Cumulative%
Simuliidae	0.10	2.24	4.78	4.78
Chironominae	4.33	2.67	3.83	8.61
Mystacides longicornis (azurea)	0.18	1.71	3.59	12.20
Planorbis contortus	1.92	0.74	2.87	15.07
Agapetus fuscipes	0.00	1.25	2.86	17.93
Baetis rhodani	0.33	1.46	2.77	20.70
Sperchon sp.	0.67	1.25	2.60	23.29
Lumbriculidae	0.00	1.10	2.48	25.78
Limnephilus lunatus.	0.26	1.31	2.47	28.25
Ceratopogonidae	0.80	1.45	2.43	30.68
Lebirtia porosa	1.37	2.31	2.35	33.03
Nais sp.	3.94	3.20	2.26	35.29
Sericostoma personatum	0.19	1.00	2.21	37.50

Glossiphonia complanata	1.23	0.26	2.19	39.70
Chaetopteryx villosa	0.13	1.02	2.16	41.86
Ceraclea sp.	0.18	0.91	2.09	43.95
Centroptilum luteolum	0.00	0.93	2.09	46.05
Prodiamesinae	2.19	1.39	2.05	48.10
Habrophlebia fusca	1.12	0.46	1.92	50.02
Polycentropus flavomaculatus	0.00	0.84	1.90	51.92
Bithynia tentaculata	0.95	0.36	1.88	53.80
Beraea pullata	0.00	0.81	1.86	55.66
Tanypodinae	2.47	1.80	1.84	57.51
Lymnaea (Radix) peregra	0.09	0.84	1.82	59.32
Pediciidae	0.00	0.83	1.78	61.11
Tubificidae	2.69	2.86	1.61	62.71
Potamopyrgus antipodarum	1.51	1.58	1.61	64.32
Erpobdella octoculata	0.96	0.97	1.59	65.91
Sphaerium sp.	1.15	1.13	1.48	67.39
Psychodidae	0.64	0.00	1.38	68.77
Caenis luctuosa	1.46	1.32	1.36	70.13

Spring 2016

Average dissimilarity between both reaches = 51.32

	Average Abundance			
Taxa	Degraded	Rehabilitated	Contribution%	Cumulative%
Potamopyrgus antipodarum	1.29	3.65	3.56	3.56
Lumbriculidae	0.00	2.26	3.40	6.96
Mystacides longicornis (azurea)	0.00	2.22	3.34	10.30
Sphaerium sp.	0.86	2.92	3.11	13.41
Limnephilus lunatus.	0.00	2.04	3.07	16.48
Hydropsyche siltatay	0.00	2.02	3.03	19.51
Gammarus pulex	1.46	3.44	2.99	22.50
Lymnaea (Radix) peregra	0.00	1.94	2.92	25.42
Beraea pullata	0.00	1.91	2.87	28.29
Micropterna sp.	0.00	1.86	2.80	31.09
Baetis rhodani	0.49	2.19	2.56	33.65
Sericostoma personatum	0.28	1.96	2.55	36.20
Ceraclea sp.	0.00	1.60	2.41	38.62
Helobdella stagnalis	0.00	1.59	2.38	41.00
Bithynia tentaculata	0.46	2.04	2.37	43.37
Chaetopteryx villosa	0.00	1.57	2.37	45.75
Ancylus fluviatilis	0.53	2.08	2.34	48.08
Pisidium sp.	0.00	1.47	2.20	50.28
Simuliidae	0.13	1.58	2.17	52.45
Lasiocephala basalis	0.00	1.40	2.10	54.56
Centroptilum luteolum	0.00	1.39	2.10	56.66
Lebirtia porosa	1.17	2.57	2.10	58.75
Polycentropus flavomaculatus	0.00	1.37	2.07	60.83
Asellus aquaticus	1.23	2.59	2.05	62.88
Glyphotaelius pellucidus	0.00	1.31	1.98	64.86
Chironominae	4.17	2.87	1.96	66.82
Ceratopogonidae	0.61	1.79	1.96	68.77
Agapetus fuscipes	0.00	1.27	1.90	70.68

Spring 2014

Average dissimilarity between both reaches = 54.28

	Average Abundance			
Taxa	Natural	Rehabilitated	Contribution%	Cumulative%
Potamopyrgus antipodarum	4.31	0.00	5.19	5.19
Ancylus fluviatilis	2.77	0.00	3.33	8.52
Baetis rhodani	4.24	1.53	3.26	11.78

Habrophlebia fusca	2.34	0.00	2.82	14.60
Beraea pullata	2.56	0.27	2.75	17.35
Lymnaea truncatula	2.05	0.00	2.47	19.82
Simuliidae	3.07	1.03	2.47	22.29
Lasiocephala basalis	1.98	0.00	2.39	24.68
Ephemera danica	1.96	0.00	2.36	27.04
Sphaerium sp.	2.24	0.33	2.32	29.35
Gammarus pulex	2.96	1.08	2.25	31.60
Crunoecia irrorata	2.07	0.25	2.18	33.78
Lepidostoma hirtum	1.80	0.00	2.15	35.94
Elmidae	1.71	0.00	2.06	38.00
Glyphotaelius pellucidus	1.68	0.00	2.04	40.04
Planorbis contortus	1.60	0.00	1.92	41.96
Serratella ignita	1.57	0.00	1.89	43.85
Micropterna sp.	1.96	0.46	1.82	45.67
Limnesia sp	1.48	0.00	1.79	47.47
Ceraclea sp.	2.00	0.56	1.72	49.18
Hydropsyche siltatay	2.26	0.93	1.63	50.81
Limnephilus nigriceps	1.29	0.00	1.55	52.36
Limnephilus lunatus.	2.10	0.84	1.52	53.88
Ceratopogonidae	2.19	1.05	1.52	55.40
Sericostoma personatum	1.91	0.72	1.42	56.83
Paraleptophlebia werneri	1.17	0.00	1.41	58.24
Lymnaea (Radix) peregra	1.91	0.76	1.40	59.64
Caenis luctuosa	2.24	1.10	1.37	61.02
Polycentropus flavomaculatus	1.11	0.00	1.32	62.33
Silo pallipes	1.11	0.00	1.32	63.65
Hydropsyche instabilus	1.07	0.00	1.29	64.95
Orthocladiinae	2.47	1.40	1.28	66.23
Sperchon sp.	1.15	0.13	1.26	67.49
Pisidium sp.	1.03	0.90	1.25	68.74
Bithynia leachii	1.02	0.76	1.22	69.96
Ancylus lacustris	0.99	0.00	1.18	71.14
Spring 2015				
Average dissimilarity between both reaches = 44.09				
	Average Abundance			
Taxa	Natural	Rehabilitated	Contribution%	Cumulative%
Potamopyrgus antipodarum	4.38	1.58	4.02	4.02
Baetis rhodani	4.09	1.46	3.79	7.81
Ancylus fluviatilis	2.80	0.48	3.33	11.14
Hydropsyche siltatay	2.23	0.09	3.07	14.22
Micropterna sp.	2.01	0.08	2.74	16.96
Bithynia leachii	1.86	0.00	2.70	19.66
Habrophlebia fusca	2.34	0.46	2.70	22.36
Crunoecia irrorata	2.14	0.29	2.64	25.00
Lasiocephala basalis	1.95	0.41	2.26	27.26
Lepidostoma hirtum	1.67	0.19	2.12	29.38
Ephemera danica	1.48	0.00	2.10	31.48
Beraea pullata	2.21	0.81	2.09	33.57
Lymnaea truncatula	1.60	0.23	1.99	35.56
Serratella ignita	1.60	0.31	1.98	37.55
Paraleptophlebia werneri	1.43	0.08	1.98	39.53
Pisidium sp.	1.67	0.40	1.96	41.49
Polycentropus flavomaculatus	1.17	0.84	1.86	43.35
Diplodontus despiciens	1.20	0.00	1.74	45.09
Lymnaea (Radix) peregra	2.01	0.84	1.72	46.81
Glyphotaelius pellucidus	1.14	0.00	1.57	48.38

Sperchon sp.	0.85	1.25	1.56	49.94
Ceraclea sp.	1.77	0.91	1.53	51.46
Sphaerium sp.	2.14	1.13	1.50	52.96
Elmidae	1.16	0.20	01.49	54.46
Pediciidae	1.12	0.83	1.47	55.92
Gammarus pulex	3.05	2.05	1.44	57.36
Caenis luctuosa	1.34	1.32	1.39	58.75
Plectrocnemia conspersa	0.91	0.08	1.35	60.09
Sericostoma personatum	1.63	1.00	1.34	61.43
Agapetus fuscipes	2.09	1.25	1.31	62.73
Ptychopteridae	0.93	0.00	1.30	64.03
Ceratopogonidae	2.19	1.45	1.29	65.32
Simuliidae	2.89	2.24	1.28	66.60
Mystacides longicornis (azurea)	1.08	1.71	1.24	67.83
Hydroptilidae	0.63	0.54	1.23	69.07
Planorbis contortus	0.98	0.74	1.23	70.30

Spring 2016

Average dissimilarity between both reaches = 32.44

	Average Abundance			
Taxa	Natural	Rehabilitated	Contribution%	Cumulative%
Crunoecia irrorata	2.28	0.00	3.66	3.66
Serratella ignita	2.02	0.00	3.26	6.92
Baetis rhodani	4.13	2.19	3.10	10.03
Bithynia tentaculata	0.14	2.04	3.07	13.10
Lepidostoma hirtum	1.67	0.00	2.65	15.75
Simuliidae	3.18	1.58	2.57	18.32
Helobdella stagnalis	0.00	1.59	2.54	20.86
Bithynia leachii	2.24	0.69	2.49	23.35
Diplodontus despiciens	1.50	0.00	2.39	25.74
Mystacides longicornis (azurea)	0.80	2.22	2.31	28.05
Paraleptophlebia werneri	1.41	0.00	2.28	30.33
Caenis luctuosa	1.13	2.36	2.21	32.54
Lymnaea truncatula	2.33	0.98	2.17	34.71
Beraea pullata	1.61	1.91	2.14	36.85
Prodiamesinae	1.23	2.55	2.11	38.96
Ephemera danica	1.31	0.00	2.06	41.02
Glyphotaelius pellucidus	0.38	1.31	2.02	43.04
Ancylus lacustris	1.72	0.78	1.91	44.95
Pediciidae	1.28	0.33	1.74	46.69
Glossiphonia complanata	0.68	1.72	1.72	48.41
Limnephilus lunatus.	1.16	2.04	1.69	50.10
Plectrocnemia conspersa	1.04	0.00	1.67	51.78
Polycentropus flavomaculatus	0.35	1.37	1.63	53.41
Habrophlebia fusca	2.31	1.32	1.60	55.01
Centroptilum luteolum	0.43	1.39	1.59	56.59
Hydroptilidae	0.94	0.00	1.58	58.17
Agapetus fuscipes	2.23	1.27	1.54	59.71
Pisidium sp.	2.38	1.47	1.48	61.19
Lebirtia porosa	1.67	2.57	1.47	62.67
Elmidae	1.01	1.16	1.47	64.14
Tabanidae	0.95	0.00	1.46	65.59
Psychodidae	0.92	0.00	1.44	67.03
Silo pallipes	0.90	0.68	1.42	68.45
Orthocladiinae	2.84	2.14	1.27	69.72
Ancylus fluviatilis	2.87	2.08	1.26	70.98

Appendix 4.13. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomical composition (Count m^{-2}) data, identifying families contributing 70% of the spatial dissimilarity in community composition between the study reaches. Reaches were compared seasonally before and after the rehabilitation process. Average abundances presented in individuals m^{-2}.

Spring 2014				
Average dissimilarity between both reaches= 78.16				
	Average Abundance			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	3	347	16.55	16.55
Baetidae	2	335	15.96	32.51
Chironomidae (non- Tanypodinae)	415	93	15.05	47.56
Naididae	161	43	5.62	53.18
Simuliidae	0.09	99.07	4.71	57.89
Tubificidae	107.58	96.69	4.18	62.07
Planorbidae	9.57	79.86	3.40	65.47
Gammaridae	9.78	78.84	3.34	68.81
Limnephilidae	0.63	64.18	3.04	71.85
Summer 2014				
Average dissimilarity between both reaches = 63.60				
	Average Abundance			
Family	Degraded	Natural	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	404.93	1158.72	28.03	28.03
Simuliidae	0.00	464.78	17.06	45.09
Gammaridae	10.18	242.94	8.59	53.68
Baetidae	0.11	225.55	8.24	61.93
Hydrobiidae	173.06	359.99	7.29	69.22
Ephemerellidae	2.46	142.39	5.16	74.37
Winter 2015				
Average dissimilarity between both reaches = 85.71				
	Average Abundance			
Family	Degraded	Natural	Contribution%	Cumulative%
Naididae	514.53	13.83	26.00	26.00
Chironomidae (non- Tanypodinae)	300.68	34.67	16.23	42.24
Tubificidae	265.11	53.88	14.16	56.40
Baetidae	0.28	131.75	7.78	64.18
Hydrobiidae	1.72	111.34	6.49	70.67
Spring 2015				
Average dissimilarity between both reaches = 78.66				
	Average Abundance			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	7.69	403.53	17.63	17.63
Chironomidae (non- Tanypodinae)	476.77	112.34	15.78	33.40
Baetidae	1.13	309.33	13.56	46.97
Naididae	304.16	35.64	11.31	58.28
Simuliidae	0.09	83.05	3.57	61.85
Gammaridae	7.70	85.64	3.51	65.35
Tubificidae	76.86	70.05	2.99	68.35
Planorbidae	20.41	80.00	2.71	71.06

Summer 2015				
Average dissimilarity between both reaches = 58.21				
	Average Abundance			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	310.68	1012.12	25.15	25.15
Chironomidae (non- Tanypodinae)	517.06	990.79	19.30	44.45
Simuliidae	0.00	296.35	10.86	55.31
Gammaridae	6.18	223.64	7.81	63.13
Baetidae	0.54	139.74	5.09	68.22
Ephemerellidae	0.25	94.00	3.44	71.66
Autumn 2015				
Average dissimilarity between both reaches = 74.03				
	Average Abundance			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	80.11	1408.05	44.39	44.39
Chironomidae (non- Tanypodinae)	314.83	343.20	7.84	52.23
Leptoceridae	0.57	171.56	5.98	58.21
Tubificidae	178.77	95.32	5.31	63.52
Planorbidae	136.13	36.03	4.32	67.84
Goeridae	0.29	102.68	3.67	71.51
Winter 2016				
Average dissimilarity between both reaches = 84.21				
	Average Abundance			
Family	Degraded	Natural	Contribution%	Cumulative%
Tubificidae	912.43	44.98	39.56	39.56
Chironomidae (non- Tanypodinae)	199.98	53.22	7.91	47.47
Baetidae	0.88	114.86	7.32	54.79
Naididae	147.94	18.91	6.03	60.82
Hydrobiidae	0.03	89.04	5.82	66.63
Simuliidae	0.97	47.64	2.99	69.63
Limnephilidae	0.32	45.59	2.93	72.56
Spring 2016				
Average dissimilarity between both reaches = 79.96				
	Average Abundance			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	3.63	377.05	17.68	17.68
Chironomidae (non- Tanypodinae)	470.82	92.53	17.36	35.04
Baetidae	1.61	290.79	13.68	48.72
Simuliidae	0.07	107.71	5.03	53.75
Naididae	143.28	48.96	4.55	58.30
Planorbidae	8.50	92.29	3.93	62.23
Tubificidae	106.51	54.15	3.83	66.06
Gammaridae	6.58	79.00	3.43	69.49
Sphaeriidae	1.03	54.61	2.56	72.05
Summer 2016				
Average dissimilarity between both reaches = 59.85				
	Average Abundance			
Family	Degraded	Natural	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	373.05	1067.36	26.97	26.97
Simuliidae	0.00	476.23	18.44	45.41
Gammaridae	6.96	249.31	9.41	54.82
Hydrobiidae	266.04	487.66	8.66	63.48
Baetidae	0.08	165.68	6.43	69.91
Ephemerellidae	2.26	135.92	5.20	75.11

Spring 2014

Average dissimilarity between both reaches= 49.45

	Average Abundance			
Family	Degraded	Before-Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	415	206	31.40	31.40
Naididae	161.93	20	21.91	53.32
Tubificidae	107.58	107	13.89	67.21
Hygrobatidae	51.25	10	6.64	73.85

Winter 2015

Average dissimilarity between both reaches = 89.71

	Average Abundance			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Naididae	514.53	4	34.94	34.94
Chironomidae (non- Tanypodinae)	300.68	29	23.68	58.62
Tubificidae	265	22.48	23.00	81.61

Spring 2015

Average dissimilarity between both reaches = 57.03

	Average Abundance			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	476.77	132	35.73	35.73
Naididae	304	108	21.90	57.63
Tubificidae	76.86	75	7.55	65.18
Simuliidae	0.09	42	4.26	69.44
Hygrobatidae	51	69	3.49	72.93

Summer 2015

Average dissimilarity between both reaches = 53.31

	Average Abundance			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	517	275	22.42	22.42
Hydrobiidae	310.68	492	20.06	42.48
Hygrobatidae	31	135	7.22	49.70
Lymnaeidae	7.34	101.48	5.84	55.54
Naididae	97.56	15	5.49	61.03
Asellidae	29.70	116	5.27	66.30
Tubificidae	91	91.48	4.06	70.37

Autumn 2015

Average dissimilarity between both reaches = 68.94

	Average Abundance			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	314.83	54.68	18.78	18.78
Caenidae	0	144.15	10.39	29.18
Tubificidae	178.77	68.38	10.07	39.24
Planorbidae	136.13	53	9.16	48.40
Naididae	108.96	38.82	6.17	54.57
Lymnaeidae	11.16	73.76	5.51	60.07
Hydrobiidae	80.11	67	5.01	65.08
Asellidae	8.11	67.37	4.78	69.86
Hygrobatidae	27.70	88.03	4.51	74.37

Winter 2016

Average dissimilarity between both reaches = 73.70

Family	Average Abundance: Degraded	Average Abundance: Rehabilitated	Contribution%	Cumulative%
Tubificidae	912	130	41.61	41.61
Chironomidae (non- Tanypodinae)	199.98	47	9.71	51.33
Naididae	147.94	46	7.27	58.60
Caenidae	0	77.51	5.37	63.97
Sphaeriidae	0	40.61	3.00	66.97
Libertiidae	8.56	40	2.49	69.45
Lumbriculidae	0	25	2.33	71.78

Spring 2016

Average dissimilarity between both reaches = 66.01

Family	Average Abundance: Degraded	Average Abundance: Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	470.82	137	23.99	23.99
Hydrobiidae	3.63	180	12.97	36.96
Gammaridae	6.58	141	9.94	46.90
Naididae	143.28	69	7.01	53.91
Tubificidae	106.51	65	6.05	59.96
Sphaeriidae	1	75	5.48	65.43
Asellidae	4	46	3.13	68.56
Limnephilidae	0.56	41	2.99	71.55

Summer 2016

Average dissimilarity between both reaches = 46.20

Family	Average Abundance: Degraded	Average Abundance: Rehabilitated	Contribution%	Cumulative%
Asellidae	24	220	11.97	11.97
Gammaridae	7	188	11.96	23.93
Naididae	54.84	201	10.38	34.31
Hygrobatidae	47.75	142	7.13	41.44
Chironomidae (non- Tanypodinae)	373.05	288	6.92	48.36
Hydrobiidae	266.04	243.85	6.45	54.80
Ephemerellidae	2.26	80	5.73	60.53
Lymnaeidae	2.52	65	4.17	64.70
Tubificidae	105	58.86	3.77	68.47
Limnephilidae	1.37	57.63	3.42	71.89

Spring 2014

Average dissimilarity between both reaches= 77.06

Family	Average Abundance: Natural	Average Abundance: Before-Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	347	0	20.11	20.11
Baetidae	335	6	18.95	39.06
Chironomidae (non- Tanypodinae)	93	206	6.51	45.57
Simuliidae	99	1	5.58	51.15
Planorbidae	79.86	0	4.64	55.79
Gammaridae	78.84	3	4.45	60.24
Limnephilidae	64.18	1.38	3.61	63.85
Lepidostomatidae	49.69	0.10	2.85	66.70
Leptophlebiidae	46.54	0	2.68	69.38
Beraeidae	45.36	0.15	2.59	71.97

Winter 2015				
Average dissimilarity between both reaches = 79.85				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Baetidae	131.75	4.67	17.35	17.35
Hydrobiidae	111.34	1.74	14.92	32.26
Simuliidae	50.19	7.54	5.82	38.09
Hydropsychidae	40.16	0.07	5.35	43.43
Tubificidae	53.88	22.48	5.16	48.59
Planorbidae	29.90	0.65	4.07	52.66
Lumbriculidae	30.55	2.39	3.86	56.52
Limnephilidae	30.45	6.42	3.75	60.27
Leptoceridae	28.61	1.63	3.65	63.92
Libertiidae	12.20	30.98	3.55	67.47
Ceratopogonidae	23.59	0.17	3.23	70.70
Spring 2015				
Average dissimilarity between both reaches = 69.57				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	403.53	18	22.50	22.50
Baetidae	309.33	14.17	17.07	39.56
Planorbidae	80.00	2.81	4.54	44.11
Naididae	35.64	108.00	4.23	48.34
Chironomidae	112.34	131.60	3.99	52.32
Gammaridae	85.64	21	3.83	56.16
Simuliidae	83.05	42	3.66	59.82
Polycentropodidae	58.07	1.79	3.54	63.36
Limnephilidae	62.14	7	3.18	66.53
Hygrobatidae	22.61	69	2.73	69.27
Lepidostomatidae	49.50	3.42	2.66	71.93
Summer 2015				
Average dissimilarity between both reaches = 63.60				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	1012.12	492	26.06	26.06
Chironomidae (non- Tanypodinae)	990.79	275	23.60	49.66
Simuliidae	296.35	0.42	9.60	59.25
Gammaridae	223.64	53	5.41	64.66
Baetidae	139.74	2.84	4.43	69.09
Asellidae	3.06	116	3.45	72.55
Autumn 2015				
Average dissimilarity between both reaches = 74.30				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	1408.05	67.02	44.97	44.97
Chironomidae (non- Tanypodinae)	343.20	54.68	9.59	54.56
Leptoceridae	171.56	60.86	4.87	59.43
Caenidae	13.30	144.15	4.81	64.24
Goeridae	102.68	4.14	3.52	67.76
Gammaridae	100.05	20.45	2.90	70.66

Winter 2016				
Average dissimilarity between both reaches = 58.16				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Baetidae	114.86	33.70	9.56	9.56
Tubificidae	44.98	130	8.23	17.79
Hydrobiidae	89.04	23.43	8.17	25.96
Caenidae	7.15	77.51	7.00	32.96
Naididae	18.91	46	4.56	37.52
Libertiidae	2.65	40	4.40	41.92
Hygrobatidae	5.45	40	4.04	45.96
Simuliidae	47.64	17.86	4.02	49.98
Hydropsychidae	35.83	0	3.96	53.93
Lepidostomatidae	34.27	1.42	3.65	57.58
Lumbriculidae	28.32	25	3.42	61.00
Planorbidae	23.14	35.66	3.27	64.27
Chironomidae (non- Tanypodinae)	53.22	47	3.13	67.40
Beraeidae	21.81	27.29	3.08	70.48
Spring 2016				
Average dissimilarity between both reaches = 47.24				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Baetidae	290.79	28.30	18.78	18.78
Hydrobiidae	377.05	180	14.24	33.02
Simuliidae	107.71	6.44	7.15	40.17
Planorbidae	92.29	30.41	4.44	44.61
Gammaridae	79.00	141	4.35	48.96
Naididae	48.96	69.34	3.38	52.34
Lepidostomatidae	50.38	4	3.30	55.64
Chironomidae (non- Tanypodinae)	92.53	137	3.15	58.79
Leptophlebiidae	48.05	3.66	3.15	61.94
Beraeidae	38.19	14.95	2.61	64.54
Limnephilidae	53.49	41	2.52	67.07
Libertiidae	11.84	45	2.35	69.41
Hygrobatidae	26.91	54	1.95	71.37
Summer 2016				
Average dissimilarity between both reaches = 55.77				
	Average Abundance			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Chironomidae (non- Tanypodinae)	1067	288	26.98	26.98
Simuliidae	476.23	0.43	16.39	43.37
Hydrobiidae	487.66	244	8.79	52.16
Asellidae	1.17	219.54	6.80	58.96
Naididae	12	201	6.45	65.41
Baetidae	165.68	19.11	5.11	70.52

Appendix 4.14. Summary of the two-way PERMANOVA pair-wise results for most affected macroinvertebrate family Density for each reach separately

Degraded reach				Natural reach				Rehabilitated reach			
Chironomidae (individual m^{-2})				**Chironomidae (individual m^{-2})**				**Chironomidae (individual m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.96247	0.3536	4305	Sp.14, Sp.15	0.7786	0.451	462	Sp.14, Sp.15	2.3283	**0.0441**	2544
Sp.14, Sp.16	0.54207	0.5781	460	Sp.14, Sp.16	1.895	0.1232	460	Sp.14, Sp.16	2.5076	**0.0443**	245
Sp.15, Sp.16	0.25032	0.8275	4324	Sp.15, Sp.16	1.3138	0.2125	462	Sp.15, Sp.16	0.56158	0.5857	4283
Su.14, Su.15	0.92497	0.3821	4300	Su.14, Su.15	1.3044	0.231	4297				
Su.14, Su.16	0.16271	0.9353	462	Su.14, Su.16	2.0728	0.0629	462				
Su.15, Su.16	1.2622	0.2304	4296	Su.15, Su.16	0.74811	0.466	4325	Su.15, Su.16	0.88595	0.3983	4317
Gammaridae (individual m^{-2})				**Gammaridae (individual m^{-2})**				**Gammaridae (individual m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.91839	0.3585	4320	Sp.14, Sp.15	0.8449	0.4033	4315	Sp.14, Sp.15	4.713	**0.0002**	2589
Sp.14, Sp.16	1.3252	0.2182	462	Sp.14, Sp.16	0.1207	0.9062	439	Sp.14, Sp.16	13.803	**0.0019**	245
Sp.15, Sp.16	0.56683	0.5733	4298	Sp.15, Sp.16	0.84595	0.3974	4289	Sp.15, Sp.16	8.2042	**0.0002**	4277
Su.14, Su.15	1.4161	0.197	3369	Su.14, Su.15	1.3661	0.2028	4278				
Su.14, Su.16	0.88691	0.3955	462	Su.14, Su.16	0.65228	0.5326	462				
Su.15, Su.16	0.96166	0.3664	3353	Su.15, Su.16	1.7569	0.1033	4296	Su.15, Su.16	4.2461	**0.0008**	4319
Hydrobiidae (individual m^{-2})				**Hydrobiidae (individual m^{-2})**				**Hydrobiidae (individual m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.5455	0.1299	2561	Sp.14, Sp.15	0.62565	0.5356	4324	Sp.14, Sp.15	4.646	**0.0004**	339
Sp.14, Sp.16	0.59133	0.5567	245	Sp.14, Sp.16	1.222	0.2559	462	Sp.14, Sp.16	43.936	**0.0023**	32
Sp.15, Sp.16	1.0839	0.3046	2552	Sp.15, Sp.16	0.21405	0.846	4287	Sp.15, Sp.16	5.9727	**0.0004**	3366
Su.14, Su.15	1.9351	0.0754	4311	Su.14, Su.15	1.8768	0.0579	4300				
Su.14, Su.16	1.7428	0.1435	462	Su.14, Su.16	1.2517	0.0525	462				
Su.15, Su.16	0.28688	0.7758	4327	Su.15, Su.16	1.1807	0.2785	4305	Su.15, Su.16	0.62166	0.676	4333

Simuliidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms

Simuliidae (individual/m^{2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.71282	0.4889	4293
Sp.14, Sp.16	0.50153	0.6223	462
Sp.15, Sp.16	1.2657	0.2266	4295
Su.14, Su.15	1.66	0.1016	2267
Su.14, Su.16	0.18787	0.752	462
Su.15, Su.16	1.6858	0.101	2270

Simuliidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	3.4326	**0.01**	1460
Sp.14, Sp.16	5.3839	**0.0017**	131
Sp.15, Sp.16	1.8995	0.0783	2592
Su.15, Su.16	0.68728	0.503	246

Limnephilidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.7133	0.1166	421
Sp.14, Sp.16	0.42803	0.637	72
Sp.15, Sp.16	2.0514	0.0602	251
Su.14, Su.15	2.3941	0.0534	520
Su.14, Su.16	0.42334	0.5797	154
Su.15, Su.16	2.1759	0.0514	425

Limnephilidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.1614	0.2604	4329
Sp.14, Sp.16	0.99439	0.3468	462
Sp.15, Sp.16	0.22545	0.8276	4268
Su.14, Su.15	1.9114	0.0678	4328
Su.14, Su.16	1.3844	0.184	461
Su.15, Su.16	1.3411	0.2072	4317

Limnephilidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	3.6755	**0.0048**	1948
Sp.14, Sp.16	13.819	**0.0025**	131
Sp.15, Sp.16	6.8345	**0.0002**	3342
Su.15, Su.16	2.2078	**0.0464**	4300

Libertiidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.068834	0.9489	1410
Sp.14, Sp.16	0.26114	0.8092	119
Sp.15, Sp.16	0.39623	0.6981	1408
Su.14, Su.15	0.62178	0.5519	4337
Su.14, Su.16	0.55228	0.5968	461
Su.15, Su.16	1.3025	0.2271	4295

Libertiidae (individual/m^{2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.0477	0.3137	4286
Sp.14, Sp.16	1.5224	0.1633	462
Sp.15, Sp.16	1.0156	0.3292	4280
Su.14, Su.15	1.3343	0.1959	4292
Su.14, Su.16	2.7764	0.0589	462
Su.15, Su.16	1.8466	0.0518	4275

Libertiidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	5.6088	**0.0005**	3351
Sp.14, Sp.16	12.294	**0.0025**	245
Sp.15, Sp.16	1.3673	0.1908	3333
Su.15, Su.16	0.3042	0.848	4292

Hygrobatidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.00538	0.9973	4356
Sp.14, Sp.16	0.65972	0.5336	461
Sp.15, Sp.16	0.72032	0.4721	4282
Su.14, Su.15	2.0714	0.064	4297
Su.14, Su.16	0.45248	0.6171	462
Su.15, Su.16	1.5902	0.1404	4315

Hygrobatidae (individual/m^{2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.0844	0.2787	4302
Sp.14, Sp.16	0.10224	0.9188	461
Sp.15, Sp.16	1.2451	0.2296	4294
Su.14, Su.15	0.53051	0.6035	4288
Su.14, Su.16	1.6562	0.1164	462
Su.15, Su.16	0.58967	0.5657	4331

Hygrobatidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	6.3599	**0.0005**	4289
Sp.14, Sp.16	13.522	**0.002**	459
Sp.15, Sp.16	0.70259	0.4984	4290
Su.15, Su.16	0.60746	0.5485	4261

Tubificidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.55317	0.5769	4302
Sp.14, Sp.16	0.082545	0.8586	457
Sp.15, Sp.16	0.67698	0.4775	4310
Su.14, Su.15	0.24187	0.8529	4302
Su.14, Su.16	0.52663	0.8287	462
Su.15, Su.16	0.91892	0.3641	4277

Tubificidae (individual/m^{2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	2.0646	0.0607	4267
Sp.14, Sp.16	2.3275	0.0532	462
Sp.15, Sp.16	0.33787	0.7315	4284
Su.14, Su.15	0.6079	0.54	4299
Su.14, Su.16	0.33723	0.7406	462
Su.15, Su.16	0.83412	0.4124	4248

Tubificidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.9351	0.0745	3342
Sp.14, Sp.16	3.1219	**0.017**	245
Sp.15, Sp.16	0.2758	0.8159	3371
Su.15, Su.16	1.2582	0.229	3310

Naididae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.1336	0.2682	4284
Sp.14, Sp.16	0.42879	0.6194	461
Sp.15, Sp.16	1.4267	0.1693	4304
Su.14, Su.15	1.3913	0.1802	4295
Su.14, Su.16	0.14465	0.8798	461
Su.15, Su.16	1.3104	0.2144	4331

Naididae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.11782	0.9087	4245
Sp.14, Sp.16	0.35067	0.8056	462
Sp.15, Sp.16	0.43536	0.6854	4285
Su.14, Su.15	0.15675	0.8789	3339
Su.14, Su.16	0.016148	0.9858	461
Su.15, Su.16	0.14319	0.8973	3283

Naididae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	10.676	**0.0005**	1964
Sp.14, Sp.16	3.3073	**0.002**	179
Sp.15, Sp.16	2.2417	0.0522	4243
Su.15, Su.16	6.2554	**0.0003**	2583

Sphaeriidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.5361	0.1485	1726
Sp.14, Sp.16	0.56243	0.6258	154
Sp.15, Sp.16	1.0657	0.3102	3317
Su.14, Su.15	0.44256	0.6747	2258
Su.14, Su.16	0.043347	0.9001	333
Su.15, Su.16	0.39757	0.6972	2265

Sphaeriidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.82402	0.4143	4319
Sp.14, Sp.16	0.67698	0.4775	460
Sp.15, Sp.16	0.56683	0.5733	4306
Su.14, Su.15	0.25733	0.8127	4318
Su.14, Su.16	1.2451	0.2296	462
Su.15, Su.16	1.895	0.1232	4300

Sphaeriidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	2.5629	**0.0265**	453
Sp.14, Sp.16	11.142	**0.0027**	88
Sp.15, Sp.16	6.3343	**0.0004**	3331
Su.15, Su.16	2.3574	**0.0321**	4290

Leptoceridae (individual/m^{2})			
Seasons	t	P(perm)	Unique perms

Leptoceridae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.33491	0.7335	4278
Sp.14, Sp.16	2.2899	0.0594	462
Sp.15, Sp.16	2.4691	**0.0284**	4162
Su.14, Su.15	1.016	0.3247	4303
Su.14, Su.16	0.56243	0.6258	462
Su.15, Su.16	0.0542	0.9565	4232

Leptoceridae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	5.4447	**0.0002**	3367
Sp.14, Sp.16	36.885	**0.0012**	179
Sp.15, Sp.16	3.0335	**0.0089**	2557
Su.15, Su.16	0.91802	0.3956	4305

Asellidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.29485	0.7946	4319
Sp.14, Sp.16	1.2986	0.2167	462
Sp.15, Sp.16	0.64144	0.5325	3321
Su.14, Su.15	1.0048	0.3305	4294
Su.14, Su.16	0.24639	0.7989	462
Su.15, Su.16	1.0887	0.2957	4314

Asellidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.56158	0.5857	2264
Sp.14, Sp.16	1.7666	0.0905	210
Sp.15, Sp.16	2.0274	0.0613	4251
Su.14, Su.15	1.6962	0.16	64
Su.14, Su.16	0.88168	0.4606	4
Su.15, Su.16	0.81014	0.455	126

Asellidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.51188	0.6518	4307
Sp.14, Sp.16	3.7111	**0.0047**	462
Sp.15, Sp.16	7.6979	**0.0001**	4316
Su.15, Su.16	1.4599	0.1583	4303

Planorbidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.2122	0.25	2581
Sp.14, Sp.16	0.14647	0.8589	336
Sp.15, Sp.16	1.373	0.1932	3325
Su.14, Su.15	1.9992	0.0683	4289
Su.14, Su.16	0.19351	0.8293	462
Su.15, Su.16	2.325	0.0511	4254

Planorbidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.73838	0.5053	4342
Sp.14, Sp.16	1.0893	0.3136	462
Sp.15, Sp.16	1.7666	0.0905	4266
Su.14, Su.15	1.6805	0.1192	4240
Su.14, Su.16	1.5736	0.1376	460
Su.15, Su.16	0.69537	0.4945	4287

Planorbidae (individual m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	4.1938	**0.0024**	244
Sp.14, Sp.16	14.245	**0.0022**	32
Sp.15, Sp.16	5.0032	**0.0007**	4304
Su.15, Su.16	3.6045	**0.0019**	4285

Appendix 4.15. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate community taxonomical composition (Biomass m^{-2}) data, identifying families contributing 70% of the spatial dissimilarity in community composition between the study reaches. Reaches were compared seasonally before and after the rehabilitation process. Average biomass presented in mgDM m^{-2}.

Spring 2014				
Average dissimilarity between both reaches= 92.37				
	Average Biomass			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	15	873	32.98	32.98
Lymnaeidae	0.13	350	12.79	45.77
Limnephilidae	0.69	268.81	10.88	56.65
Pisidiidae	0	214.63	6.94	63.59
Planorbidae	2.23	156.74	5.59	69.18
Erpobdellidae	57.35	103.76	3.93	73.11
Summer 2014				
Average dissimilarity between both reaches = 65.72				
	Average Biomass			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	454.41	730.15	24.85	24.85
Erpobdellidae	160.60	156.59	9.96	34.81
Gammaridae	3.38	140.09	7.40	42.21
Limnephilidae	4.92	121.81	6.47	48.68
Ephemerellidae	3.15	120.19	6.24	54.91
Ephemeridae	0.00	91.93	5.12	60.03
Glossiphoniidae	87.84	10.26	4.34	64.38
Simuliidae	0.00	71.86	4.03	68.41
Planorbidae	4.27	74.84	3.83	72.24
Winter 2015				
Average dissimilarity between both reaches = 87.69				
	Average Biomass			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	5.63	263.39	26.63	26.63
Erpobdellidae	147.10	46.72	12.46	39.09
Planorbidae	4.59	70.30	7.45	46.54
Pisidiidae	2.74	81.89	6.80	53.34
Tubificidae	60.08	10.99	5.37	58.71
Sericostomatidae	0.00	43.41	4.62	63.34
Tipulidae	17.14	50.88	4.61	67.94
Hydropsychidae	0.00	39.63	4.34	72.29
Spring 2015				
Average dissimilarity between both reaches = 89.16				
	Average Biomass			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	27.79	848.30	29.60	29.60
Lymnaeidae	0.51	431.95	15.33	44.93
Pisidiidae	0.49	335.94	11.20	56.13
Limnephilidae	3.21	201.86	7.65	63.79
Planorbidae	3.09	174.97	6.04	69.83
Baetidae	0.44	111.97	4.07	73.90

Summer 2015

Average dissimilarity between both reaches = 62.55

	Average Biomass			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	1022.52	2855.91	47.42	47.42
Erpobdellidae	223.69	156.57	7.28	54.70
Bithyniidae	131.56	3.54	4.28	58.98
Gammaridae	5.17	124.34	4.01	62.99
Lymnaeidae	61.02	120.02	3.94	66.93
Pisidiidae	49.93	182.18	3.87	70.81

Autumn 2015

Average dissimilarity between both reaches = 80.75

	Average Biomass			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	324.10	4131.85	66.46	66.46
Pisidiidae	2.35	483.36	11.54	78.00

Winter 2016

Average dissimilarity between both reaches = 95.59

	Average Biomass			
Family	Degraded	Natural	Contribution%	Cumulative%
Pisidiidae	0.00	199.79	18.47	18.47
Hydrobiidae	0.06	165.12	18.00	36.47
Limnephilidae	0.24	129.16	13.45	49.92
Sphaeriidae	0.00	73.19	7.30	57.22
Hydropsychidae	0.00	46.35	5.03	62.25
Erpobdellidae	58.39	1.45	4.84	67.09
Valvatidae	44.38	0.00	4.25	71.34

Spring 2016

Average dissimilarity between both reaches = 93.31

	Average Biomass			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	15.78	837.20	25.21	25.21
Pisidiidae	0.00	804.18	24.98	50.19
Lymnaeidae	0.78	411.30	12.94	63.14
Limnephilidae	0.75	157.20	5.03	68.17
Planorbidae	2.06	164.17	4.90	73.07

Summer 2016

Average dissimilarity between both reaches = 52.59

	Average Biomass			
Family	Degraded	Natural	Contribution%	Cumulative%
Hydrobiidae	664.86	1038.92	21.31	21.31
Erpobdellidae	141.45	295.87	13.24	34.55
Lymnaeidae	6.94	241.30	12.27	46.82
Gammaridae	2.59	156.84	7.92	54.74
Ephemerellidae	2.89	119.23	5.96	60.71
Limnephilidae	4.31	95.16	4.73	65.44
Ephemeridae	0.00	83.14	4.22	69.65
Planorbidae	3.70	73.38	3.62	73.27

Spring 2014				
Average dissimilarity between both reaches= 70.95				
	Average Biomass			
Family	Degraded	Before-Rehabilitated	Contribution%	Cumulative%
Pisidiidae	0	98	17.77	17.77
Erpobdellidae	57.35	29	13.74	31.52
Bithyniidae	45.94	6.18	12.71	44.23
Tubificidae	33.22	20.32	8.16	52.39
Glossiphoniidae	11.90	49	7.87	60.26
Chironomidae (non- Tanypodinae)	35.67	21.24	5.99	66.25
Sericostomatidae	15.22	4.30	5.20	71.45
Winter 2015				
Average dissimilarity between both reaches = 91.32				
	Average Biomass			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Erpobdellidae	147.10	2.21	20.60	20.60
Tubificidae	60.08	4.52	17.20	37.80
Chironomidae (non- Tanypodinae)	27.03	2.18	8.43	46.24
Glossiphoniidae	25.21	0.04	7.16	53.40
Tipulidae	17.14	1.01	7.15	60.54
Naididae	14.06	0.06	5.71	66.26
Lumbriculidae	17.45	0.76	5.15	71.41
Spring 2015				
Average dissimilarity between both reaches = 73.44				
	Average Biomass			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Erpobdellidae	103.49	33	19.73	19.73
Lymnaeidae	0.51	107.57	19.21	38.94
Hydrobiidae	27.79	26	7.75	46.69
Chironomidae (non- Tanypodinae)	39.26	9	7.17	53.86
Glossiphoniidae	27.31	1	6.23	60.09
Sericostomatidae	10.19	16	5.41	65.50
Bithyniidae	23.59	1.35	5.40	70.90
Summer 2015				
Average dissimilarity between both reaches = 61.21				
	Average Biomass			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	1022.52	1890	40.66	40.66
Lymnaeidae	61.02	448	14.00	54.66
Erpobdellidae	223.69	210	9.98	64.64
Limnephilidae	1.28	131.89	6.50	71.14
Autumn 2015				
Average dissimilarity between both reaches = 64.71				
	Average Biomass			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Lymnaeidae	153.48	601.58	32.07	32.07
Hydrobiidae	324.10	243.46	19.80	51.87
Glossiphoniidae	106.85	144.70	8.87	60.73
Planorbidae	9.85	102.85	7.71	68.45
Bithyniidae	103.39	15.60	6.79	75.24

Winter 2016				
Average dissimilarity between both reaches = 87.24				
	Average Biomass			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Lymnaeidae	1	209	22.95	22.95
Glossiphoniidae	19	157	11.91	34.87
Limnephilidae	0.24	49	9.72	44.59
Planorbidae	0	97	9.39	53.97
Erpobdellidae	58.39	59	8.18	62.15
Hydrobiidae	0.06	68	6.54	68.69
Valvatidae	44.38	2.12	5.55	74.25

Spring 2016				
Average dissimilarity between both reaches = 89.24				
	Average Biomass			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Lymnaeidae	0.78	444	22.89	22.89
Hydrobiidae	15.78	403	21.11	44.00
Bithyniidae	18.71	203	10.53	54.53
Gammaridae	2.31	134	7.39	61.92
Sphaeriidae	0.67	114	6.32	68.25
Glossiphoniidae	11	121	6.13	74.37

Summer 2016				
Average dissimilarity between both reaches = 64.46				
	Average Biomass			
Family	Degraded	Rehabilitated	Contribution%	Cumulative%
Lymnaeidae	6.94	761	24.83	24.83
Hydrobiidae	664.86	502	13.91	38.73
Erpobdellidae	141.45	380.44	12.49	51.22
Pisidiidae	24.64	279	9.07	60.30
Gammaridae	2.59	190	7.27	67.57
Limnephilidae	4.31	186.52	6.03	73.60

Spring 2014				
Average dissimilarity between both reaches= 90.76				
	Average Biomass			
Family	Natural	Before-Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	873	0	33.71	33.71
Lymnaeidae	350	10	12.46	46.17
Limnephilidae	268.81	1.74	10.89	57.06
Pisidiidae	214.63	98	7.51	64.58
Planorbidae	156.74	0	5.71	70.29

Winter 2015				
Average dissimilarity between both reaches = 92.67				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	263.39	2.71	34.83	34.83
Planorbidae	70.30	0.24	10.45	45.28
Pisidiidae	81.89	0	8.48	53.76
Tipulidae	50.88	1.01	6.68	60.44
Erpobdellidae	46.72	2.21	5.96	66.40
Sericostomatidae	43.41	0.06	5.95	72.35

Spring 2015				
Average dissimilarity between both reaches = 84.50				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	848.30	26	31.20	31.20
Lymnaeidae	431.95	108	12.98	44.18
Pisidiidae	335.94	17	11.55	55.74
Limnephilidae	201.86	12	7.71	63.45
Planorbidae	174.97	1.26	6.42	69.87
Erpobdellidae	139.98	33	4.46	74.33
Summer 2015				
Average dissimilarity between both reaches = 62.63				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	2855.91	1890	50.27	50.27
Lymnaeidae	120.02	448	9.36	59.63
Erpobdellidae	156.57	210	6.62	66.25
Pisidiidae	182.18	107	4.26	70.51
Autumn 2015				
Average dissimilarity between both reaches = 76.67				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	4131.85	243.46	65.03	65.03
Pisidiidae	483.36	48.64	9.87	74.90
Winter 2016				
Average dissimilarity between both reaches = 76.25				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Pisidiidae	199.79	3.99	15.93	15.93
Lymnaeidae	18.49	209	15.90	31.84
Hydrobiidae	165	68	13.94	45.77
Glossiphoniidae	1.10	157	9.46	55.23
Limnephilidae	129	49	7.49	62.72
Planorbidae	28.32	97	7.38	70.10
Spring 2016				
Average dissimilarity between both reaches = 50.14				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Pisidiidae	804.18	105	27.41	27.41
Hydrobiidae	837.20	403	16.63	44.03
Lymnaeidae	411.30	444	8.84	52.87
Planorbidae	164.17	38.77	4.93	57.80
Limnephilidae	157.20	84.34	4.79	62.59
Glossiphoniidae	8.14	121	4.44	67.03
Baetidae	120.44	8.62	4.40	71.43
Summer 2016				
Average dissimilarity between both reaches = 52.00				
	Average Biomass			
Family	Natural	Rehabilitated	Contribution%	Cumulative%
Hydrobiidae	1038.92	502	22.92	22.92
Lymnaeidae	241.30	761	15.80	38.72
Erpobdellidae	295.87	380.44	9.72	48.44
Pisidiidae	25.31	279	8.26	56.71
Bithyniidae	3.82	152	5.12	61.83
Asellidae	1.19	151.68	4.76	66.59
Limnephilidae	95.16	186.52	3.81	70.40

Appendix 4.16. Summary of the two-way PERMANOVA pair-wise results for most affected macroinvertebrate family Biomass for each reach separately

Degraded reach				Natural reach				Rehabilitated reach			
Lymnaeidae (mgDM m^{-2})				**Lymnaeidae (mgDM m^{-2})**				**Lymnaeidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.38069	0.7154	127	Sp.14, Sp.15	0.88131	0.3837	4292	Sp.14, Sp.15	2.0864	**0.0293**	786
Sp.14, Sp.16	0.65127	0.5462	32	Sp.14, Sp.16	0.44579	0.6707	461	Sp.14, Sp.16	6.8899	**0.0022**	179
Sp.15, Sp.16	0.31313	0.7299	126	Sp.15, Sp.16	0.2913	0.7761	4292	Sp.15, Sp.16	3.2688	**0.0106**	3333
Su.14, Su.15	1.2691	0.2284	1407	Su.14, Su.15	2.4508	0.0595	4312				
Su.14, Su.16	0.0365	1	119	Su.14, Su.16	0.35302	0.5933	461				
Su.15, Su.16	1.2621	0.2199	1054	Su.15, Su.16	2.2598	0.0504	4308	Su.15, Su.16	1.3061	0.2158	4268
Erpobdellidae (mgDM m^{-2})				**Erpobdellidae (mgDM m^{-2})**				**Erpobdellidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.44839	0.6524	2271	Sp.14, Sp.15	1.404	0.1792	4271	Sp.14, Sp.15	0.76088	0.4683	1938
Sp.14, Sp.16	0.45677	0.67	210	Sp.14, Sp.16	0.88866	0.3931	461	Sp.14, Sp.16	2.0513	0.077	96
Sp.15, Sp.16	0.88061	0.3851	1416	Sp.15, Sp.16	0.50909	0.6039	4303	Sp.15, Sp.16	0.26544	0.7965	1464
Su.14, Su.15	1.6898	0.1165	2274	Su.14, Su.15	0.27441	0.771	3345				
Su.14, Su.16	0.04849	0.876	32	Su.14, Su.16	1.5023	0.1914	460				
Su.15, Su.16	1.804	0.0935	2260	Su.15, Su.16	1.545	0.1426	3349	Su.15, Su.16	1.8629	0.0845	2578
Hydrobiidae (mgDM m^{-2})				**Hydrobiidae (mgDM m^{-2})**				**Hydrobiidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.0356	0.2971	3362	Sp.14, Sp.15	0.34105	0.7314	4322	Sp.14, Sp.15	4.532	**0.0007**	459
Sp.14, Sp.16	0.31636	0.7163	336	Sp.14, Sp.16	0.41374	0.696	461	Sp.14, Sp.16	41.652	**0.0015**	32
Sp.15, Sp.16	0.71728	0.4804	4319	Sp.15, Sp.16	0.07974	0.9463	4265	Sp.15, Sp.16	7.3478	**0.0003**	4310
Su.14, Su.15	1.749	0.0897	4301	Su.14, Su.15	1.7331	0.0929	4309				
Su.14, Su.16	1.4308	0.1659	462	Su.14, Su.16	0.35302	0.5933	462				
Su.15, Su.16	0.60861	0.5609	4305	Su.15, Su.16	1.1268	0.3039	4231	Su.15, Su.16	1.1299	0.3184	4283

Sericostomatidae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms

Sericostomatidae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.84292	0.4655	4298
Sp.14, Sp.16	1.1129	0.3189	462
Sp.15, Sp.16	0.33576	0.7349	3352
Su.14, Su.15	1.2244	0.2543	48
Su.14, Su.16	2.1832	0.1793	3
Su.15, Su.16	1.5838	0.2299	8

Sericostomatidae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.35566	0.7421	254
Sp.14, Sp.16	4.6272	**0.0026**	96
Sp.15, Sp.16	2.7307	**0.0121**	790
Su.15, Su.16	2.7928	**0.0438**	4

Limnephilidae (mgDM/m^2)			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.4345	0.1716	4284
Sp.14, Sp.16	0.03968	0.985	462
Sp.15, Sp.16	1.3771	0.1953	3343
Su.14, Su.15	2.4558	0.0294	797
Su.14, Su.16	0.25583	0.7974	245
Su.15, Su.16	2.2547	0.0486	423

Limnephilidae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.1256	0.2646	4249
Sp.14, Sp.16	1.6972	0.11	455
Sp.15, Sp.16	0.9268	0.3614	4305
Su.14, Su.15	1.8563	0.0833	4314
Su.14, Su.16	1.2362	0.238	462
Su.15, Su.16	1.1084	0.2977	4350

Limnephilidae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	3.0543	**0.0075**	1964
Sp.14, Sp.16	9.7661	**0.0026**	131
Sp.15, Sp.16	5.6829	**0.0008**	3357
Su.15, Su.16	0.76356	0.4516	4287

Gammaridae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.538	0.1581	4237
Sp.14, Sp.16	1.7728	0.1002	462
Sp.15, Sp.16	0.031248	0.9753	4330
Su.14, Su.15	0.28021	0.783	3350
Su.14, Su.16	0.35302	0.5933	460
Su.15, Su.16	0.0011	0.9999	3339

Gammaridae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.4534	0.1678	4304
Sp.14, Sp.16	1.4094	0.1727	461
Sp.15, Sp.16	0.47638	0.6816	4345
Su.14, Su.15	1.0727	0.3127	4286
Su.14, Su.16	0.64411	0.5354	462
Su.15, Su.16	1.6151	0.1373	4337

Gammaridae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	3.2137	**0.0065**	2581
Sp.14, Sp.16	21.47	**0.0022**	244
Sp.15, Sp.16	10.405	**0.0001**	4312
Su.15, Su.16	7.1098	**0.0003**	4307

Bithyniidae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.30617	0.7567	1421
Sp.14, Sp.16	0.95521	0.3784	63
Sp.15, Sp.16	0.91406	0.381	818
Su.14, Su.15	1.8531	0.0799	4328
Su.14, Su.16	0.38156	0.704	462
Su.15, Su.16	2.2493	**0.0464**	4305

Bithyniidae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.7764	0.0925	1728
Sp.14, Sp.16	1.5896	0.1649	154
Sp.15, Sp.16	0.4902	0.6411	2560
Su.14, Su.15	0.12129	0.9312	126
Su.14, Su.16	0.31012	0.6568	32
Su.15, Su.16	0.43909	0.6639	126

Bithyniidae (mgDM m^{-2})			
Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	3.4946	**0.0041**	463
Sp.14, Sp.16	12.126	**0.0026**	245
Sp.15, Sp.16	10.068	**0.0004**	825
Su.15, Su.16	5.4966	**0.0006**	4304

Planorbidae (mgDM m^{-2})				**Planorbidae (mgDM m^{-2})**				**Planorbidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.69832	0.477	4288	Sp.14, Sp.15	0.43958	0.6641	4301	Sp.14, Sp.15	4.1795	**0.0036**	243
Sp.14, Sp.16	0.08829	0.9146	461	Sp.14, Sp.16	0.13448	0.8869	462	Sp.14, Sp.16	13.298	**0.002**	32
Sp.15, Sp.16	0.80568	0.43	4303	Sp.15, Sp.16	0.52376	0.611	4324	Sp.15, Sp.16	6.374	**0.0004**	4330
Su.14, Su.15	1.5959	0.1189	4290	Su.14, Su.15	0.56958	0.5705	4266				
Su.14, Su.16	0.26202	0.7893	462	Su.14, Su.16	0.12799	0.9222	462				
Su.15, Su.16	1.792	0.073	4298	Su.15, Su.16	0.49326	0.6248	4317	Su.15, Su.16	1.4396	0.1703	4297
Pisidiidae (mgDM m^{-2})				**Pisidiidae (mgDM m^{-2})**				**Pisidiidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
				Sp.14, Sp.15	1.4957	0.1767	1719	Sp.14, Sp.15	3.6403	**0.0109**	70
				Sp.14, Sp.16	0.2593	0.7997	210	Sp.14, Sp.16	1.2558	0.2491	178
				Sp.15, Sp.16	2.5018	0.0261	3337	Sp.15, Sp.16	4.1251	**0.0047**	453
Su.14, Su.15	1.3187	0.2251	241	Su.14, Su.15	0.95031	0.3605	1411				
Su.14, Su.16	0.35332	0.6987	8	Su.14, Su.16	0.13556	0.8302	119				
Su.15, Su.16	0.83816	0.4001	245	Su.15, Su.16	1.0956	0.3014	1400	Su.15, Su.16	2.1862	**0.0367**	4322
Glossiphoniidae (mgDM m^{-2})				**Glossiphoniidae (mgDM m^{-2})**				**Glossiphoniidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	1.782	0.1032	3342	Sp.14, Sp.15	0.15166	0.8683	610	Sp.14, Sp.15	6.2126	**0.0003**	340
Sp.14, Sp.16	0.18757	0.8546	336	Sp.14, Sp.16	0.5426	0.6258	65	Sp.14, Sp.16	2.95	**0.0202**	179
Sp.15, Sp.16	1.8926	0.0828	2579	Sp.15, Sp.16	0.46704	0.6423	617	Sp.15, Sp.16	10.493	**0.0004**	822
Su.14, Su.15	0.28652	0.7755	4321	Su.14, Su.15	1.6883	0.119	3334				
Su.14, Su.16	0.50071	0.6188	462	Su.14, Su.16	1.6998	0.1059	336				
Su.15, Su.16	0.25292	0.8104	4295	Su.15, Su.16	0.26682	0.8078	4281	Su.15, Su.16	0.19686	0.849	4291
Chironomidae (mgDM m^{-2})				**Chironomidae (mgDM m^{-2})**				**Chironomidae (mgDM m^{-2})**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Sp.15	0.47437	0.6449	4301	Sp.14, Sp.15	1.7636	0.1038	4291	Sp.14, Sp.15	2.624	**0.0244**	2573
Sp.14, Sp.16	0.16894	0.8439	461	Sp.14, Sp.16	1.5475	0.0525	462	Sp.14, Sp.16	0.42801	0.6688	245
Sp.15, Sp.16	0.2593	0.7997	4301	Sp.15, Sp.16	1.172	0.2513	4351	Sp.15, Sp.16	2.4988	**0.0299**	4307
Su.14, Su.15	1.0694	0.2984	4301	Su.14, Su.15	0.70627	0.5184	4293				
Su.14, Su.16	0.6751	0.5211	462	Su.14, Su.16	0.12893	0.9095	462				
Su.15, Su.16	0.51625	0.6017	4205	Su.15, Su.16	0.75157	0.4634	4276	Su.15, Su.16	0.1632	0.8672	4320

Appendix 4.17. Summary of the PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate FFGs composition (Count m^{-2}, and Biomass m^{-2}) between reaches. Reaches were compared seasonally. Bold font indicates significant ($P<0.05$) differences.

Community metrics	Seasons	PERMANOVA results			
FFGs Count/m^2	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.1039	0.0019	462
		Degraded, Rehabilitated	4.3505	0.0021	462
		Natural, Rehabilitated	8.8541	0.0024	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.851	0.0022	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.99	0.0023	462
		Degraded, Rehabilitated	5.0593	0.0015	462
		Natural, Rehabilitated	4.8975	0.003	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.3996	0.0001	8155
		Degraded, Rehabilitated	2.8854	0.0022	8161
		Natural, Rehabilitated	5.6702	0.0001	8138
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.7553	0.0001	8173
		Degraded, Rehabilitated	2.0759	0.0066	8197
		Natural, Rehabilitated	4.372	0.0001	8148
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.6685	0.0001	9913
		Degraded, Rehabilitated	2.4577	0.0015	9907
		Natural, Rehabilitated	5.4601	0.0001	9909
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.5415	0.0017	461
		Degraded, Rehabilitated	1.9587	0.0256	462
		Natural, Rehabilitated	2.2339	0.0056	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.6275	0.0017	462
		Degraded, Rehabilitated	4.1916	0.0019	462
		Natural, Rehabilitated	4.1749	0.0035	461
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	10.514	0.0021	461
		Degraded, Rehabilitated	3.4455	0.0015	462
		Natural, Rehabilitated	4.9372	0.0029	462
FFGs Biomass/m^2	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.7678	0.0017	461
		Degraded, Rehabilitated	1.1024	0.3015	462
		Natural, Rehabilitated	5.3069	0.0022	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.3309	0.0026	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.5198	0.0023	462
		Degraded, Rehabilitated	4.557	0.0028	462
		Natural, Rehabilitated	6.4674	0.0019	461
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.0407	0.0001	8129
		Degraded, Rehabilitated	3.068	0.0001	8189
		Natural, Rehabilitated	6.225	0.0001	8163
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.5488	0.0002	8136
		Degraded, Rehabilitated	2.9477	0.0004	8161
		Natural, Rehabilitated	1.2206	0.2195	8145

	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.8904	0.0001	9916
		Degraded, Rehabilitated	1.9553	0.0432	9911
		Natural, Rehabilitated	5.0026	0.0001	9919
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.0238	0.0027	462
		Degraded, Rehabilitated	2.4766	0.0113	462
		Natural, Rehabilitated	2.496	0.0038	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.2231	0.0025	462
		Degraded, Rehabilitated	3.2379	0.0021	462
		Natural, Rehabilitated	5.2552	0.0032	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.2074	0.0028	462
		Degraded, Rehabilitated	2.1682	0.0142	461
		Natural, Rehabilitated	1.9246	0.005	462

Appendix 4.18. Summary of PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate FFGs composition (Count m^{-2}, and Biomass m^{-2}) for each reach separately. Bold font indicates significant ($P<0.05$) differences.

Degraded reach seasonal differences				Natural reach seasonal differences				Rehabilitated reach seasonal differences			
FFGs Count m^{-2}				**FFGs Count m^{-2}**				**FFGs Count m^{-2}**			
Seasons	t	*P*(perm)	Unique perms	Seasons	t	*P*(perm)	Unique perms	Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	1.7012	0.0381	462	Sp.14, Su.14	6.2309	0.0019	462				
Sp.14, Wi.15	2.3371	0.0019	462	Sp.14, Wi.15	5.9911	0.0012	461	Sp.14, Wi.15	4.221	0.0015	462
Sp.14, Sp.15	1.1975	0.2367	4340	Sp.14, Sp.15	1.694	0.1457	4312	Sp.14, Sp.15	2.984	**0.0002**	4287
Sp.14, Su.15	3.5659	0.0002	4330	Sp.14, Su.15	4.3015	0.0001	4319	Sp.14, Su.15	5.4121	0.0004	4337
Sp.14, Au.15	1.9226	0.0273	7689	Sp.14, Au.15	2.1278	0.0299	7734	Sp.14, Au.15	4.7316	0.0002	7759
Sp.14, Wi.16	2.3007	0.0026	462	Sp.14, Wi.16	5.8743	0.0018	462	Sp.14, Wi.16	2.3632	0.0115	462
Sp.14, Sp.16	0.27145	0.9	462	Sp.14, Sp.16	2.2494	0.0505	462	Sp.14, Sp.16	7.306	**0.002**	462
Sp.14, Su.16	2.7758	0.0039	462	Sp.14, Su.16	7.2167	0.0026	461	Sp.14, Su.16	8.4078	0.0019	462
Su.14, Wi.15	3.022	0.0022	462	Su.14, Wi.15	12.741	0.0018	462				
Su.14, Sp.15	1.6431	0.0335	4287	Su.14, Sp.15	7.6096	0.0001	4321				
Su.14, Su.15	0.5811	0.0549	4328	Su.14, Su.15	1.7654	0.0796	4298				
Su.14, Au.15	1.2498	0.1949	7694	Su.14, Au.15	3.9764	0.0001	7699				
Su.14, Wi.16	2.7939	0.0024	462	Su.14, Wi.16	12.718	0.0022	461				
Su.14, Sp.16	1.6787	0.0282	462	Su.14, Sp.16	6.9166	0.0026	462				
Su.14, Su.16	0.74892	0.7666	462	Su.14, Su.16	1.7846	0.1068	462				
Wi.15, Sp.15	2.6462	0.0014	4296	Wi.15, Sp.15	7.6896	0.0004	4323	Wi.15, Sp.15	4.5603	0.0005	4321
Wi.15, Su.15	4.5082	0.0006	4324	Wi.15, Su.15	9.0517	0.0002	4332	Wi.15, Su.15	6.989	0.0005	4286
Wi.15, Au.15	2.4996	0.0031	7669	Wi.15, Au.15	5.9106	0.0001	7710	Wi.15, Au.15	6.4228	0.0001	7682
Wi.15, Wi.16	1.1565	0.2764	462	Wi.15, Wi.16	1.4204	0.0963	462	Wi.15, Wi.16	4.1983	**0.0025**	462
Wi.15, Sp.16	2.2881	0.0043	462	Wi.15, Sp.16	7.7596	0.0016	461	Wi.15, Sp.16	6.5027	0.0018	461
Wi.15, Su.16	3.7505	0.0024	462	Wi.15, Su.16	15.426	0.002	461	Wi.15, Su.16	7.2197	0.002	462
Sp.15, Su.15	3.0507	0.0002	8156	Sp.15, Su.15	4.7625	0.0001	8171	Sp.15, Su.15	3.779	0.0002	8199
Sp.15, Au.15	1.9075	0.023	9784	Sp.15, Au.15	2.2652	0.0145	9767	Sp.15, Au.15	3.1438	0.0001	9788
Sp.15, Wi.16	3.1729	0.0005	4336	Sp.15, Wi.16	7.474	0.0002	4333	Sp.15, Wi.16	1.7663	0.0381	4309
Sp.15, Sp.16	1.0642	0.3086	4324	Sp.15, Sp.16	1.4573	0.0963	4304	Sp.15, Sp.16	3.5434	**0.0011**	4328
Sp.15, Su.16	2.3448	0.0008	4305	Sp.15, Su.16	7.8389	0.0002	4333	Sp.15, Su.16	4.7837	0.0001	4319
Su.15, Au.15	2.2736	0.0007	9778	Su.15, Au.15	2.957	0.0003	9779	Su.15, Au.15	2.3378	0.0001	9814
Su.15, Wi.16	4.3573	0.0001	4306	Su.15, Wi.16	8.9729	0.0002	4347	Su.15, Wi.16	2.4774	0.0006	4371
Su.15, Sp.16	3.468	0.0002	4331	Su.15, Sp.16	3.8733	0.0002	4335	Su.15, Sp.16	1.5273	0.0596	4336
Su.15, Su.16	1.6686	0.0539	4313	Su.15, Su.16	1.2466	0.2474	4332	Su.15, Su.16	1.6454	0.0522	4323
Au.15, Wi.16	2.7644	0.001	7708	Au.15, Wi.16	5.8427	0.0001	7757	Au.15, Wi.16	1.6352	0.0267	7767
Au.15, Sp.16	1.8653	0.0338	7694	Au.15, Sp.16	2.1667	0.0193	7670	Au.15, Sp.16	2.2254	0.0017	7733
Au.15, Su.16	1.194	0.2416	7732	Au.15, Su.16	3.8434	0.0002	7662	Au.15, Su.16	3.5527	0.0001	7725
Wi.16, Sp.16	2.3083	0.0053	462	Wi.16, Sp.16	7.5984	0.0017	462	Wi.16, Sp.16	2.0277	0.0177	462
Wi.16, Su.16	3.2331	0.0019	462	Wi.16, Su.16	15.535	0.0018	462	Wi.16, Su.16	3.391	0.0023	462
Sp.16, Su.16	2.6281	0.0019	462	Sp.16, Su.16	7.5969	0.0014	461	Sp.16, Su.16	3.3016	0.0052	462

FFGs Biomass m^{-2}

Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	2.3414	0.0099	462
Sp.14, Wi.15	1.4701	0.0916	461
Sp.14, Sp.15	0.28714	0.924	4318
Sp.14, Su.15	3.4394	0.0006	4328
Sp.14, Au.15	1.5826	0.0903	7701
Sp.14, Wi.16	2.0976	0.0356	462
Sp.14, Sp.16	0.397	0.8523	462
Sp.14, Su.16	2.2257	0.0176	462
Su.14, Wi.15	3.9331	0.0046	462
Su.14, Sp.15	2.7078	0.0035	4313
Su.14, Su.15	1.7709	0.067	4307
Su.14, Au.15	1.9451	0.0294	7688
Su.14, Wi.16	4.5705	0.0021	462
Su.14, Sp.16	2.7183	0.0099	462
Su.14, Su.16	1.0995	0.0554	462
Wi.15, Sp.15	1.9525	0.0322	4340
Wi.15, Su.15	5.4862	0.0007	4298
Wi.15, Au.15	2.6485	0.0067	7712
Wi.15, Wi.16	1.5343	0.1083	462
Wi.15, Sp.16	1.2749	0.2145	462
Wi.15, Su.16	3.5913	0.0044	462
Sp.15, Su.15	3.7483	0.0001	8147
Sp.15, Au.15	1.8776	0.0348	9782
Sp.15, Wi.16	2.6194	0.006	4326
Sp.15, Sp.16	0.61298	0.6936	4325
Sp.15, Su.16	2.3797	0.0053	4306
Su.15, Au.15	2.2983	0.0108	9792
Su.15, Wi.16	6.3634	0.0003	4319
Su.15, Sp.16	3.8997	0.0006	4316
Su.15, Su.16	1.8584	0.0536	4318
Au.15, Wi.16	3.0997	0.0034	7712
Au.15, Sp.16	1.7175	0.0628	7736
Au.15, Su.16	0.95545	0.3899	7708
Wi.16, Sp.16	1.6744	0.0966	462
Wi.16, Su.16	4.1915	0.0021	462
Sp.16, Su.16	2.446	0.0135	462

FFGs Biomass m^{-2}

Seasons	t	*P*(perm)	Unique perms
Sp.14, Su.14	1.703	0.0339	462
Sp.14, Wi.15	3.6879	0.0024	462
Sp.14, Sp.15	1.1055	0.3366	4319
Sp.14, Su.15	1.385	0.1314	4321
Sp.14, Au.15	1.9284	0.0233	7720
Sp.14, Wi.16	4.2653	0.0025	462
Sp.14, Sp.16	1.7108	0.0537	462
Sp.14, Su.16	1.6765	0.0543	462
Su.14, Wi.15	4.5102	0.0021	462
Su.14, Sp.15	2.6242	0.0003	4296
Su.14, Su.15	1.7461	0.0668	4337
Su.14, Au.15	3.0225	0.0005	7728
Su.14, Wi.16	5.2617	0.0018	461
Su.14, Sp.16	3.3813	0.0027	462
Su.14, Su.16	1.008	0.0605	462
Wi.15, Sp.15	5.577	0.0004	4292
Wi.15, Su.15	4.5301	0.0003	4311
Wi.15, Au.15	4.8937	0.0002	7711
Wi.15, Wi.16	1.0529	0.0543	462
Wi.15, Sp.16	5.5949	0.003	462
Wi.15, Su.16	6.175	0.0023	462
Sp.15, Su.15	1.3934	0.1461	8179
Sp.15, Au.15	1.9484	0.0173	9790
Sp.15, Wi.16	5.8444	0.0004	4323
Sp.15, Sp.16	1.3253	0.1652	4320
Sp.15, Su.16	2.0614	0.0179	4313
Su.15, Au.15	1.6731	0.0609	9769
Su.15, Wi.16	4.8457	0.0002	4314
Su.15, Sp.16	1.9504	0.0169	4338
Su.15, Su.16	1.1858	0.271	4338
Au.15, Wi.16	4.8162	0.0001	7715
Au.15, Sp.16	1.7116	0.0539	7679
Au.15, Su.16	2.652	0.0005	7643
Wi.16, Sp.16	5.5043	0.0027	462
Wi.16, Su.16	7.0216	0.0019	461
Sp.16, Su.16	3.2631	0.0016	462

FFGs Biomass m^{-2}

Seasons	t	*P*(perm)	Unique perms
Sp.14, Wi.15	4.5476	0.0018	462
Sp.14, Sp.15	2.6853	**0.0002**	4330
Sp.14, Su.15	4.4703	0.0003	4305
Sp.14, Au.15	4.5637	0.0001	7707
Sp.14, Wi.16	2.2213	0.0027	461
Sp.14, Sp.16	5.1272	**0.0031**	462
Sp.14, Su.16	4.9144	0.002	462
Wi.15, Sp.15	3.5057	0.0005	4290
Wi.15, Su.15	8.4299	0.0002	4329
Wi.15, Au.15	9.035	0.0001	7658
Wi.15, Wi.16	4.947	**0.0023**	461
Wi.15, Sp.16	9.9	0.0023	462
Wi.15, Su.16	8.6986	0.0017	462
Sp.15, Su.15	4.8707	0.0004	8169
Sp.15, Au.15	4.9775	0.0001	9785
Sp.15, Wi.16	2.1488	0.01	4334
Sp.15, Sp.16	5.4178	**0.0002**	4325
Sp.15, Su.16	5.054	0.0001	4318
Su.15, Au.15	2.1359	0.0023	9793
Su.15, Wi.16	2.5533	0.0009	4315
Su.15, Sp.16	2.0659	0.0043	4306
Su.15, Su.16	1.3024	0.1648	4275
Au.15, Wi.16	2.0034	0.0167	7700
Au.15, Sp.16	2.4253	0.0021	7731
Au.15, Su.16	3.0991	0.0002	7695
Wi.16, Sp.16	2.7452	0.0018	462
Wi.16, Su.16	3.0783	0.0018	461
Sp.16, Su.16	2.9304	0.0019	462

Appendix 4.19. Results of Similarity Percentages (SIMPER) analysis based on macroinvertebrate FFGs composition (Count m^{-2}) 4th root transformed data, identifying feeding groups contributing at least 70% of the spatial dissimilarity in community composition between the study reaches, reaches were compared seasonally before and after the rehabilitation. Average abundances presented in individuals m^{-2} (4th root transformed).

Spring 2014
Average dissimilarity = 12.40

Feeding group	Average Abundance Degraded	Natural	Contribution%	Cumulative%
Shredders	3.10	4.83	28.43	28.43
Scraper	3.44	4.97	25.05	53.48
Piercer	1.04	1.04	11.59	65.07
Filter-feeder	3.01	3.61	10.04	75.11

Spring 2015
Average dissimilarity = 10.70

Feeding group	Average Abundance Degraded	Natural	Contribution%	Cumulative%
Shredders	3.26	4.84	29.24	29.24
Scraper	3.77	4.95	22.01	51.24
Parasite	2.68	2.19	9.26	60.50
Filter-feeder	3.15	3.64	9.21	69.71
Deposit feeder	4.39	3.95	9.01	78.72

Spring 2016
Average dissimilarity = 12.83

Feeding group	Average Abundance Degraded	Natural	Contribution%	Cumulative%
Shredders	3.13	4.85	26.82	26.82
Scraper	3.44	5.06	25.18	52.00
Filter-feeder	3.09	3.98	13.91	65.91
Piercer	1.02	1.72	10.86	76.78

Spring 2014
Average dissimilarity = 10.62

Feeding group	Average Abundance Degraded	B-Rehabilitated	Contribution%	Cumulative%
Scraper	3.44	2.49	20.94	20.94
Predator	3.47	2.60	19.71	40.65
Absorber	2.07	2.38	12.36	53.01
Deposit feeder	4.16	3.64	11.70	64.71
Piercer	1.04	1.47	9.18	73.89

Spring 2015
Average dissimilarity = 9.99

Feeding group	Average Abundance Degraded	Rehabilitated	Contribution%	Cumulative%
Deposit feeder	4.39	3.6	18.78	18.78
Parasite	2.68	2.01	15.13	33.91
Scraper	3.77	3.37	13.95	47.87
Piercer	1.18	0.82	13.58	61.45
Filter-feeder	3.15	2.70	11.84	73.29

Spring 2016
Average dissimilarity = 10.45

Feeding group	Average Abundance Degraded	Rehabilitated	Contribution%	Cumulative%
Shredders	3.13	4.44	26.02	26.02
Piercer	1.02	2.03	19.94	45.95
Parasite	2.66	2.07	11.54	57.50
Scraper	3.44	3.97	10.41	67.91

Absorber	2.10	2.18	9.93	77.83
Spring 2014				
Average dissimilarity = 17.39				
	Average Abundance			
Feeding group	Natural	B-Rehabilitated	Contribution%	Cumulative%
Scraper	4.97	2.49	30.78	30.78
Shredders	4.83	2.78	25.42	56.20
Filter-feeder	3.61	2.61	12.39	68.58
Predator	3.51	2.60	11.50	80.08
Spring 2015				
Average dissimilarity = 14.07				
	Average Abundance			
Feeding group	Natural	Rehabilitated	Contribution%	Cumulative%
Shredders	4.84	3.00	27.60	27.60
Scraper	4.95	3.37	24.58	52.18
Filter-feeder	3.64	2.70	14.21	66.39
Piercer	1.59	0.82	13.54	79.93
Spring 2016				
Average dissimilarity = 6.80				
	Average Abundance			
Feeding group	Natural	Rehabilitated	Contribution%	Cumulative%
Scraper	5.06	3.97	30.98	30.98
Filter-feeder	3.98	3.43	15.50	46.48
Shredders	4.85	4.44	11.74	58.21
Piercer	1.72	2.03	10.94	69.15
Deposit feeder	3.96	3.70	9.70	78.86

Appendix 4.20. average abundance and standard deviation of FFGs according to study reaches.

FFGs average abundance	Seasons	Degraded reach		Rehabilitated reach		Natural Reach	
		Mean	SD	Mean	SD	Mean	SD
Absorber	Sp.14	26.9	24.1	32.8	8.2	28.4	9.0
	Su.14	26.6	13.9	-	-	22.1	3.5
	Wi.15	85.9	65.0	6.3	5.9	21.5	8.5
	Sp.15	19.2	19.9	19.7	12.2	17.5	9.9
	Su.15	17	17.1	19.7	12.2	26	3.5
	Au.15	44.7	50.4	17.3	14.6	28.5	13.9
	Wi.16	228.1	181.1	38.9	26.3	18.3	8.1
	Sp.16	26.6	23.0	23.0	5.9	16.6	5.7
	Su.16	26.8	9.2	14.7	2.6	20.0	4.5
Deposit-feeder	Sp.14	302.3	54.7	176	35.8	284.6	24.1
	Su.14	227.9	83.6	-	-	522.9	41.9
	Wi.15	655.7	176.3	31	21.3	148.0	12.9
	Sp.15	384.3	112.5	168	60.5	245.8	47.5
	Su.15	271.9	65.1	213	89.8	535.8	14.3
	Au.15	289.8	255.4	222.9	118.6	266.8	23.4
	Wi.16	833.8	631.7	240	109.0	135.7	26.7
	Sp.16	305.3	67.6	193.9	64.0	247.4	18.1
	Su.16	217.7	39.2	306	73.5	472.8	17.4
Shredders	Sp.14	97.0	41.6	61	14.3	544.7	54.1
	Su.14	232.5	114.2	-	-	829.1	23.0
	Wi.15	71.4	27.6	19	5.4	208.0	50.4
	Sp.15	117.6	37.2	87.9	41.8	552.4	80.8
	Su.15	352.0	57.2	438	83.6	862.4	59.3
	Au.15	165.7	41.5	263.1	67.7	1244.6	486.3
	Wi.16	60.1	15.7	184	91.0	236.6	37.3
	Sp.16	100.9	40.8	392	66.3	560.1	109.8
	Su.16	272.4	72.4	714	481.0	881.0	57.4
Scraper	Sp.14	145.7	49.0	39	9.0	613.3	80.5
	Su.14	173.2	71.6	-	-	801.4	94.3
	Wi.15	256.8	233.6	16	11.4	222.7	34.4
	Sp.15	219.3	99.2	129	54.2	603.2	70.3
	Su.15	260.5	41.3	220.1	51.7	807.3	47.1
	Au.15	234.4	70.7	199.6	70.6	851.9	297.9
	Wi.16	96.7	71.5	136	106.8	210.1	28.9
	Sp.16	146.0	49.3	249	61.0	655.5	55.4
	Su.16	214.0	28.1	425	159.9	773.1	62.8
Filter-feeder	Sp.14	86.3	38.1	48.3	15.4	170.9	26.6
	Su.14	109.9	34.9	-	-	629.3	77.5
	Wi.15	62.4	30.4	13.1	9.8	89.1	30.3
	Sp.15	101.6	31.2	63	36.4	176.3	20.9
	Su.15	165.3	55.0	89.6	60.8	626.1	60.1
	Au.15	84.9	39.6	42.8	23.2	157.5	41.2
	Wi.16	55.0	33.3	67.1	44.4	126.9	12.3
	Sp.16	95.6	39.3	141	36.4	251.1	29.6
	Su.16	100.8	28.7	129.8	42.3	635.5	75.2
Piercer	Sp.14	1.3	0.6	5.3	3.4	4.6	4.8
	Su.14	10.9	5.3	-	-	4.7	5.1
	Wi.15	3.6	4.6	0.1	0.1	0.4	0.2
	Sp.15	2.4	1.7	2.8	6.8	7.1	3.4
	Su.15	15.1	13.6	10.5	8.4	6.8	4.9

	Au.15	15.5	13.3	17.6	17.2	7.9	9.7
	Wi.16	7.6	9.8	20.7	25.0	0.7	0.5
	Sp.16	1.2	0.5	18.7	9.2	9.5	5.4
	Su.16	8.5	4.6	14.2	13.7	9.6	2.3
Predator	Sp.14	147.8	30.0	46	12.7	154.7	45.8
	Su.14	196.9	41.1	-	-	322.9	47.2
	Wi.15	61.2	15.1	54.9	49.2	77.3	22.8
	Sp.15	157.2	33.4	163	57.4	155.6	34.6
	Su.15	250.8	87.1	364.4	55.6	328.4	51.0
	Au.15	98.2	24.7	178.5	91.2	194.8	70.2
	Wi.16	72.4	19.9	120.9	34.0	63.5	10.5
	Sp.16	140.6	38.4	151	20.8	127.3	31.0
	Su.16	173.4	29.9	377.5	55.5	344.8	37.5
Parasite	Sp.14	46.3	20.1	22.5	6.4	15.7	3.8
	Su.14	45.7	17.1	-	-	126.9	7.9
	Wi.15	33.4	18.0	3.3	2.1	6.3	2.3
	Sp.15	53.2	16.3	18.3	10.8	24.6	11.6
	Su.15	66.8	31.2	41.2	29.2	132.2	3.5
	Au.15	39.2	17.5	14.4	14.3	37.5	21.7
	Wi.16	20.8	10.6	9.6	8.4	6.9	1.9
	Sp.16	52.5	20.2	18.7	3.6	27.3	14.7
	Su.16	43.1	7.8	36.9	8.3	114.8	10.5

Appendix 4.21. Summary of the PERMANOVA pair-wise analysis for between reach differences in macroinvertebrate FFGs, based on groups' average density. Reaches compared seasonally. Bold font indicates significant (P<0.05) differences.

Community metrics	Seasons	PERMANOVA results			
Absorber	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.79984	0.4499	459
		Degraded, Rehabilitated	1.1679	0.2361	460
		Natural, Rehabilitated	0.86409	0.4117	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.14121	0.9978	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.2028	0.0466	461
		Degraded, Rehabilitated	3.8613	0.0081	462
		Natural, Rehabilitated	3.2817	0.0069	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.46325	0.637	8095
		Degraded, Rehabilitated	0.735	0.4654	8108
		Natural, Rehabilitated	0.4265	0.6788	8110
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.9689	0.3231	8153
		Degraded, Rehabilitated	0.49351	0.62	8046
		Natural, Rehabilitated	0.67796	0.4999	8117
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.17598	0.8598	9794
		Degraded, Rehabilitated	1.6425	0.1148	9789
		Natural, Rehabilitated	2.4021	0.0254	9804
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.3141	0.0022	462
		Degraded, Rehabilitated	3.1117	0.013	462
		Natural, Rehabilitated	2.1054	0.0547	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.41494	0.6847	462
		Degraded, Rehabilitated	0.34562	0.7306	336
		Natural, Rehabilitated	2.0989	0.0573	336
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.376	0.2138	462
		Degraded, Rehabilitated	1.694	0.1457	336
		Natural, Rehabilitated	0.28714	0.924	336
Deposit-feeder	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.6846	0.5909	462
		Degraded, Rehabilitated	4.9563	0.0029	461
		Natural, Rehabilitated	5.4972	0.0022	461
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.0353	0.0036	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.421	0.0028	462
		Degraded, Rehabilitated	12.489	0.002	462
		Natural, Rehabilitated	6.7594	0.0022	461
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.5199	0.0033	8033
		Degraded, Rehabilitated	5.6029	0.0003	8107
		Natural, Rehabilitated	3.3207	0.005	8073
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.8121	0.0015	462
		Degraded, Rehabilitated	1.474	0.1646	462
		Natural, Rehabilitated	6.6255	0.003	462

	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.6345	0.5382	9820
		Degraded, Rehabilitated	0.5768	0.5653	9811
		Natural, Rehabilitated	1.6114	0.1593	9873
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.4988	0.0027	462
		Degraded, Rehabilitated	2.359	0.0532	462
		Natural, Rehabilitated	2.2923	0.0501	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.5102	0.0021	462
		Degraded, Rehabilitated	3.0735	0.0162	462
		Natural, Rehabilitated	2.2298	0.0516	456
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.139	0.0024	462
		Degraded, Rehabilitated	2.6232	0.0362	462
		Natural, Rehabilitated	4.7109	0.0021	462
Shredders	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.495	0.0021	462
		Degraded, Rehabilitated	2.1471	0.0524	461
		Natural, Rehabilitated	23.355	0.0017	461
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.1495	0.0021	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.2004	0.0019	462
		Degraded, Rehabilitated	6.3367	0.0024	459
		Natural, Rehabilitated	15.686	0.0019	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	14.742	0.0002	8135
		Degraded, Rehabilitated	1.6882	0.1113	8071
		Natural, Rehabilitated	12.853	0.0001	8059
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.759	0.0023	462
		Degraded, Rehabilitated	1.98	0.0814	462
		Natural, Rehabilitated	8.6216	0.0021	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.001	0.0001	9786
		Degraded, Rehabilitated	4.2666	0.001	9809
		Natural, Rehabilitated	8.7182	0.0001	9791
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.051	0.0024	454
		Degraded, Rehabilitated	3.9368	0.0041	461
		Natural, Rehabilitated	1.487	0.1651	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	10.799	0.0022	462
		Degraded, Rehabilitated	8.7535	0.0029	461
		Natural, Rehabilitated	3.3384	0.0044	460
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.645	0.0023	458
		Degraded, Rehabilitated	3.2944	0.0013	461
		Natural, Rehabilitated	1.4331	0.1846	462
Scraper	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.23	0.0017	462
		Degraded, Rehabilitated	7.1903	0.0021	462
		Natural, Rehabilitated	28.252	0.0019	458
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	10.248	0.003	462

	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.39893	0.7021	462
		Degraded, Rehabilitated	4.0388	0.0018	462
		Natural, Rehabilitated	11.947	0.0021	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.0028	0.0002	8034
		Degraded, Rehabilitated	2.205	0.0452	8093
		Natural, Rehabilitated	12.056	0.0001	8100
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	18.45	0.0024	459
		Degraded, Rehabilitated	1.619	0.1337	462
		Natural, Rehabilitated	16.339	0.003	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.0806	0.0001	9801
		Degraded, Rehabilitated	1.3068	0.1975	9813
		Natural, Rehabilitated	8.5711	0.0001	9790
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.1172	0.0086	462
		Degraded, Rehabilitated	0.50784	0.598	462
		Natural, Rehabilitated	1.8565	0.1576	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.883	0.0013	462
		Degraded, Rehabilitated	3.2085	0.0087	462
		Natural, Rehabilitated	10.426	0.0028	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	21.897	0.0025	461
		Degraded, Rehabilitated	3.946	0.0026	462
		Natural, Rehabilitated	4.5911	0.0033	461
Filter-feeder	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.5162	0.0059	462
		Degraded, Rehabilitated	2.6871	0.0127	462
		Natural, Rehabilitated	9.3217	0.0021	461
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	11.956	0.0025	456
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.7544	0.1172	462
		Degraded, Rehabilitated	4.5548	0.0023	462
		Natural, Rehabilitated	6.2583	0.0022	459
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.7038	0.0003	8063
		Degraded, Rehabilitated	2.4378	0.0251	8087
		Natural, Rehabilitated	5.4833	0.0001	8057
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.014	0.003	462
		Degraded, Rehabilitated	2.4827	0.0506	460
		Natural, Rehabilitated	9.2622	0.0032	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.1866	0.0001	9818
		Degraded, Rehabilitated	3.1485	0.0053	9831
		Natural, Rehabilitated	8.7817	0.0001	9784
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.909	0.0021	458
		Degraded, Rehabilitated	0.67006	0.5312	461
		Natural, Rehabilitated	3.5979	0.0147	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.5052	0.0023	461

		Reaches	t	P(perm)	Unique perms
		Degraded, Rehabilitated	2.1163	0.07	458
		Natural, Rehabilitated	5.1072	0.0013	461
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	16.195	0.002	461
		Degraded, Rehabilitated	1.4453	0.1918	461
		Natural, Rehabilitated	13.976	0.0026	461
Piercer	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.02418	0.9897	245
		Degraded, Rehabilitated	3.7002	0.0018	131
		Natural, Rehabilitated	1.2013	0.3014	131
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.0966	0.0736	336
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.4477	0.0175	179
		Degraded, Rehabilitated	3.9833	0.0027	154
		Natural, Rehabilitated	3.0002	0.0135	113
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.6156	0.0048	8084
		Degraded, Rehabilitated	1.6017	0.1362	7371
		Natural, Rehabilitated	3.3695	0.005	7353
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.0965	0.2991	8105
		Degraded, Rehabilitated	0.15439	0.8769	8123
		Natural, Rehabilitated	1.1714	0.2645	8081
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.7738	0.4395	9765
		Degraded, Rehabilitated	0.88877	0.391	9784
		Natural, Rehabilitated	2.3221	0.0281	9808
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.41807	0.6693	119
		Degraded, Rehabilitated	1.1407	0.2643	119
		Natural, Rehabilitated	1.974	0.0714	336
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.5375	0.0023	462
		Degraded, Rehabilitated	7.5399	0.0021	460
		Natural, Rehabilitated	2.0221	0.0807	461
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.81873	0.3968	462
		Degraded, Rehabilitated	1.0062	0.3688	462
		Natural, Rehabilitated	0.57943	0.7443	462
Predator	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.24937	0.819	462
		Degraded, Rehabilitated	8.1567	0.0024	461
		Natural, Rehabilitated	7.4264	0.0023	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.0679	0.0019	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.4161	0.1955	461
		Degraded, Rehabilitated	0.93571	0.3895	459
		Natural, Rehabilitated	1.4753	0.1767	461
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.10236	0.9214	8035
		Degraded, Rehabilitated	0.08092	0.9393	8084
		Natural, Rehabilitated	0.15838	0.8761	8073
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.7963	0.013	8127

		Degraded, Rehabilitated	2.0311	0.0471	8085
		Natural, Rehabilitated	0.26832	0.7919	8071
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.52	0.0004	9813
		Degraded, Rehabilitated	3.7178	0.0005	9822
		Natural, Rehabilitated	0.59067	0.5584	9796
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.82269	0.4267	462
		Degraded, Rehabilitated	3.0364	0.0131	462
		Natural, Rehabilitated	4.4169	0.004	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.58184	0.5652	462
		Degraded, Rehabilitated	0.69319	0.4998	460
		Natural, Rehabilitated	1.6405	0.1279	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.6929	0.0019	462
		Degraded, Rehabilitated	8.3969	0.0023	462
		Natural, Rehabilitated	1.1302	0.2657	461
Parasite	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.246	0.0019	462
		Degraded, Rehabilitated	3.4381	0.0046	336
		Natural, Rehabilitated	2.2269	0.058	336
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.5702	0.0026	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.7837	0.0022	462
		Degraded, Rehabilitated	6.9627	0.002	462
		Natural, Rehabilitated	2.2546	0.053	460
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.6035	0.0001	8102
		Degraded, Rehabilitated	5.8466	0.0003	8107
		Natural, Rehabilitated	1.3344	0.1947	8050
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.2805	0.008	8066
		Degraded, Rehabilitated	2.3803	0.0312	8072
		Natural, Rehabilitated	4.9488	0.0006	8098
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.5601	0.5703	9776
		Degraded, Rehabilitated	4.7738	0.0002	9799
		Natural, Rehabilitated	3.3227	0.0032	9787
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.9365	0.0094	462
		Degraded, Rehabilitated	2.2941	0.0529	462
		Natural, Rehabilitated	0.31446	0.7503	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.5198	0.0345	462
		Degraded, Rehabilitated	5.2481	0.0026	461
		Natural, Rehabilitated	1.0461	0.304	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	13.123	0.0025	462
		Degraded, Rehabilitated	1.4487	0.168	462
		Natural, Rehabilitated	13.139	0.002	462

Appendix 4.22. Summary of PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate FFGs, based on groups' average density, for each reach separately. Bold font indicates significant (P<0.05) differences.

Degraded reach seasonal differences				Natural reach seasonal differences				Rehabilitated reach seasonal differences			
Absorber				**Absorber**				**Absorber**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.16881	0.8464	460	Sp.14, Su.14	1.3381	0.2057	462				
Sp.14, Wi.15	1.9029	0.1014	460	Sp.14, Wi.15	1.3237	0.2091	462	Sp.14, Wi.15	4.5616	0.0023	462
Sp.14, Sp.15	0.55317	0.5708	4323	Sp.14, Sp.15	2.2283	0.0532	4326	Sp.14, Sp.15	1.4564	0.1636	4258
Sp.14, Su.15	0.16726	0.905	4302	Sp.14, Su.15	0.85321	0.3968	4302	Sp.14, Su.15	1.7656	0.1068	4301
Sp.14, Au.15	0.68257	0.5055	7582	Sp.14, Au.15	0.15474	0.8766	7644	Sp.14, Au.15	2.5066	0.0261	7578
Sp.14, Wi.16	3.5594	0.0026	455	Sp.14, Wi.16	1.9714	0.0791	461	Sp.14, Wi.16	0.24483	0.8323	461
Sp.14, Sp.16	0.082545	0.8631	457	Sp.14, Sp.16	2.6087	0.0378	462	Sp.14, Sp.16	2.3584	0.0627	336
Sp.14, Su.16	0.6602	0.5145	456	Sp.14, Su.16	1.8171	0.1046	453	Sp.14, Su.16	5.4603	0.002	336
Su.14, Wi.15	1.8002	0.0991	462	Su.14, Wi.15	0.40378	0.6913	462				
Su.14, Sp.15	0.77264	0.4472	4246	Su.14, Sp.15	1.4675	0.1614	4285				
Su.14, Su.15	0.36898	0.7922	4309	Su.14, Su.15	0.60373	0.5632	4295				
Su.14, Au.15	0.5186	0.6086	7613	Su.14, Au.15	0.89055	0.3837	7721				
Su.14, Wi.16	3.4969	0.0018	461	Su.14, Wi.16	1.2737	0.2468	461				
Su.14, Sp.16	0.092022	0.9336	462	Su.14, Sp.16	2.1136	0.059	462				
Su.14, Su.16	0.46793	0.83	462	Su.14, Su.16	0.94011	0.3759	462				
Wi.15, Sp.15	2.8112	0.0173	4322	Wi.15, Sp.15	1.0014	0.3279	4312	Wi.15, Sp.15	3.2411	0.0037	4278
Wi.15, Su.15	2.4083	0.0288	4244	Wi.15, Su.15	0.84433	0.407	4107	Wi.15, Su.15	3.4267	0.0041	4320
Wi.15, Au.15	1.4564	0.1636	7598	Wi.15, Au.15	1.0994	0.2918	7622	Wi.15, Au.15	2.196	0.0416	7653
Wi.15, Wi.16	1.6988	0.1105	462	Wi.15, Wi.16	0.70927	0.4922	461	Wi.15, Wi.16	3.9673	**0.0023**	462
Wi.15, Sp.16	1.902	0.0991	462	Wi.15, Sp.16	1.1589	0.275	458	Wi.15, Sp.16	3.7119	0.0026	336
Wi.15, Su.16	1.8123	0.0967	458	Wi.15, Su.16	0.20763	0.827	462	Wi.15, Su.16	2.6466	0.0158	336
Sp.15, Su.15	0.44526	0.6464	8103	Sp.15, Su.15	2.0285	0.0603	8107	Sp.15, Su.15	0.51443	0.6076	8084
Sp.15, Au.15	1.4133	0.1678	9721	Sp.15, Au.15	2.2653	0.0379	9642	Sp.15, Au.15	0.85613	0.3973	9673
Sp.15, Wi.16	4.8	0.0005	4308	Sp.15, Wi.16	0.30233	0.7664	4281	Sp.15, Wi.16	2.1614	0.0476	4329
Sp.15, Sp.16	0.67698	0.4787	4321	Sp.15, Sp.16	0.017015	0.9879	4341	Sp.15, Sp.16	1.0511	0.3072	3365
Sp.15, Su.16	1.4951	0.153	4311	Sp.15, Su.16	0.92849	0.359	4317	Sp.15, Su.16	0.82538	0.4476	3357
Su.15, Au.15	0.9945	0.3369	9659	Su.15, Au.15	0.59314	0.561	9658	Su.15, Au.15	1.2477	0.2283	9711
Su.15, Wi.16	4.3961	0.0003	4302	Su.15, Wi.16	1.7104	0.1163	4299	Su.15, Wi.16	1.6152	0.1285	4277
Su.15, Sp.16	0.27042	0.8152	4338	Su.15, Sp.16	2.4229	0.0301	4295	Su.15, Sp.16	0.40073	0.6859	3380
Su.15, Su.16	0.95345	0.346	4296	Su.15, Su.16	1.3087	0.2158	4288	Su.15, Su.16	1.2582	0.2317	3321
Au.15, Wi.16	3.4739	0.0035	7631	Au.15, Wi.16	1.7695	0.098	7652	Au.15, Wi.16	2.4256	0.0304	7650
Au.15, Sp.16	0.61407	0.5378	7632	Au.15, Sp.16	2.185	0.0394	7548	Au.15, Sp.16	1.4716	0.1654	6892
Au.15, Su.16	0.18348	0.8513	7608	Au.15, Su.16	1.3576	0.2023	7673	Au.15, Su.16	0.24035	0.8016	6874
Wi.16, Sp.16	3.6042	0.0047	462	Wi.16, Sp.16	0.32699	0.7499	460	Wi.16, Sp.16	1.458	0.1629	335
Wi.16, Su.16	3.7498	0.0029	462	Wi.16, Su.16	0.64831	0.5421	462	Wi.16, Su.16	2.9011	0.0123	336
Sp.16, Su.16	0.60523	0.5674	462	Sp.16, Su.16	1.2351	0.2521	462	Sp.16, Su.16	3.5165	0.0018	245

Deposit-feeder			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	1.6806	0.091	462
Sp.14, Wi.15	5.8117	0.0027	461
Sp.14, Sp.15	1.5679	0.1373	4261
Sp.14, Su.15	0.87597	0.415	4295
Sp.14, Au.15	0.79403	0.4407	7571
Sp.14, Wi.16	1.9072	0.1673	462
Sp.14, Sp.16	0.024521	0.9809	462
Sp.14, Su.16	3.2165	0.0034	462
Su.14, Wi.15	5.3072	0.0019	462
Su.14, Sp.15	2.8065	0.0092	4330
Su.14, Su.15	1.0387	0.3816	462
Su.14, Au.15	0.17543	0.8632	7663
Su.14, Wi.16	2.4554	0.0522	461
Su.14, Sp.16	1.6093	0.1212	462
Su.14, Su.16	0.027495	0.9898	462
Wi.15, Sp.15	3.6791	0.0027	4269
Wi.15, Su.15	7.1952	0.0002	4318
Wi.15, Au.15	3.2732	0.0075	7633
Wi.15, Wi.16	0.073896	0.9404	462
Wi.15, Sp.16	5.303	0.0027	462
Wi.15, Su.16	7.9865	0.0023	461
Sp.15, Su.15	2.4912	0.0247	8088
Sp.15, Au.15	1.7455	0.1014	9712
Sp.15, Wi.16	1.6802	0.1164	4283
Sp.15, Sp.16	1.4594	0.1608	4274
Sp.15, Su.16	3.7639	0.0041	4319
Su.15, Au.15	0.65692	0.5212	9668
Su.15, Wi.16	2.582	0.0296	4311
Su.15, Sp.16	0.80091	0.4279	4307
Su.15, Su.16	1.7467	0.1083	462
Au.15, Wi.16	2.527	0.0249	7547
Au.15, Sp.16	0.79581	0.4372	7649
Au.15, Su.16	0.16938	0.8592	7638
Wi.16, Sp.16	1.883	0.1458	462
Wi.16, Su.16	2.5963	0.0123	462
Sp.16, Su.16	2.7269	0.0234	461

Deposit-feeder			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	13.004	0.0029	462
Sp.14, Wi.15	13.328	0.0027	461
Sp.14, Sp.15	1.9508	0.0815	4289
Sp.14, Su.15	3.3398	0.0153	4269
Sp.14, Au.15	1.5195	0.1454	7618
Sp.14, Wi.16	9.2157	0.0025	462
Sp.14, Sp.16	1.0387	0.3816	462
Sp.14, Su.16	14.342	0.0017	462
Su.14, Wi.15	26.233	0.0025	449
Su.14, Sp.15	10.174	0.0002	4211
Su.14, Su.15	0.76711	0.4396	462
Su.14, Au.15	16.443	0.0001	7565
Su.14, Wi.16	17.652	0.0021	459
Su.14, Sp.16	16.746	0.0023	462
Su.14, Su.16	2.7746	0.0518	462
Wi.15, Sp.15	5.7967	0.0003	4248
Wi.15, Su.15	7.6721	0.0002	4284
Wi.15, Au.15	13.106	0.0001	7605
Wi.15, Wi.16	1.1197	0.3006	462
Wi.15, Sp.16	11.156	0.0028	462
Wi.15, Su.16	33.255	0.0023	459
Sp.15, Su.15	4.9393	0.0005	8051
Sp.15, Au.15	1.5148	0.1472	9667
Sp.15, Wi.16	5.8492	0.0003	4273
Sp.15, Sp.16	0.2087	0.8503	4284
Sp.15, Su.16	9.2814	0.0002	4243
Su.15, Au.15	5.3569	0.0003	9716
Su.15, Wi.16	7.8205	0.0001	4300
Su.15, Sp.16	4.3398	0.0017	4290
Su.15, Su.16	0.53957	0.5834	4277
Au.15, Wi.16	10.767	0.0003	7580
Au.15, Sp.16	1.7824	0.092	7678
Au.15, Su.16	16.23	0.0001	7534
Wi.16, Sp.16	7.5798	0.0019	462
Wi.16, Su.16	17.988	0.0023	458
Sp.16, Su.16	20.235	0.002	461

Deposit-feeder			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	6.9904	0.0017	462
Sp.14, Sp.15	0.45193	0.6622	4284
Sp.14, Su.15	0.0928	0.9308	4277
Sp.14, Au.15	0.27579	0.7706	7639
Sp.14, Wi.16	1.161	0.263	462
Sp.14, Sp.16	0.55561	0.618	462
Sp.14, Su.16	4.0888	0.0051	462
Wi.15, Sp.15	6.9711	0.0002	4281
Wi.15, Su.15	6.691	0.0003	4298
Wi.15, Au.15	4.5833	0.0011	7638
Wi.15, Wi.16	6.1348	**0.0019**	462
Wi.15, Sp.16	6.835	0.0026	462
Wi.15, Su.16	9.203	0.002	461
Sp.15, Su.15	0.49642	0.6289	8090
Sp.15, Au.15	0.5735	0.5657	9674
Sp.15, Wi.16	1.5498	0.1465	4266
Sp.15, Sp.16	0.91778	0.3726	4295
Sp.15, Su.16	4.0736	0.0028	4299
Su.15, Au.15	0.25922	0.7945	9669
Su.15, Wi.16	1.0566	0.2986	4315
Su.15, Sp.16	0.35382	0.7264	4278
Su.15, Su.16	2.0895	0.0786	462
Au.15, Wi.16	0.4986	0.6249	7633
Au.15, Sp.16	0.016863	0.9796	7629
Au.15, Su.16	1.5163	0.1464	7566
Wi.16, Sp.16	0.73911	0.4556	460
Wi.16, Su.16	1.3535	0.2076	462
Sp.16, Su.16	2.9946	0.0184	462

Shredders

Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	2.8686	0.0238	462
Sp.14, Wi.15	1.3043	0.2266	462
Sp.14, Sp.15	1.1039	0.2807	4304
Sp.14, Su.15	9.0123	0.0001	4323
Sp.14, Au.15	3.6463	0.001	7588
Sp.14, Wi.16	2.2301	0.0524	462
Sp.14, Sp.16	0.18347	0.7654	457
Sp.14, Su.16	5.4444	0.0047	462
Su.14, Wi.15	3.878	0.006	462
Su.14, Sp.15	2.7011	0.0183	4265
Su.14, Su.15	2.1922	0.0611	462
Su.14, Au.15	1.4271	0.1651	7622
Su.14, Wi.16	4.6235	0.0042	462
Su.14, Sp.16	2.7427	0.0343	462
Su.14, Su.16	0.8993	0.3936	462
Wi.15, Sp.15	2.7334	0.0183	4300
Wi.15, Su.15	11.455	0.0004	4261
Wi.15, Au.15	5.6929	0.0003	7651
Wi.15, Wi.16	0.77095	0.4521	462
Wi.15, Sp.16	1.5062	0.1629	462
Wi.15, Su.16	7.216	0.0017	462
Sp.15, Su.15	9.2614	0.0002	8129
Sp.15, Au.15	2.8125	0.011	9647
Sp.15, Wi.16	3.9902	0.0028	4300
Sp.15, Sp.16	0.88751	0.3823	4272
Sp.15, Su.16	5.3769	0.0003	4269
Su.15, Au.15	7.6925	0.0001	9673
Su.15, Wi.16	14.937	0.0004	4312
Su.15, Sp.16	8.813	0.0005	4314
Su.15, Su.16	2.0381	0.0685	455
Au.15, Wi.16	7.5622	0.0001	7614
Au.15, Sp.16	3.4028	0.0022	7613
Au.15, Su.16	3.8254	0.0018	7612
Wi.16, Sp.16	2.4755	0.0413	462
Wi.16, Su.16	9.4509	0.0022	460
Sp.16, Su.16	5.2783	0.0046	462

Shredders

Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	10.26	0.002	462
Sp.14, Wi.15	9.9384	0.0014	462
Sp.14, Sp.15	0.1484	0.8813	4303
Sp.14, Su.15	4.2113	0.0012	4306
Sp.14, Au.15	3.5756	0.0066	7607
Sp.14, Wi.16	11.094	0.0024	461
Sp.14, Sp.16	0.21901	0.8356	462
Sp.14, Su.16	9.9316	0.0022	462
Su.14, Wi.15	16.896	0.0026	455
Su.14, Sp.15	7.1134	0.0004	4315
Su.14, Su.15	1.28	0.2596	462
Su.14, Au.15	1.6856	0.1083	7584
Su.14, Wi.16	21.674	0.0021	462
Su.14, Sp.16	5.3521	0.0015	462
Su.14, Su.16	2.0175	0.0772	461
Wi.15, Sp.15	10.184	0.0002	4269
Wi.15, Su.15	8.5818	0.0005	4293
Wi.15, Au.15	7.1462	0.0002	7619
Wi.15, Wi.16	1.1783	0.2583	462
Wi.15, Sp.16	8.0686	0.0016	462
Wi.15, Su.16	16.714	0.0022	461
Sp.15, Su.15	4.9724	0.0001	8119
Sp.15, Au.15	4.2923	0.0005	9621
Sp.15, Wi.16	10.318	0.0004	4290
Sp.15, Sp.16	0.10602	0.9167	4296
Sp.15, Su.16	7.7081	0.0001	4285
Su.15, Au.15	0.27305	0.7847	9660
Su.15, Wi.16	8.2202	0.0006	4312
Su.15, Sp.16	3.9434	0.0019	4326
Su.15, Su.16	0.55427	0.5834	462
Au.15, Wi.16	6.7661	0.0001	7625
Au.15, Sp.16	3.428	0.0069	7636
Au.15, Su.16	1.3946	0.1878	7620
Wi.16, Sp.16	8.1299	0.0021	462
Wi.16, Su.16	20.446	0.0024	462
Sp.16, Su.16	5.8431	0.0023	462

Shredders

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	7.7265	0.0022	461
Sp.14, Sp.15	1.2614	0.2314	4333
Sp.14, Su.15	7.161	0.0002	4243
Sp.14, Au.15	10.009	0.0001	7623
Sp.14, Wi.16	3.8756	0.0039	462
Sp.14, Sp.16	15.68	**0.0025**	462
Sp.14, Su.16	7.7842	0.0022	462
Wi.15, Sp.15	5.5149	0.0006	4267
Wi.15, Su.15	9.7569	0.0003	4170
Wi.15, Au.15	16.313	0.0001	7519
Wi.15, Wi.16	7.3888	**0.0016**	462
Wi.15, Sp.16	24.464	0.0032	424
Wi.15, Su.16	10.352	0.0018	462
Sp.15, Su.15	6.9861	0.0001	8038
Sp.15, Au.15	6.9774	0.0001	9676
Sp.15, Wi.16	2.6567	0.0211	4306
Sp.15, Sp.16	8.3108	**0.0002**	4265
Sp.15, Su.16	7.3613	0.0004	4302
Su.15, Au.15	3.7762	0.0002	9717
Su.15, Wi.16	3.7605	0.0005	4275
Su.15, Sp.16	1.2761	0.2198	4331
Su.15, Su.16	1.6219	0.0616	462
Au.15, Wi.16	2.2738	0.0355	7677
Au.15, Sp.16	3.5323	0.0036	7557
Au.15, Su.16	4.6553	0.0003	7594
Wi.16, Sp.16	3.9187	0.0044	462
Wi.16, Su.16	4.1707	0.0024	462
Sp.16, Su.16	2.0528	0.0117	462

Scraper			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.6773	0.512	462
Sp.14, Wi.15	0.57651	0.5742	462
Sp.14, Sp.15	1.4697	0.1678	4309
Sp.14, Su.15	5.1231	0.0005	4337
Sp.14, Au.15	3.0941	0.0065	7706
Sp.14, Wi.16	1.632	0.1318	462
Sp.14, Sp.16	0.011795	0.9944	461
Sp.14, Su.16	2.9174	0.0195	462
Su.14, Wi.15	0.25689	0.8026	462
Su.14, Sp.15	0.81471	0.4184	4292
Su.14, Su.15	2.5506	0.0567	462
Su.14, Au.15	1.9347	0.0684	7626
Su.14, Wi.16	1.9772	0.0872	462
Su.14, Sp.16	0.66837	0.5102	462
Su.14, Su.16	1.4745	0.1843	462
Wi.15, Sp.15	0.2076	0.8313	4265
Wi.15, Su.15	1.2114	0.2588	4273
Wi.15, Au.15	0.63783	0.5268	7625
Wi.15, Wi.16	1.4654	0.1717	462
Wi.15, Sp.16	0.57773	0.5695	462
Wi.15, Su.16	0.3141	0.7776	462
Sp.15, Su.15	1.8851	0.0795	8046
Sp.15, Au.15	0.68016	0.5074	9654
Sp.15, Wi.16	2.7444	0.0192	4303
Sp.15, Sp.16	1.4574	0.1614	4305
Sp.15, Su.16	0.24435	0.8068	4277
Su.15, Au.15	1.9477	0.0666	9652
Su.15, Wi.16	5.0089	0.0004	4261
Su.15, Sp.16	4.9248	0.0004	4293
Su.15, Su.16	2.348	0.0663	462
Au.15, Wi.16	4.2694	0.0007	7621
Au.15, Sp.16	3.0294	0.0075	7626
Au.15, Su.16	0.52859	0.6055	7579
Wi.16, Sp.16	1.6022	0.1433	461
Wi.16, Su.16	3.1951	0.0073	462
Sp.16, Su.16	2.7503	0.0142	452

Scraper			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	3.7802	0.0097	462
Sp.14, Wi.15	12.525	0.0025	460
Sp.14, Sp.15	0.24748	0.7993	4298
Sp.14, Su.15	4.5111	0.0009	4279
Sp.14, Au.15	1.5439	0.1451	7618
Sp.14, Wi.16	13.91	0.0022	445
Sp.14, Sp.16	1.1027	0.2932	462
Sp.14, Su.16	3.814	0.0061	462
Su.14, Wi.15	16.615	0.0027	462
Su.14, Sp.15	4.6813	0.001	4296
Su.14, Su.15	0.1959	0.8526	462
Su.14, Au.15	0.064021	0.9399	7624
Su.14, Wi.16	18.279	0.0029	458
Su.14, Sp.16	3.3142	0.0038	462
Su.14, Su.16	0.57606	0.5629	460
Wi.15, Sp.15	14.38	0.0002	4107
Wi.15, Su.15	14.52	0.0002	4243
Wi.15, Au.15	6.3388	0.0001	7601
Wi.15, Wi.16	0.67534	0.5114	460
Wi.15, Sp.16	16.005	0.0026	462
Wi.15, Su.16	18.929	0.0021	462
Sp.15, Su.15	5.6521	0.0001	8132
Sp.15, Au.15	2.0012	0.0583	9684
Sp.15, Wi.16	15.863	0.0002	4323
Sp.15, Sp.16	1.5508	0.142	4260
Sp.15, Su.16	4.6662	0.0022	4277
Su.15, Au.15	0.77613	0.4487	9668
Su.15, Wi.16	15.343	0.0001	4247
Su.15, Sp.16	3.9759	0.0018	4282
Su.15, Su.16	1.0761	0.306	462
Au.15, Wi.16	6.5963	0.0002	7560
Au.15, Sp.16	1.1816	0.2515	7622
Au.15, Su.16	0.25802	0.7944	7531
Wi.16, Sp.16	18.168	0.0018	460
Wi.16, Su.16	21.364	0.0033	461
Sp.16, Su.16	3.403	0.0041	453

Scraper			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	3.5016	0.0072	462
Sp.14, Sp.15	5.0416	**0.0009**	4329
Sp.14, Su.15	5.9148	0.0003	4252
Sp.14, Au.15	8.1973	0.0001	7644
Sp.14, Wi.16	2.1235	0.0951	462
Sp.14, Sp.16	13.06	**0.0028**	462
Sp.14, Su.16	11.552	0.0028	462
Wi.15, Sp.15	7.0319	0.0001	4263
Wi.15, Su.15	7.3523	0.0005	4298
Wi.15, Au.15	10.118	0.0001	7668
Wi.15, Wi.16	3.5344	**0.0055**	462
Wi.15, Sp.16	11.415	0.002	462
Wi.15, Su.16	11.586	0.0018	461
Sp.15, Su.15	3.3338	0.0003	8069
Sp.15, Au.15	2.4974	0.0231	9669
Sp.15, Wi.16	0.41663	0.6834	4311
Sp.15, Sp.16	3.6478	**0.0037**	4300
Sp.15, Su.16	5.7494	0.0003	4310
Su.15, Au.15	2.0719	0.0331	9703
Su.15, Wi.16	2.594	0.0156	4293
Su.15, Sp.16	0.79308	0.5363	4314
Su.15, Su.16	3.5611	**0.007**	462
Au.15, Wi.16	1.9812	0.0599	7700
Au.15, Sp.16	1.5156	0.1395	7639
Au.15, Su.16	4.2636	0.0004	7630
Wi.16, Sp.16	2.2585	0.0702	462
Wi.16, Su.16	3.5823	0.0024	462
Sp.16, Su.16	2.841	0.0126	461

Filter-feeder			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	1.0392	0.3224	461
Sp.14, Wi.15	1.4193	0.1771	462
Sp.14, Sp.15	1.042	0.3256	4335
Sp.14, Su.15	2.2176	0.044	4315
Sp.14, Au.15	0.23844	0.8146	7654
Sp.14, Wi.16	1.7375	0.1163	462
Sp.14, Sp.16	0.43666	0.6563	462
Sp.14, Su.16	0.8825	0.3966	462
Su.14, Wi.15	2.3321	0.053	462
Su.14, Sp.15	0.32439	0.7536	4317
Su.14, Su.15	2.0602	0.0502	462
Su.14, Au.15	1.2246	0.2239	7631
Su.14, Wi.16	2.4842	0.0337	460
Su.14, Sp.16	0.59742	0.5596	462
Su.14, Su.16	0.31204	0.7873	460
Wi.15, Sp.15	2.7727	0.0182	4244
Wi.15, Su.15	3.6009	0.0033	4288
Wi.15, Au.15	1.0827	0.288	7670
Wi.15, Wi.16	0.59704	0.5581	461
Wi.15, Sp.16	1.7912	0.1031	460
Wi.15, Su.16	2.392	0.0402	462
Sp.15, Su.15	1.7069	0.1063	8086
Sp.15, Au.15	1.2395	0.2326	9722
Sp.15, Wi.16	2.9686	0.0085	4279
Sp.15, Sp.16	0.45977	0.6594	4270
Sp.15, Su.16	0.041868	0.9664	4223
Su.15, Au.15	2.5407	0.0216	9718
Su.15, Wi.16	3.727	0.0015	4348
Su.15, Sp.16	1.721	0.108	4312
Su.15, Su.16	2.8184	0.0527	462
Au.15, Wi.16	1.6129	0.1262	7593
Au.15, Sp.16	0.64313	0.5199	7662
Au.15, Su.16	1.0095	0.3333	7700
Wi.16, Sp.16	2.0385	0.0746	462
Wi.16, Su.16	2.4845	0.0329	462
Sp.16, Su.16	0.36891	0.706	462

Filter-feeder			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	16.053	0.002	462
Sp.14, Wi.15	4.8339	0.0061	462
Sp.14, Sp.15	0.47467	0.6464	4269
Sp.14, Su.15	2.7735	0.0256	4299
Sp.14, Au.15	0.83576	0.4121	7602
Sp.14, Wi.16	3.7648	0.0116	462
Sp.14, Sp.16	0.32395	0.7367	462
Sp.14, Su.16	16.521	0.0033	460
Su.14, Wi.15	16.525	0.0018	456
Su.14, Sp.15	20.15	0.0004	4305
Su.14, Su.15	0.049999	0.9504	459
Su.14, Au.15	14.096	0.0001	7605
Su.14, Wi.16	23.098	0.0023	461
Su.14, Sp.16	12.858	0.0021	462
Su.14, Su.16	0.14313	0.8396	460
Wi.15, Sp.15	6.4673	0.0003	4300
Wi.15, Su.15	4.4405	0.0007	4294
Wi.15, Au.15	4.034	0.0013	7549
Wi.15, Wi.16	2.9212	0.0592	462
Wi.15, Sp.16	8.377	0.0027	458
Wi.15, Su.16	16.808	0.002	462
Sp.15, Su.15	3.3243	0.0094	7915
Sp.15, Au.15	1.4126	0.1762	9655
Sp.15, Wi.16	5.5223	0.001	4243
Sp.15, Sp.16	1.4574	0.1614	4292
Sp.15, Su.16	20.766	0.0002	4326
Su.15, Au.15	4.1944	0.0007	9703
Su.15, Wi.16	3.5974	0.0075	4334
Su.15, Sp.16	1.6277	0.1333	4290
Su.15, Su.16	0.21164	0.8118	462
Au.15, Wi.16	1.7059	0.1095	7661
Au.15, Sp.16	4.4936	0.001	7604
Au.15, Su.16	14.305	0.0001	7564
Wi.16, Sp.16	10.685	0.0028	462
Wi.16, Su.16	23.972	0.0024	460
Sp.16, Su.16	13.325	0.0017	462

Filter-feeder			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	4.2119	0.0018	462
Sp.14, Sp.15	0.40806	0.6792	4344
Sp.14, Su.15	1.2794	0.2299	4289
Sp.14, Au.15	0.77134	0.4474	7610
Sp.14, Wi.16	1.0228	0.3728	462
Sp.14, Sp.16	6.2004	**0.0026**	462
Sp.14, Su.16	5.4477	0.0027	462
Wi.15, Sp.15	3.6608	0.0061	4281
Wi.15, Su.15	4.6467	0.0001	4302
Wi.15, Au.15	3.894	0.0009	7597
Wi.15, Wi.16	4.3396	**0.0024**	462
Wi.15, Sp.16	8.2088	0.0018	462
Wi.15, Su.16	7.7217	0.0027	462
Sp.15, Su.15	0.73549	0.4708	8089
Sp.15, Au.15	1.1315	0.263	9655
Sp.15, Wi.16	0.37847	0.7105	4267
Sp.15, Sp.16	3.272	**0.0063**	4304
Sp.15, Su.16	2.9106	0.012	4285
Su.15, Au.15	2.1787	0.0398	9685
Su.15, Wi.16	0.33295	0.7692	4301
Su.15, Sp.16	2.778	0.0186	4251
Su.15, Su.16	1.6358	0.1203	462
Au.15, Wi.16	1.717	0.104	7601
Au.15, Sp.16	6.0887	0.0002	7626
Au.15, Su.16	5.5327	0.0001	7617
Wi.16, Sp.16	3.5077	0.0122	462
Wi.16, Su.16	3.038	0.0132	461
Sp.16, Su.16	0.53412	0.5985	461

Piercer

Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	6.4409	0.0022	336
Sp.14, Wi.15	0.96785	0.3952	245
Sp.14, Sp.15	1.3104	0.213	3326
Sp.14, Su.15	5.2044	0.0007	3222
Sp.14, Au.15	1.7363	0.098	6086
Sp.14, Wi.16	0.17889	0.8579	154
Sp.14, Sp.16	0.32395	0.7367	336
Sp.14, Su.16	5.4658	0.0027	336
Su.14, Wi.15	2.878	0.0251	336
Su.14, Sp.15	4.7399	0.0002	4275
Su.14, Su.15	0.55064	0.5871	4327
Su.14, Au.15	0.34063	0.7656	6933
Su.14, Wi.16	1.8076	0.1408	210
Su.14, Sp.16	6.6749	0.0028	461
Su.14, Su.16	0.81847	0.4155	461
Wi.15, Sp.15	0.19291	0.855	3363
Wi.15, Su.15	3.2269	0.0085	3364
Wi.15, Au.15	1.1953	0.2552	6060
Wi.15, Wi.16	0.5328	0.6083	154
Wi.15, Sp.16	1.1104	0.3514	336
Wi.15, Su.16	2.2943	0.0502	336
Sp.15, Su.15	4.7248	0.0006	8088
Sp.15, Au.15	1.6226	0.1172	9592
Sp.15, Wi.16	0.59931	0.5569	2254
Sp.15, Sp.16	1.5485	0.1461	4243
Sp.15, Su.16	3.8355	0.0028	4288
Su.15, Au.15	0.71573	0.4931	9630
Su.15, Wi.16	2.3708	0.0337	2265
Su.15, Sp.16	5.3653	0.0006	4292
Su.15, Su.16	1.2192	0.2458	4240
Au.15, Wi.16	1.4976	0.1553	3007
Au.15, Sp.16	1.8075	0.0865	6917
Au.15, Su.16	0.018418	0.989	6838
Wi.16, Sp.16	0.12226	0.9026	210
Wi.16, Su.16	1.5524	0.1646	210
Sp.16, Su.16	5.6992	0.002	461

Piercer

Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.034673	0.9392	119
Sp.14, Wi.15	0.71352	0.4309	179
Sp.14, Sp.15	1.8899	0.0814	3381
Sp.14, Su.15	1.8733	0.0855	3375
Sp.14, Au.15	1.2374	0.2306	6918
Sp.14, Wi.16	0.7016	0.54	210
Sp.14, Sp.16	1.9168	0.0931	336
Sp.14, Su.16	2.0667	0.0662	336
Su.14, Wi.15	0.65629	0.4519	179
Su.14, Sp.15	1.9258	0.0774	3369
Su.14, Su.15	1.9074	0.081	3386
Su.14, Au.15	1.2813	0.2184	6925
Su.14, Wi.16	0.64988	0.5794	210
Su.14, Sp.16	1.941	0.106	336
Su.14, Su.16	2.0891	0.0632	336
Wi.15, Sp.15	7.4947	0.0002	2554
Wi.15, Su.15	4.56	0.0018	2564
Wi.15, Au.15	2.914	0.0095	6046
Wi.15, Wi.16	0.1097	0.9597	245
Wi.15, Sp.16	9.0125	0.0027	245
Wi.15, Su.16	14.783	0.0025	244
Sp.15, Su.15	0.40989	0.6972	8133
Sp.15, Au.15	0.81658	0.4058	9626
Sp.15, Wi.16	5.0604	0.0007	4300
Sp.15, Sp.16	1.0344	0.3377	4291
Sp.15, Su.16	1.5307	0.1461	4295
Su.15, Au.15	1.0273	0.317	9675
Su.15, Wi.16	3.9273	0.0031	4287
Su.15, Sp.16	0.28997	0.8032	4257
Su.15, Su.16	0.48687	0.7018	4339
Au.15, Wi.16	2.7121	0.0106	7661
Au.15, Sp.16	1.2457	0.2368	7632
Au.15, Su.16	1.4393	0.1654	7616
Wi.16, Sp.16	5.1629	0.002	462
Wi.16, Su.16	5.9439	0.0019	462
Sp.16, Su.16	0.33662	0.7532	462

Piercer

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	6.4259	0.002	83
Sp.14, Sp.15	1.9577	0.0728	1468
Sp.14, Su.15	2.2554	0.0509	1954
Sp.14, Au.15	2.1604	0.0474	5241
Sp.14, Wi.16	0.44597	0.6687	179
Sp.14, Sp.16	3.5583	**0.0094**	178
Sp.14, Su.16	2.1126	0.0465	179
Wi.15, Sp.15	1.6928	0.101	810
Wi.15, Su.15	7.4389	0.0005	2258
Wi.15, Au.15	7.3138	0.0003	5683
Wi.15, Wi.16	2.9854	**0.0211**	119
Wi.15, Sp.16	8.9176	0.0025	210
Wi.15, Su.16	7.2923	0.0028	210
Sp.15, Su.15	4.2187	0.0012	7385
Sp.15, Au.15	4.5215	0.0002	9632
Sp.15, Wi.16	1.9577	0.0728	2267
Sp.15, Sp.16	4.2721	**0.0022**	3361
Sp.15, Su.16	3.5226	0.0039	3331
Su.15, Au.15	0.0058934	0.9952	9677
Su.15, Wi.16	0.64007	0.5434	4306
Su.15, Sp.16	0.6175	0.5463	4317
Su.15, Su.16	0.28608	0.7784	4280
Au.15, Wi.16	0.70781	0.497	7667
Au.15, Sp.16	0.59215	0.569	7611
Au.15, Su.16	0.28661	0.7826	7631
Wi.16, Sp.16	0.83931	0.4584	461
Wi.16, Su.16	0.40986	0.701	462
Sp.16, Su.16	0.96787	0.3459	461

Predator			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	2.3618	0.0512	457
Sp.14, Wi.15	6.5654	0.002	462
Sp.14, Sp.15	0.50069	0.635	4266
Sp.14, Su.15	2.0105	0.0661	4324
Sp.14, Au.15	3.4942	0.0047	7734
Sp.14, Wi.16	4.948	0.0024	461
Sp.14, Sp.16	0.41433	0.6772	462
Sp.14, Su.16	1.4734	0.1796	462
Su.14, Wi.15	9.0138	0.0022	457
Su.14, Sp.15	2.0027	0.0642	4266
Su.14, Su.15	0.43704	0.673	4330
Su.14, Au.15	6.1228	0.0001	7627
Su.14, Wi.16	7.1633	0.0021	462
Su.14, Sp.16	2.4139	0.0425	462
Su.14, Su.16	1.132	0.259	462
Wi.15, Sp.15	7.3902	0.0005	4294
Wi.15, Su.15	6.2754	0.0002	4312
Wi.15, Au.15	3.6113	0.0023	7685
Wi.15, Wi.16	1.0187	0.3223	462
Wi.15, Sp.16	5.0666	0.0024	462
Wi.15, Su.16	8.8514	0.0017	462
Sp.15, Su.15	1.9961	0.0602	8090
Sp.15, Au.15	4.4853	0.0003	9650
Sp.15, Wi.16	5.8075	0.0008	4308
Sp.15, Sp.16	0.89925	0.3851	4303
Sp.15, Su.16	0.97968	0.3578	4355
Su.15, Au.15	5.3955	0.0001	9653
Su.15, Wi.16	5.4112	0.0003	4236
Su.15, Sp.16	2.2151	0.0475	4308
Su.15, Su.16	1.1507	0.2804	4285
Au.15, Wi.16	2.2799	0.0391	7620
Au.15, Sp.16	2.6592	0.0171	7659
Au.15, Su.16	5.2606	0.0002	7602
Wi.16, Sp.16	3.8626	0.004	460
Wi.16, Su.16	6.7566	0.002	462
Sp.16, Su.16	1.6542	0.138	462

Predator			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	6.3359	0.0026	462
Sp.14, Wi.15	4.2419	0.0047	462
Sp.14, Sp.15	0.096875	0.9209	4296
Sp.14, Su.15	6.4982	0.0002	4276
Sp.14, Au.15	1.0659	0.2909	7616
Sp.14, Wi.16	6.3624	0.002	461
Sp.14, Sp.16	1.2735	0.235	462
Sp.14, Su.16	7.3516	0.0024	462
Su.14, Wi.15	11.951	0.0021	461
Su.14, Sp.15	7.4421	0.0002	4288
Su.14, Su.15	0.58236	0.5714	4334
Su.14, Au.15	3.3865	0.0025	7639
Su.14, Wi.16	18.477	0.0025	460
Su.14, Sp.16	8.8155	0.002	461
Su.14, Su.16	0.93959	0.3767	461
Wi.15, Sp.15	5.2159	0.0005	4275
Wi.15, Su.15	12.458	0.0004	4292
Wi.15, Au.15	4.428	0.0006	7582
Wi.15, Wi.16	1.2739	0.2423	462
Wi.15, Sp.16	3.3233	0.0089	462
Wi.15, Su.16	13.42	0.0016	460
Sp.15, Su.15	7.6472	0.0001	8120
Sp.15, Au.15	1.2239	0.2379	9670
Sp.15, Wi.16	7.6689	0.0003	4319
Sp.15, Sp.16	1.6359	0.1242	4277
Sp.15, Su.16	8.6044	0.0003	4308
Su.15, Au.15	3.6836	0.0014	9685
Su.15, Wi.16	17.351	0.0005	4282
Su.15, Sp.16	8.8693	0.0006	4332
Su.15, Su.16	1.5379	0.146	4316
Au.15, Wi.16	5.4641	0.0003	7611
Au.15, Sp.16	2.0674	0.0613	7629
Au.15, Su.16	3.8837	0.0011	7614
Wi.16, Sp.16	5.6558	0.0025	462
Wi.16, Su.16	22.098	0.0024	462
Sp.16, Su.16	10.233	0.0024	460

Predator			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	0.22339	0.8244	462
Sp.14, Sp.15	6.6121	**0.0003**	4306
Sp.14, Su.15	10.022	0.0002	4294
Sp.14, Au.15	6.0543	0.0002	7600
Sp.14, Wi.16	5.7359	0.0025	462
Sp.14, Sp.16	9.9103	**0.0024**	461
Sp.14, Su.16	17.549	0.0026	460
Wi.15, Sp.15	3.966	0.0009	4317
Wi.15, Su.15	6.181	0.0002	4329
Wi.15, Au.15	4.3608	0.0001	7614
Wi.15, Wi.16	2.6533	**0.0261**	460
Wi.15, Sp.16	3.4985	0.0073	461
Wi.15, Su.16	6.6031	0.0014	460
Sp.15, Su.15	3.9124	0.0022	8148
Sp.15, Au.15	0.37122	0.7274	9680
Sp.15, Wi.16	1.5879	0.134	4297
Sp.15, Sp.16	0.25838	0.803	4311
Sp.15, Su.16	6.0926	0.0004	4262
Su.15, Au.15	3.4079	0.003	9659
Su.15, Wi.16	5.2235	0.0005	4319
Su.15, Sp.16	4.3366	0.0016	4289
Su.15, Su.16	1.6323	0.1283	4232
Au.15, Wi.16	1.74	0.0985	7670
Au.15, Sp.16	0.57586	0.612	7672
Au.15, Su.16	4.8571	0.0005	7586
Wi.16, Sp.16	1.8735	0.0888	461
Wi.16, Su.16	9.2627	0.0039	461
Sp.16, Su.16	10.489	0.0018	462

Parasite			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.10114	0.9197	462
Sp.14, Wi.15	1.4059	0.2035	462
Sp.14, Sp.15	0.92278	0.3758	4311
Sp.14, Su.15	0.72596	0.4966	4285
Sp.14, Au.15	0.88397	0.4007	7638
Sp.14, Wi.16	3.2022	0.0078	462
Sp.14, Sp.16	0.57419	0.5533	460
Sp.14, Su.16	0.18941	0.8792	462
Su.14, Wi.15	1.213	0.2413	462
Su.14, Sp.15	0.97295	0.3738	4304
Su.14, Su.15	0.78881	0.4544	4280
Su.14, Au.15	0.72566	0.4834	7514
Su.14, Wi.16	2.8683	0.0269	461
Su.14, Sp.16	0.62819	0.5666	462
Su.14, Su.16	0.040925	0.9772	460
Wi.15, Sp.15	2.6237	0.0236	4277
Wi.15, Su.15	2.0572	0.0595	4319
Wi.15, Au.15	0.75925	0.4511	7652
Wi.15, Wi.16	1.6236	0.1475	462
Wi.15, Sp.16	1.919	0.0816	462
Wi.15, Su.16	1.5636	0.1509	462
Sp.15, Su.15	0.054532	0.9582	8066
Sp.15, Au.15	2.0974	0.0524	9675
Sp.15, Wi.16	4.9259	0.0007	4276
Sp.15, Sp.16	0.18278	0.8559	4314
Sp.15, Su.16	1.4495	0.1695	4295
Su.15, Au.15	1.7872	0.0884	9684
Su.15, Wi.16	3.7796	0.0019	4285
Su.15, Sp.16	0.17922	0.8616	4312
Su.15, Su.16	0.98194	0.3692	4274
Au.15, Wi.16	2.7458	0.0133	7598
Au.15, Sp.16	1.5116	0.1491	7688
Au.15, Su.16	0.82274	0.4269	7676
Wi.16, Sp.16	3.7098	0.0067	462
Wi.16, Su.16	3.8271	0.0084	462
Sp.16, Su.16	0.92213	0.4089	462

Parasite			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	24.929	0.0017	461
Sp.14, Wi.15	4.9031	0.0014	462
Sp.14, Sp.15	1.7791	0.1008	4271
Sp.14, Su.15	8.6651	0.0004	4313
Sp.14, Au.15	2.2029	0.0487	7530
Sp.14, Wi.16	5.4083	0.002	460
Sp.14, Sp.16	1.656	0.1354	462
Sp.14, Su.16	21.603	0.0021	461
Su.14, Wi.15	25.294	0.0023	460
Su.14, Sp.15	10.714	0.0001	4298
Su.14, Su.15	1.3335	0.2171	4244
Su.14, Au.15	5.4671	0.0002	7638
Su.14, Wi.16	34.927	0.0021	461
Su.14, Sp.16	8.0887	0.0019	462
Su.14, Su.16	2.2751	0.0455	462
Wi.15, Sp.15	5.1472	0.0003	4308
Wi.15, Su.15	11.309	0.0001	4310
Wi.15, Au.15	4.4374	0.0015	7669
Wi.15, Wi.16	0.56159	0.6034	460
Wi.15, Sp.16	4.2894	0.0023	462
Wi.15, Su.16	22.928	0.0024	462
Sp.15, Su.15	7.2183	0.0001	8131
Sp.15, Au.15	1.1963	0.2402	9651
Sp.15, Wi.16	5.0554	0.0006	4305
Sp.15, Sp.16	0.25088	0.8066	4312
Sp.15, Su.16	9.8031	0.0002	4321
Su.15, Au.15	4.6815	0.0004	9618
Su.15, Wi.16	11.451	0.0003	4320
Su.15, Sp.16	5.5342	0.0005	4289
Su.15, Su.16	0.69299	0.4981	4273
Au.15, Wi.16	4.263	0.0014	7602
Au.15, Sp.16	0.77032	0.4545	7619
Au.15, Su.16	4.9753	0.0004	7696
Wi.16, Sp.16	4.2221	0.0044	462
Wi.16, Su.16	30.204	0.0015	458
Sp.16, Su.16	7.3866	0.0021	461

Parasite			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	7.5962	0.0017	336
Sp.14, Sp.15	1.1643	0.2568	3314
Sp.14, Su.15	0.37564	0.7074	3308
Sp.14, Au.15	2.0603	0.0554	6947
Sp.14, Wi.16	3.0909	0.0203	336
Sp.14, Sp.16	1.1785	0.2566	334
Sp.14, Su.16	3.4614	0.0081	336
Wi.15, Sp.15	5.0927	0.0006	4289
Wi.15, Su.15	4.4826	0.0012	4315
Wi.15, Au.15	3.2912	0.0038	7601
Wi.15, Wi.16	2.0092	0.0796	462
Wi.15, Sp.16	7.5776	0.0025	462
Wi.15, Su.16	10.699	0.0026	462
Sp.15, Su.15	1.2281	0.2471	8069
Sp.15, Au.15	1.1806	0.2575	9678
Sp.15, Wi.16	2.11	0.0567	4267
Sp.15, Sp.16	0.48938	0.6256	4318
Sp.15, Su.16	3.5127	0.0071	4290
Su.15, Au.15	2.1935	0.0427	9677
Su.15, Wi.16	2.5356	0.0284	4327
Su.15, Sp.16	0.83823	0.4259	4292
Su.15, Su.16	1.0787	0.2916	4264
Au.15, Wi.16	1.0014	0.3373	7692
Au.15, Sp.16	1.5226	0.1474	7626
Au.15, Su.16	3.9668	0.0022	7609
Wi.16, Sp.16	2.6678	0.0405	462
Wi.16, Su.16	4.9905	0.0017	461
Sp.16, Su.16	5.6278	0.0015	462

Appendix 4.23. average biomass and standard deviation of FFGs according to study reaches.

FFGs average biomass	Seasons	Degraded reach		Rehabilitated reach		Natural Reach	
		Mean	SD	Mean	SD	Mean	SD
Absorber	Sp.14	8.3	12.1	8.4	3.0	7.9	3.4
	Su.14	6.4	3.5	-	-	5.1	0.9
	Wi.15	22.5	13.1	1.4	1.2	6.2	2.7
	Sp.15	3.3	2.9	4.7	2.7	4.6	3.6
	Su.15	4.3	4.1	6.7	5.1	5.0	1.3
	Au.15	7.0	8.3	3.8	2.8	6.5	3.2
	Wi.16	10.5	3.8	8.5	5.3	3.8	1.8
	Sp.16	5.1	4.4	5.2	1.4	3.6	1.1
	Su.16	5.4	1.8	2.8	0.8	4.8	1.2
Deposit-feeder	Sp.14	38.8	32.1	34.2	8.6	69.2	15.7
	Su.14	39.1	19.1	-	-	97.0	20.1
	Wi.15	89.0	26.2	5.7	3.6	43.6	16.3
	Sp.15	25.3	6.7	22.4	13.6	61.7	20.9
	Su.15	48.5	11.3	46.6	12.6	91.9	10.7
	Au.15	33.7	32.5	19.6	9.9	43.7	5.8
	Wi.16	44.5	4.8	33.4	14.1	26.3	6.7
	Sp.16	29.4	10.1	26.9	8.1	58.3	13.9
	Su.16	37.4	12.3	35.9	7.7	91.6	21.4
Shredders	Sp.14	36.7	25.3	29	17.0	1049.0	173.1
	Su.14	317.3	273.8	-	-	816.9	56.9
	Wi.15	21.6	17.2	17.8	10.8	270.3	77.0
	Sp.15	52.9	34.9	88	61.8	1023.6	194.2
	Su.15	496.0	279.6	645	154.9	852.0	217.3
	Au.15	254.6	223.0	359.1	194.2	2721.1	1692.1
	Wi.16	20.3	11.4	196.3	57.9	284.1	56.5
	Sp.16	36.3	26.9	630	118.1	1046.2	197.8
	Su.16	443.1	168.0	924	178.7	1021.3	76.3
Scraper	Sp.14	35.6	14.6	18	14.9	925.6	209.4
	Su.14	232.7	197.6	-	-	549.4	52.7
	Wi.15	19.8	15.1	9.4	9.2	220.7	35.2
	Sp.15	34.9	19.3	111	126.1	1018.9	143.1
	Su.15	369.6	193.6	430.4	129.1	678.9	197.8
	Au.15	301.6	221.4	655.4	418.8	2013.1	1093.6
	Wi.16	24.1	22.9	288	208.5	148.9	63.8
	Sp.16	28.3	15.3	661	218.8	1085.2	230.6
	Su.16	315.1	120.7	891	738.2	115.3	48.4
Filter-feeder	Sp.14	403.6	605.6	107	138.0	378.5	348.8
	Su.14	1566.6	1249.0	-	-	186.9	59.8
	Wi.15	70.9	140.2	2.4	2.1	128.7	146.7
	Sp.15	311.4	497.6	30	44.0	513.5	313.0
	Su.15	638.6	274.4	128.1	111.9	189.8	38.1
	Au.15	448.4	703.3	76.4	53.5	582.0	345.4
	Wi.16	25.6	23.9	31.9	22.4	324.9	205.8
	Sp.16	326.2	617.3	371	78.2	1039.2	253.2
	Su.16	312.1	347.4	492.1	209.6	187.4	37.7
Piercer	Sp.14	130.6	202.6	37.6	32.7	15.9	17.5
	Su.14	552.7	440.6	-	-	9.6	13.4
	Wi.15	38.1	39.4	0.1	0.1	1.0	1.5
	Sp.15	114.9	166.8	1.1	0.9	12.8	14.1

	Su.15	213.9	71.3	19.3	15.9	11.6	14.9
	Au.15	200.0	268.4	106.8	143.9	16.5	22.8
	Wi.16	17.0	22.8	122.4	217.5	1.2	1.9
	Sp.16	109.8	205.9	99.6	35.5	7.8	13.0
	Su.16	120.6	96.8	28.9	28.4	18.8	15.0
Predator	Sp.14	80.1	86.2	51	28.1	166.7	116.3
	Su.14	204.9	263.4	-	-	275.3	273.9
	Wi.15	186.0	331.7	10.9	5.8	90.8	71.6
	Sp.15	128.9	105.2	58	47.5	229.7	104.9
	Su.15	365.4	313.3	253.3	331.6	312.8	311.0
	Au.15	34.2	41.8	106.8	89.9	154.4	141.9
	Wi.16	74.1	116.0	90.5	126.2	30.5	13.6
	Sp.16	70.5	82.1	40.6	7.6	358.2	512.4
	Su.16	186.0	130.7	522.2	289.2	408.2	298.0
Parasite	Sp.14	128.5	203.3	14.3	10.5	5.5	5.4
	Su.14	516.4	427.2	-	-	8.3	2.8
	Wi.15	28.3	43.3	0.2	0.1	0.5	0.6
	Sp.15	105.6	166.4	1.5	1.2	5.1	4.0
	Su.15	187.5	77.3	9.5	7.2	8.8	2.9
	Au.15	150.7	233.6	38.9	46.2	6.5	7.4
	Wi.16	5.7	3.7	34.7	62.5	1.0	0.7
	Sp.16	108.2	206.5	23.7	6.3	4.2	3.8
	Su.16	92.4	99.1	11.8	9.9	9.3	2.6

Appendix 4.24. Summary of the PERMANOVA pair-wise analysis for between reach differences in macroinvertebrate FFGs, based on groups' biomass. Reaches compared seasonally. Bold font indicates significant (P<0.05) differences.

Community metrics	Seasons	PERMANOVA results			
Absorber	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.83978	0.4105	462
		Degraded, Rehabilitated	1.0036	0.3508	462
		Natural, Rehabilitated	0.31935	0.7513	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.038704	0.9937	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.2652	0.0464	462
		Degraded, Rehabilitated	4.2891	0.0091	461
		Natural, Rehabilitated	3.7909	0.0034	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.1838	0.259	8069
		Degraded, Rehabilitated	1.5288	0.1426	8077
		Natural, Rehabilitated	0.29744	0.7734	8148
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.108	0.2643	462
		Degraded, Rehabilitated	1.0056	0.3266	462
		Natural, Rehabilitated	0.1949	0.8302	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.8584	0.3918	9807
		Degraded, Rehabilitated	0.79778	0.4444	9805
		Natural, Rehabilitated	2.498	0.0224	9794
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.3358	0.0055	456
		Degraded, Rehabilitated	0.96294	0.3554	462
		Natural, Rehabilitated	2.336	0.0296	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.12327	0.8994	462
		Degraded, Rehabilitated	0.75671	0.4492	336
		Natural, Rehabilitated	2.4003	0.0457	336
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.54686	0.5929	462
		Degraded, Rehabilitated	3.2384	0.0095	462
		Natural, Rehabilitated	3.3126	0.0084	462
Deposit-feeder	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.5714	0.032	462
		Degraded, Rehabilitated	0.04736	0.9764	462
		Natural, Rehabilitated	4.9515	0.0021	461
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.7469	0.0025	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.6188	0.0073	461
		Degraded, Rehabilitated	10.627	0.0029	461
		Natural, Rehabilitated	7.7349	0.0026	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.2152	0.0001	8106
		Degraded, Rehabilitated	1.0127	0.316	8063
		Natural, Rehabilitated	5.299	0.0005	8090
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.4565	0.0024	462
		Degraded, Rehabilitated	0.32293	0.7316	462
		Natural, Rehabilitated	6.2454	0.0024	461

	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.1638	0.0428	9793
		Degraded, Rehabilitated	1.2453	0.2292	9787
		Natural, Rehabilitated	5.567	0.0001	9814
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.9718	0.0025	462
		Degraded, Rehabilitated	2.0148	0.0703	462
		Natural, Rehabilitated	1.0363	0.3333	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.9452	0.0018	458
		Degraded, Rehabilitated	0.37063	0.7042	462
		Natural, Rehabilitated	5.1404	0.0043	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.6353	0.0021	462
		Degraded, Rehabilitated	0.14567	0.8875	462
		Natural, Rehabilitated	6.7983	0.002	462
Shredders	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	15.636	0.0024	462
		Degraded, Rehabilitated	0.39571	0.6862	459
		Natural, Rehabilitated	19.977	0.0024	461
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.4246	0.005	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	9.2212	0.0024	461
		Degraded, Rehabilitated	0.20709	0.8286	462
		Natural, Rehabilitated	11.778	0.0027	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	15.321	0.0002	8117
		Degraded, Rehabilitated	1.5624	0.1405	8110
		Natural, Rehabilitated	13.848	0.0003	8134
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.3338	0.0307	462
		Degraded, Rehabilitated	1.338	0.2532	457
		Natural, Rehabilitated	1.9491	0.0481	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.9948	0.0001	9806
		Degraded, Rehabilitated	1.8171	0.0842	9787
		Natural, Rehabilitated	6.6056	0.0001	9788
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	12.887	0.0018	462
		Degraded, Rehabilitated	9.3567	0.0027	462
		Natural, Rehabilitated	2.6248	0.0302	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	14.724	0.002	461
		Degraded, Rehabilitated	12.044	0.002	461
		Natural, Rehabilitated	4.6229	0.0015	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.681	0.0022	461
		Degraded, Rehabilitated	2.1638	0.0428	462
		Natural, Rehabilitated	0.93285	0.4239	460
Scraper	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	18.018	0.0027	459
		Degraded, Rehabilitated	2.1646	0.0659	459
		Natural, Rehabilitated	16.503	0.0022	456
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.2952	0.0097	462

	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	9.4489	0.0024	462
		Degraded, Rehabilitated	1.4523	0.1753	462
		Natural, Rehabilitated	11.88	0.0019	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	22.944	0.0002	8152
		Degraded, Rehabilitated	1.2586	0.2179	8174
		Natural, Rehabilitated	8.1206	0.0001	8058
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.668	0.0242	461
		Degraded, Rehabilitated	0.8053	0.4229	462
		Natural, Rehabilitated	2.518	0.037	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.5456	0.0001	9773
		Degraded, Rehabilitated	2.8569	0.0081	9796
		Natural, Rehabilitated	4.5287	0.0005	9787
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.5753	0.0025	462
		Degraded, Rehabilitated	3.4575	0.0225	462
		Natural, Rehabilitated	0.75366	0.4532	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	17.899	0.0017	462
		Degraded, Rehabilitated	12.446	0.0022	461
		Natural, Rehabilitated	3.3075	0.0115	461
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.963	0.0031	462
		Degraded, Rehabilitated	2.0926	0.0616	460
		Natural, Rehabilitated	0.36719	0.749	462
Filter-feeder	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.50229	0.6116	462
		Degraded, Rehabilitated	1.0657	0.3009	462
		Natural, Rehabilitated	2.0195	0.0714	461
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.2476	0.0154	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.6605	0.1409	462
		Degraded, Rehabilitated	2.5199	0.0067	461
		Natural, Rehabilitated	6.2859	0.0021	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.0148	0.0657	8044
		Degraded, Rehabilitated	2.3531	0.0296	8016
		Natural, Rehabilitated	7.0303	0.0001	8075
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.6873	0.0141	462
		Degraded, Rehabilitated	4.0853	0.0065	459
		Natural, Rehabilitated	1.8098	0.1086	461
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.2179	0.0349	9796
		Degraded, Rehabilitated	1.2074	0.2387	9827
		Natural, Rehabilitated	7.9324	0.0001	9784
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.4078	0.0012	462
		Degraded, Rehabilitated	0.89648	0.3882	462
		Natural, Rehabilitated	5.7608	0.002	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.3527	0.0146	462

		Degraded, Rehabilitated	1.6695	0.1166	462
		Natural, Rehabilitated	6.7957	0.0024	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.15413	0.8701	460
		Degraded, Rehabilitated	1.6558	0.1336	462
		Natural, Rehabilitated	4.3125	0.0029	462
Piercer	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.0443	0.0775	336
		Degraded, Rehabilitated	0.78967	0.4993	178
		Natural, Rehabilitated	1.8672	0.1075	131
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.4964	0.0026	336
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	5.5351	0.0022	336
		Degraded, Rehabilitated	7.2809	0.0024	154
		Natural, Rehabilitated	1.6903	0.1337	210
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.672	0.0181	8104
		Degraded, Rehabilitated	4.83	0.0001	7387
		Natural, Rehabilitated	3.0068	0.0095	7404
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	8.558	0.0019	462
		Degraded, Rehabilitated	8.3246	0.0026	462
		Natural, Rehabilitated	1.3078	0.2231	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.4261	0.0241	9780
		Degraded, Rehabilitated	0.00983	0.9932	9766
		Natural, Rehabilitated	4.0828	0.0003	9819
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.6645	0.5198	119
		Degraded, Rehabilitated	1.462	0.181	119
		Natural, Rehabilitated	2.3575	0.0355	336
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.813	0.0499	462
		Degraded, Rehabilitated	1.2324	0.2818	462
		Natural, Rehabilitated	6.9246	0.0025	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.5593	0.0082	462
		Degraded, Rehabilitated	2.7963	0.0244	461
		Natural, Rehabilitated	0.75745	0.466	462
Predator	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.7666	0.0272	462
		Degraded, Rehabilitated	0.6175	0.5631	462
		Natural, Rehabilitated	2.4534	0.0413	462
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.8318	0.43	462
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.06122	0.9649	462
		Degraded, Rehabilitated	1.9625	0.0263	462
		Natural, Rehabilitated	4.657	0.0029	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.1219	0.0541	8145
		Degraded, Rehabilitated	1.5111	0.1468	8145
		Natural, Rehabilitated	4.7031	0.0009	8153
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.43299	0.6317	462

		Degraded, Rehabilitated	1.1068	0.2888	462
		Natural, Rehabilitated	0.7282	0.4809	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.2853	0.0044	9807
		Degraded, Rehabilitated	3.7852	0.0016	9786
		Natural, Rehabilitated	0.46759	0.6349	9777
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	0.5935	0.7171	462
		Degraded, Rehabilitated	0.49799	0.5571	462
		Natural, Rehabilitated	1.3682	0.1707	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	1.9461	0.0434	462
		Degraded, Rehabilitated	0.37156	0.7778	462
		Natural, Rehabilitated	2.4723	0.0084	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.4534	0.0413	462
		Degraded, Rehabilitated	2.7666	0.0272	462
		Natural, Rehabilitated	0.83233	0.3989	462
Parasite	Sp.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.7925	0.0332	462
		Degraded, Rehabilitated	1.5334	0.1585	336
		Natural, Rehabilitated	2.0699	0.031	336
	Su.14	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	7.154	0.0023	461
	Wi.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	6.7517	0.0014	462
		Degraded, Rehabilitated	8.0929	0.0026	462
		Natural, Rehabilitated	1.1279	0.2994	462
	Sp.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.5668	0.0026	8133
		Degraded, Rehabilitated	5.5934	0.0001	8020
		Natural, Rehabilitated	3.0784	0.0087	8111
	Su.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	10.682	0.0026	462
		Degraded, Rehabilitated	7.9518	0.0022	462
		Natural, Rehabilitated	0.34307	0.729	462
	Au.15	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	4.4337	0.0001	9807
		Degraded, Rehabilitated	1.3127	0.2071	9803
		Natural, Rehabilitated	3.7574	0.0018	9807
	Wi.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.8486	0.0087	461
		Degraded, Rehabilitated	0.37006	0.7264	461
		Natural, Rehabilitated	2.196	0.0495	462
	Sp.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	2.4303	0.0143	461
		Degraded, Rehabilitated	0.0405	0.9859	462
		Natural, Rehabilitated	6.1446	0.0029	462
	Su.16	Reaches	t	P(perm)	Unique perms
		Degraded, Natural	3.6917	0.0053	462
		Degraded, Rehabilitated	3.1809	0.0124	461
		Natural, Rehabilitated	0.18463	0.8748	462

Appendix 4.25. Summary of PERMANOVA pair-wise analysis of seasonal differences in macroinvertebrate FFGs, based on groups' average biomass, for each reach separately. Bold font indicates significant (P<0.05) differences.

Degraded reach seasonal differences				Natural reach seasonal differences				Rehabilitated reach seasonal differences			
Absorber				**Absorber**				**Absorber**			
Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms	Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.17869	0.8961	462	Sp.14, Su.14	1.6744	0.1337	462				
Sp.14, Wi.15	1.9718	0.068	462	Sp.14, Wi.15	0.85711	0.3879	461	Sp.14, Wi.15	4.7562	0.0019	461
Sp.14, Sp.15	0.82658	0.4412	4293	Sp.14, Sp.15	2.0158	0.0662	4324	Sp.14, Sp.15	2.5393	**0.0294**	4295
Sp.14, Su.15	0.53857	0.5378	462	Sp.14, Su.15	1.7257	0.1301	461	Sp.14, Su.15	1.0528	0.3202	462
Sp.14, Au.15	0.000701	1	7639	Sp.14, Au.15	0.86706	0.3959	7633	Sp.14, Au.15	2.9403	0.0099	7614
Sp.14, Wi.16	1.4141	0.1736	462	Sp.14, Wi.16	2.5553	0.035	462	Sp.14, Wi.16	0.16904	0.8657	461
Sp.14, Sp.16	0.2135	0.9341	462	Sp.14, Sp.16	0.8198	0.438	462	Sp.14, Sp.16	2.2848	0.0577	336
Sp.14, Su.16	0.27671	0.8045	462	Sp.14, Su.16	1.9015	0.0897	462	Sp.14, Su.16	5.0435	0.0032	462
Su.14, Wi.15	2.1053	0.0476	462	Su.14, Wi.15	0.70445	0.5222	462				
Su.14, Sp.15	1.2971	0.2058	4265	Su.14, Sp.15	0.91138	0.386	4270				
Su.14, Su.15	0.85655	0.5021	459	Su.14, Su.15	0.28601	0.778	460				
Su.14, Au.15	0.2335	0.8155	7586	Su.14, Au.15	0.77938	0.439	7591				
Su.14, Wi.16	1.6117	0.088	462	Su.14, Wi.16	1.7754	0.0997	462				
Su.14, Sp.16	0.4822	0.5992	461	Su.14, Sp.16	2.6414	0.0324	462				
Su.14, Su.16	0.08452	0.9738	462	Su.14, Su.16	0.60615	0.5523	462				
Wi.15, Sp.15	3.8398	0.0027	4295	Wi.15, Sp.15	1.2783	0.2238	4301	Wi.15, Sp.15	3.3833	0.0024	4316
Wi.15, Su.15	2.8147	0.0212	462	Wi.15, Su.15	0.81983	0.438	461	Wi.15, Su.15	2.6652	0.034	459
Wi.15, Au.15	2.6161	0.0217	7642	Wi.15, Au.15	0.10511	0.919	7615	Wi.15, Au.15	2.2213	0.0417	7661
Wi.15, Wi.16	1.248	0.2536	462	Wi.15, Wi.16	1.8428	0.0948	462	Wi.15, Wi.16	4.025	**0.0019**	462
Wi.15, Sp.16	2.5649	0.0307	462	Wi.15, Sp.16	2.2593	0.0498	461	Wi.15, Sp.16	3.799	0.0017	336
Wi.15, Su.16	2.525	0.0363	462	Wi.15, Su.16	1.0082	0.3391	462	Wi.15, Su.16	2.1686	0.0451	462
Sp.15, Su.15	0.14344	0.8935	4281	Sp.15, Su.15	0.74839	0.4828	4295	Sp.15, Su.15	0.54126	0.591	4323
Sp.15, Au.15	1.0573	0.3035	9646	Sp.15, Au.15	1.6565	0.1234	9688	Sp.15, Au.15	1.0934	0.2797	9702
Sp.15, Wi.16	3.937	0.0049	4334	Sp.15, Wi.16	0.30126	0.776	4306	Sp.15, Wi.16	1.9332	0.0796	4228
Sp.15, Sp.16	0.70253	0.4776	4301	Sp.15, Sp.16	0.44058	0.6941	4338	Sp.15, Sp.16	0.77833	0.4397	3351
Sp.15, Su.16	1.9281	0.0802	4318	Sp.15, Su.16	0.61846	0.5671	4281	Sp.15, Su.16	1.7295	0.1034	4313
Su.15, Au.15	0.70326	0.495	7555	Su.15, Au.15	0.91868	0.3689	7651	Su.15, Au.15	1.2822	0.2195	7623
Su.15, Wi.16	2.641	0.0292	462	Su.15, Wi.16	1.4376	0.1587	461	Su.15, Wi.16	0.82412	0.4292	462
Su.15, Sp.16	0.40878	0.594	462	Su.15, Sp.16	2.0267	0.0822	462	Su.15, Sp.16	0.062627	0.9772	336
Su.15, Su.16	1.2083	0.2379	462	Su.15, Su.16	0.24952	0.7917	461	Su.15, Su.16	1.4973	0.1697	462
Au.15, Wi.16	1.7716	0.0938	7642	Au.15, Wi.16	2.0634	0.0537	7625	Au.15, Wi.16	2.5317	0.0196	7646
Au.15, Sp.16	0.27624	0.7857	7637	Au.15, Sp.16	2.3534	0.0313	7587	Au.15, Sp.16	1.5724	0.1407	6883
Au.15, Su.16	0.34606	0.733	7645	Au.15, Su.16	1.0932	0.2922	7660	Au.15, Su.16	0.26333	0.7939	7594
Wi.16, Sp.16	2.3287	0.0552	462	Wi.16, Sp.16	0.15844	0.8757	462	Wi.16, Sp.16	1.4046	0.2006	336
Wi.16, Su.16	3.1615	0.0152	462	Wi.16, Su.16	1.2858	0.2235	460	Wi.16, Su.16	3.334	0.007	462
Sp.16, Su.16	0.75097	0.46	462	Sp.16, Su.16	1.8658	0.0941	462	Sp.16, Su.16	3.8485	0.0032	336

Deposit-feeder			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.10324	0.911	462
Sp.14, Wi.15	3.2	0.0145	462
Sp.14, Sp.15	1.0844	0.3291	4324
Sp.14, Su.15	1.2633	0.2402	461
Sp.14, Au.15	0.58976	0.5563	7620
Sp.14, Wi.16	1.049	0.3175	461
Sp.14, Sp.16	0.45981	0.7599	462
Sp.14, Su.16	0.29633	0.7896	462
Su.14, Wi.15	3.0331	0.0067	459
Su.14, Sp.15	1.2343	0.2413	4335
Su.14, Su.15	1.1065	0.3414	462
Su.14, Au.15	0.69492	0.4911	7600
Su.14, Wi.16	0.88777	0.516	462
Su.14, Sp.16	0.58274	0.5899	462
Su.14, Su.16	0.1608	0.9046	462
Wi.15, Sp.15	7.8846	0.0002	4303
Wi.15, Su.15	3.4204	0.012	461
Wi.15, Au.15	3.6471	0.0041	7607
Wi.15, Wi.16	0.9272	0.3641	462
Wi.15, Sp.16	5.3963	0.0028	461
Wi.15, Su.16	4.4395	0.007	462
Sp.15, Su.15	5.1101	0.0006	4288
Sp.15, Au.15	0.14675	0.8829	9688
Sp.15, Wi.16	5.4362	0.0007	4299
Sp.15, Sp.16	0.80743	0.4329	4291
Sp.15, Su.16	2.4808	0.0308	4289
Su.15, Au.15	1.7867	0.0926	7652
Su.15, Wi.16	0.70808	0.4977	461
Su.15, Sp.16	2.999	0.0125	462
Su.15, Su.16	1.7075	0.1213	462
Au.15, Wi.16	1.5809	0.1302	7609
Au.15, Sp.16	0.23373	0.8128	7606
Au.15, Su.16	0.9272	0.3641	7666
Wi.16, Sp.16	2.963	0.0052	462
Wi.16, Su.16	1.4628	0.1799	462
Sp.16, Su.16	1.215	0.2393	462

Deposit-feeder			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	2.7817	0.0248	462
Sp.14, Wi.15	2.9538	0.0162	462
Sp.14, Sp.15	0.89137	0.4003	4293
Sp.14, Su.15	2.9532	0.0196	462
Sp.14, Au.15	5.4017	0.0002	7634
Sp.14, Wi.16	7.0563	0.0019	461
Sp.14, Sp.16	1.2886	0.2313	462
Sp.14, Su.16	2.0926	0.0635	462
Su.14, Wi.15	5.2511	0.0022	462
Su.14, Sp.15	3.3169	0.0061	4327
Su.14, Su.15	0.47134	0.6473	462
Su.14, Au.15	9.9346	0.0001	7692
Su.14, Wi.16	9.9785	0.0022	461
Su.14, Sp.16	3.9631	0.0024	461
Su.14, Su.16	0.48555	0.6292	462
Wi.15, Sp.15	2.0125	0.0622	4303
Wi.15, Su.15	5.6297	0.0024	462
Wi.15, Au.15	0.33326	0.7416	7573
Wi.15, Wi.16	0.3460	0.733	459
Wi.15, Sp.16	1.7972	0.1175	460
Wi.15, Su.16	4.5699	0.0053	462
Sp.15, Su.15	3.2663	0.0083	4291
Sp.15, Au.15	3.0454	0.0037	9697
Sp.15, Wi.16	5.0966	0.0008	4257
Sp.15, Sp.16	0.27281	0.7905	4305
Sp.15, Su.16	2.7523	0.0178	4275
Su.15, Au.15	12.245	0.0002	7553
Su.15, Wi.16	12.095	0.0022	461
Su.15, Sp.16	4.3409	0.0024	461
Su.15, Su.16	0.15567	0.8681	462
Au.15, Wi.16	5.8879	0.0001	7631
Au.15, Sp.16	3.0674	0.0066	7702
Au.15, Su.16	8.277	0.0002	7662
Wi.16, Sp.16	5.4117	0.0019	461
Wi.16, Su.16	8.679	0.0021	461
Sp.16, Su.16	3.2237	0.0124	462

Deposit-feeder			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	7.4223	0.002	462
Sp.14, Sp.15	2.0983	0.0581	4344
Sp.14, Su.15	1.9743	0.0862	461
Sp.14, Au.15	2.5884	0.0193	7626
Sp.14, Wi.16	0.25469	0.8136	462
Sp.14, Sp.16	1.4854	0.1707	462
Sp.14, Su.16	0.37256	0.7116	461
Wi.15, Sp.15	4.1758	0.0011	4315
Wi.15, Su.15	8.956	0.0022	462
Wi.15, Au.15	3.7279	0.0019	7636
Wi.15, Wi.16	6.2162	**0.0023**	462
Wi.15, Sp.16	6.4583	0.0029	460
Wi.15, Su.16	8.0841	0.0017	462
Sp.15, Su.15	3.5098	0.0068	4325
Sp.15, Au.15	0.52749	0.6074	9638
Sp.15, Wi.16	1.7323	0.1029	4289
Sp.15, Sp.16	1.0972	0.287	4330
Sp.15, Su.16	2.4024	0.0384	4310
Su.15, Au.15	3.9824	0.0018	7649
Su.15, Wi.16	1.8587	0.0867	462
Su.15, Sp.16	3.5289	0.0099	461
Su.15, Su.16	1.7664	0.112	462
Au.15, Wi.16	2.2357	0.0436	7622
Au.15, Sp.16	1.6019	0.1265	7662
Au.15, Su.16	2.8803	0.0114	7603
Wi.16, Sp.16	0.92429	0.3996	462
Wi.16, Su.16	0.56143	0.592	461
Sp.16, Su.16	2.0132	0.0872	462

Shredders			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	3.4383	0.0042	462
Sp.14, Wi.15	1.2046	0.2521	461
Sp.14, Sp.15	0.79691	0.4242	4275
Sp.14, Su.15	6.0326	0.0019	462
Sp.14, Au.15	3.3292	0.0048	7604
Sp.14, Wi.16	1.273	0.221	462
Sp.14, Sp.16	0.068973	0.9297	462
Sp.14, Su.16	8.0483	0.0022	462
Su.14, Wi.15	4.1523	0.002	462
Su.14, Sp.15	3.4056	0.0032	4298
Su.14, Su.15	1.2495	0.2416	462
Su.14, Au.15	0.44807	0.6622	7627
Su.14, Wi.16	4.2749	0.0027	462
Su.14, Sp.16	3.4499	0.0045	456
Su.14, Su.16	1.3332	0.2067	462
Wi.15, Sp.15	2.0079	0.0631	4308
Wi.15, Su.15	6.9345	0.0026	461
Wi.15, Au.15	4.1234	0.0013	7631
Wi.15, Wi.16	0.10793	0.9269	462
Wi.15, Sp.16	1.1052	0.285	462
Wi.15, Su.16	9.3105	0.0019	461
Sp.15, Su.15	6.0001	0.0004	4273
Sp.15, Au.15	3.2899	0.0048	9668
Sp.15, Wi.16	2.0802	0.0585	4280
Sp.15, Sp.16	0.85409	0.3946	4298
Sp.15, Su.16	7.3229	0.0003	4324
Su.15, Au.15	1.9598	0.07	7570
Su.15, Wi.16	7.3412	0.0021	460
Su.15, Sp.16	6.0041	0.0024	462
Su.15, Su.16	0.11075	0.92	462
Au.15, Wi.16	4.163	0.0014	7585
Au.15, Sp.16	3.3586	0.0044	7593
Au.15, Su.16	2.0241	0.0626	7616
Wi.16, Sp.16	1.153	0.2696	461
Wi.16, Su.16	10.525	0.0023	454
Sp.16, Su.16	7.9245	0.0031	461

Shredders			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	3.2034	0.0115	462
Sp.14, Wi.15	11.18	0.0029	460
Sp.14, Sp.15	0.29085	0.7695	4322
Sp.14, Su.15	1.7725	0.0995	462
Sp.14, Au.15	2.2994	0.035	7703
Sp.14, Wi.16	12.355	0.0021	460
Sp.14, Sp.16	0.049786	0.9587	462
Sp.14, Su.16	0.26457	0.7992	461
Su.14, Wi.15	11.184	0.0016	460
Su.14, Sp.15	2.4126	0.0392	4290
Su.14, Su.15	0.21114	0.8292	462
Su.14, Au.15	2.9369	0.0112	7566
Su.14, Wi.16	13.539	0.0027	461
Su.14, Sp.16	2.8255	0.0167	462
Su.14, Su.16	0.6595	0.5336	462
Wi.15, Sp.15	10.895	0.0004	4340
Wi.15, Su.15	7.4835	0.0021	462
Wi.15, Au.15	5.3327	0.0001	7606
Wi.15, Wi.16	0.44321	0.6566	462
Wi.15, Sp.16	10.538	0.0021	462
Wi.15, Su.16	13.648	0.0016	459
Sp.15, Su.15	1.6096	0.1154	4290
Sp.15, Au.15	2.9067	0.0105	9670
Sp.15, Wi.16	11.395	0.0003	4287
Sp.15, Sp.16	0.23014	0.8067	4254
Sp.15, Su.16	0.1062	0.9148	4311
Su.15, Au.15	2.8372	0.0149	7662
Su.15, Wi.16	7.8024	0.0027	462
Su.15, Sp.16	1.6605	0.1113	462
Su.15, Su.16	1.8703	0.1244	462
Au.15, Wi.16	5.241	0.0002	7524
Au.15, Sp.16	2.3083	0.0385	7573
Au.15, Su.16	2.3658	0.0311	7629
Wi.16, Sp.16	11.456	0.002	461
Wi.16, Su.16	16.569	0.0024	460
Sp.16, Su.16	0.17704	0.8644	462

Shredders			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	1.4099	0.1914	462
Sp.14, Sp.15	2.8842	**0.0135**	4296
Sp.14, Su.15	15.113	0.0026	456
Sp.14, Au.15	8.5092	0.0001	7642
Sp.14, Wi.16	7.9662	0.0023	462
Sp.14, Sp.16	15.992	**0.0016**	460
Sp.14, Su.16	6.8036	0.0028	462
Wi.15, Sp.15	4.0784	0.001	4291
Wi.15, Su.15	17.149	0.0022	460
Wi.15, Au.15	9.7567	0.0002	7597
Wi.15, Wi.16	9.7696	**0.0026**	462
Wi.15, Sp.16	18.244	0.002	459
Wi.15, Su.16	7.4636	0.0032	462
Sp.15, Su.15	9.0105	0.0001	4295
Sp.15, Au.15	5.8021	0.0001	9660
Sp.15, Wi.16	3.3374	0.0085	4350
Sp.15, Sp.16	9.1394	**0.0004**	4287
Sp.15, Su.16	5.8517	0.0003	4271
Su.15, Au.15	3.3024	0.0046	7610
Su.15, Wi.16	7.9342	0.0025	462
Su.15, Sp.16	0.14969	0.8816	462
Su.15, Su.16	0.55572	**0.0494**	461
Au.15, Wi.16	2.3913	0.0246	7587
Au.15, Sp.16	3.2631	0.0052	7690
Au.15, Su.16	2.7876	0.0079	7606
Wi.16, Sp.16	8.4566	0.0009	461
Wi.16, Su.16	3.5616	0.0025	461
Sp.16, Su.16	0.61462	0.641	462

Scraper			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	3.3976	0.0021	462
Sp.14, Wi.15	1.9022	0.0799	462
Sp.14, Sp.15	0.28012	0.7894	4328
Sp.14, Su.15	6.7753	0.0015	461
Sp.14, Au.15	3.5497	0.0045	7593
Sp.14, Wi.16	1.451	0.1735	462
Sp.14, Sp.16	0.89596	0.367	462
Sp.14, Su.16	8.7728	0.0021	462
Su.14, Wi.15	4.1907	0.002	462
Su.14, Sp.15	4.05	0.0006	4328
Su.14, Su.15	1.4142	0.1776	462
Su.14, Au.15	0.46205	0.6484	7662
Su.14, Wi.16	3.7705	0.0022	462
Su.14, Sp.16	3.7218	0.0024	460
Su.14, Su.16	1.2813	0.2356	462
Wi.15, Sp.15	1.6776	0.1139	4286
Wi.15, Su.15	7.2863	0.0027	461
Wi.15, Au.15	4.4143	0.0012	7607
Wi.15, Wi.16	0.061433	0.9395	461
Wi.15, Sp.16	1.0347	0.3034	462
Wi.15, Su.16	8.7053	0.0027	462
Sp.15, Su.15	7.5135	0.0002	4254
Sp.15, Au.15	4.3861	0.0009	9720
Sp.15, Wi.16	1.4108	0.1825	4268
Sp.15, Sp.16	0.59098	0.5546	4259
Sp.15, Su.16	8.7954	0.0001	4146
Su.15, Au.15	0.88697	0.3926	7598
Su.15, Wi.16	6.1476	0.0024	460
Su.15, Sp.16	6.9583	0.0019	461
Su.15, Su.16	0.37718	0.7056	462
Au.15, Wi.16	4.2391	0.0012	7600
Au.15, Sp.16	3.9013	0.0021	7666
Au.15, Su.16	0.6595	0.5336	7637
Wi.16, Sp.16	0.84877	0.3995	461
Wi.16, Su.16	6.7796	0.0024	462
Sp.16, Su.16	8.6357	0.0023	462

Scraper			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	4.7699	0.0023	462
Sp.14, Wi.15	11.499	0.0022	459
Sp.14, Sp.15	1.1103	0.2836	4324
Sp.14, Su.15	2.0978	0.068	462
Sp.14, Au.15	2.45	0.0261	7633
Sp.14, Wi.16	9.9547	0.002	461
Sp.14, Sp.16	1.2574	0.2438	462
Sp.14, Su.16	1.1335	0.2688	461
Su.14, Wi.15	12.858	0.002	460
Su.14, Sp.15	8.8332	0.0004	4319
Su.14, Su.15	1.4268	0.1823	461
Su.14, Au.15	4.1137	0.0009	7615
Su.14, Wi.16	8.3573	0.0017	461
Su.14, Sp.16	6.6113	0.0015	462
Su.14, Su.16	1.8927	0.2615	461
Wi.15, Sp.15	18.599	0.0003	4296
Wi.15, Su.15	7.3182	0.0016	462
Wi.15, Au.15	6.5397	0.0001	7512
Wi.15, Wi.16	2.3677	0.0351	461
Wi.15, Sp.16	13.443	0.0024	461
Wi.15, Su.16	21.473	0.0028	460
Sp.15, Su.15	3.8218	0.0024	4309
Sp.15, Au.15	2.6097	0.0175	9688
Sp.15, Wi.16	14.374	0.0003	4332
Sp.15, Sp.16	0.60678	0.551	4326
Sp.15, Su.16	3.4334	0.0085	4295
Su.15, Au.15	3.4384	0.0042	7620
Su.15, Wi.16	7.2919	0.002	462
Su.15, Sp.16	3.2607	0.0137	462
Su.15, Su.16	1.7192	0.1523	462
Au.15, Wi.16	7.3166	0.0003	7607
Au.15, Sp.16	1.9073	0.0754	7740
Au.15, Su.16	2.8768	0.014	7654
Wi.16, Sp.16	11.196	0.0024	462
Wi.16, Su.16	11.597	0.0026	462
Sp.16, Su.16	2.921	0.0199	462

Scraper			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	1.4073	0.1725	462
Sp.14, Sp.15	1.909	**0.0747**	4312
Sp.14, Su.15	11.088	0.0015	462
Sp.14, Au.15	8.92	0.0002	7567
Sp.14, Wi.16	3.8145	0.0139	462
Sp.14, Sp.16	12.829	**0.0026**	460
Sp.14, Su.16	6.6288	0.0022	462
Wi.15, Sp.15	2.676	0.0183	4299
Wi.15, Su.15	12.315	0.0017	462
Wi.15, Au.15	9.9186	0.0001	7591
Wi.15, Wi.16	4.5102	**0.0023**	462
Wi.15, Sp.16	13.986	0.0024	460
Wi.15, Su.16	7.3059	0.0023	462
Sp.15, Su.15	3.8584	0.0038	4275
Sp.15, Au.15	5.429	0.0001	9645
Sp.15, Wi.16	1.7727	0.0981	4317
Sp.15, Sp.16	4.9831	**0.0005**	4316
Sp.15, Su.16	4.232	0.002	4267
Su.15, Au.15	1.1863	0.2542	7716
Su.15, Wi.16	1.5071	0.2115	459
Su.15, Sp.16	2.2409	0.0519	462
Su.15, Su.16	1.3731	**0.0464**	462
Au.15, Wi.16	2.5331	0.0209	7623
Au.15, Sp.16	0.37821	0.7051	7590
Au.15, Su.16	0.62003	0.5437	7562
Wi.16, Sp.16	2.5582	0.0113	461
Wi.16, Su.16	2.1526	0.0631	462
Sp.16, Su.16	0.30386	0.7858	462

Filter-feeder

Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	2.2894	0.047	462
Sp.14, Wi.15	1.5771	0.1476	462
Sp.14, Sp.15	0.25097	0.8129	4291
Sp.14, Su.15	1.6491	0.1301	462
Sp.14, Au.15	0.095509	0.9306	7608
Sp.14, Wi.16	2.0655	0.0674	462
Sp.14, Sp.16	0.44263	0.6309	461
Sp.14, Su.16	0.18821	0.8492	462
Su.14, Wi.15	4.5295	0.0041	462
Su.14, Sp.15	2.9588	0.0127	4258
Su.14, Su.15	1.2807	0.2345	462
Su.14, Au.15	2.6359	0.0196	7644
Su.14, Wi.16	5.3677	0.0026	462
Su.14, Sp.16	2.7395	0.0239	462
Su.14, Su.16	2.5312	0.0261	462
Wi.15, Sp.15	1.5262	0.1478	4290
Wi.15, Su.15	4.9042	0.0049	462
Wi.15, Au.15	1.5259	0.1541	7679
Wi.15, Wi.16	0.53012	0.6609	461
Wi.15, Sp.16	1.0295	0.3448	462
Wi.15, Su.16	2.2895	0.0467	462
Sp.15, Su.15	2.2028	0.0481	4275
Sp.15, Au.15	0.17205	0.8641	9678
Sp.15, Wi.16	2.0391	0.0593	4270
Sp.15, Sp.16	0.27443	0.7779	4269
Sp.15, Su.16	0.50743	0.6175	4286
Su.15, Au.15	1.7606	0.1044	7613
Su.15, Wi.16	6.8562	0.0025	462
Su.15, Sp.16	2.2064	0.0511	462
Su.15, Su.16	1.9542	0.0883	462
Au.15, Wi.16	1.937	0.0669	7646
Au.15, Sp.16	0.40558	0.696	7664
Au.15, Su.16	0.30251	0.7653	7570
Wi.16, Sp.16	1.466	0.1791	462
Wi.16, Su.16	3.1377	0.009	462
Sp.16, Su.16	0.70474	0.5043	462

Filter-feeder

Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.7441	0.4741	462
Sp.14, Wi.15	1.601	0.1003	462
Sp.14, Sp.15	1.0337	0.3061	4354
Sp.14, Su.15	0.69456	0.4871	462
Sp.14, Au.15	1.6707	0.1162	7657
Sp.14, Wi.16	0.14349	0.8688	462
Sp.14, Sp.16	1.2813	0.2356	462
Sp.14, Su.16	0.71986	0.4877	461
Su.14, Wi.15	1.6977	0.1239	462
Su.14, Sp.15	2.4756	0.0291	4280
Su.14, Su.15	0.22054	0.8368	462
Su.14, Au.15	3.5987	0.0027	7696
Su.14, Wi.16	1.5034	0.1606	461
Su.14, Sp.16	10.21	0.0017	462
Su.14, Su.16	0.12837	0.8802	461
Wi.15, Sp.15	3.3773	0.0091	4298
Wi.15, Su.15	1.8545	0.0963	462
Wi.15, Au.15	4.5577	0.0006	7609
Wi.15, Wi.16	0.64217	0.5781	462
Wi.15, Sp.16	7.5116	0.0017	462
Wi.15, Su.16	1.8149	0.1053	461
Sp.15, Su.15	2.4357	0.0304	4323
Sp.15, Au.15	0.58046	0.5633	9651
Sp.15, Wi.16	1.1037	0.2781	4306
Sp.15, Sp.16	0.47089	0.6413	4251
Sp.15, Su.16	2.4699	0.0261	4316
Su.15, Au.15	3.5641	0.0032	7620
Su.15, Wi.16	1.4625	0.1781	462
Su.15, Sp.16	11.095	0.0025	462
Su.15, Su.16	0.11828	0.896	462
Au.15, Wi.16	1.8761	0.0767	7594
Au.15, Sp.16	2.7898	0.0159	7632
Au.15, Su.16	3.6051	0.0022	7668
Wi.16, Sp.16	4.8588	0.0052	462
Wi.16, Su.16	1.506	0.1735	462
Sp.16, Su.16	11.174	0.0029	460

Filter-feeder

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	3.1497	0.002	462
Sp.14, Sp.15	1.3231	0.2126	4294
Sp.14, Su.15	0.92468	0.3728	462
Sp.14, Au.15	0.4842	0.6332	7662
Sp.14, Wi.16	0.78266	0.4419	462
Sp.14, Sp.16	3.5097	**0.007**	461
Sp.14, Su.16	3.7963	0.0089	462
Wi.15, Sp.15	3.2727	0.0049	4304
Wi.15, Su.15	6.7956	0.0016	462
Wi.15, Au.15	8.6869	0.0001	7545
Wi.15, Wi.16	5.686	**0.0021**	462
Wi.15, Sp.16	20.643	0.0012	459
Wi.15, Su.16	14.452	0.002	460
Sp.15, Su.15	3.2401	0.0061	4299
Sp.15, Au.15	3.3789	0.0032	9629
Sp.15, Wi.16	0.74903	0.4747	4295
Sp.15, Sp.16	8.3284	**0.0002**	4278
Sp.15, Su.16	8.1994	0.0002	4301
Su.15, Au.15	1.2569	0.2267	7649
Su.15, Wi.16	2.8162	0.0186	462
Su.15, Sp.16	4.0744	0.0043	462
Su.15, Su.16	4.2183	**0.0068**	462
Au.15, Wi.16	2.7115	0.0129	7617
Au.15, Sp.16	7.9223	0.0001	7705
Au.15, Su.16	7.7765	0.0002	7571
Wi.16, Sp.16	11.081	0.0023	462
Wi.16, Su.16	8.9229	0.0025	462
Sp.16, Su.16	1.16	0.2823	461

Piercer			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	2.6492	0.0322	461
Sp.14, Wi.15	0.78494	0.4784	336
Sp.14, Sp.15	0.019571	0.9871	4247
Sp.14, Su.15	1.9387	0.0881	461
Sp.14, Au.15	0.18601	0.8539	6842
Sp.14, Wi.16	2.1341	0.0631	210
Sp.14, Sp.16	0.41424	0.6496	462
Sp.14, Su.16	0.6495	0.5321	462
Su.14, Wi.15	4.4847	0.0044	336
Su.14, Sp.15	3.1276	0.0116	4303
Su.14, Su.15	1.6392	0.1414	462
Su.14, Au.15	2.1547	0.0437	6936
Su.14, Wi.16	4.8367	0.003	210
Su.14, Sp.16	3.0349	0.0172	462
Su.14, Su.16	2.0666	0.0673	450
Wi.15, Sp.15	0.8705	0.4038	3351
Wi.15, Su.15	5.5712	0.0052	336
Wi.15, Au.15	0.81048	0.4187	6051
Wi.15, Wi.16	1.9723	0.1076	154
Wi.15, Sp.16	0.23001	0.8387	336
Wi.15, Su.16	2.2863	0.0488	336
Sp.15, Su.15	2.2181	0.0503	4275
Sp.15, Au.15	0.24303	0.8046	9599
Sp.15, Wi.16	2.5079	0.0277	2271
Sp.15, Sp.16	0.47089	0.6413	4320
Sp.15, Su.16	0.7697	0.4598	4282
Su.15, Au.15	1.2434	0.2308	6934
Su.15, Wi.16	4.6947	0.0021	210
Su.15, Sp.16	2.4306	0.0403	460
Su.15, Su.16	2.0655	0.0658	462
Au.15, Wi.16	2.1781	0.0447	2951
Au.15, Sp.16	0.56996	0.5828	6855
Au.15, Su.16	0.31887	0.7521	6836
Wi.16, Sp.16	1.6933	0.1223	210
Wi.16, Su.16	3.2354	0.0101	210
Sp.16, Su.16	1.1404	0.2668	462

Piercer			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.14973	0.946	119
Sp.14, Wi.15	1.0985	0.2826	336
Sp.14, Sp.15	0.62958	0.5362	3347
Sp.14, Su.15	0.64195	0.5279	336
Sp.14, Au.15	0.645	0.5119	6927
Sp.14, Wi.16	0.99609	0.329	210
Sp.14, Sp.16	0.19073	0.8001	335
Sp.14, Su.16	1.2847	0.2161	336
Su.14, Wi.15	1.0575	0.3242	336
Su.14, Sp.15	0.92797	0.369	3329
Su.14, Su.15	0.94581	0.3694	336
Su.14, Au.15	0.93074	0.3456	6832
Su.14, Wi.16	0.93768	0.3451	210
Su.14, Sp.16	0.42472	0.6546	336
Su.14, Su.16	1.7045	0.1125	336
Wi.15, Sp.15	2.8775	0.0148	4298
Wi.15, Su.15	3.3423	0.0088	461
Wi.15, Au.15	2.6083	0.0179	7604
Wi.15, Wi.16	0.17219	0.8736	461
Wi.15, Sp.16	2.4071	0.0272	462
Wi.15, Su.16	5.0222	0.0019	462
Sp.15, Su.15	0.13597	0.887	4309
Sp.15, Au.15	0.014191	0.9903	9679
Sp.15, Wi.16	2.6563	0.0213	4310
Sp.15, Sp.16	0.61979	0.5441	4295
Sp.15, Su.16	1.2299	0.2389	4269
Su.15, Au.15	0.1384	0.8935	7655
Su.15, Wi.16	3.026	0.012	460
Su.15, Sp.16	0.80421	0.4235	462
Su.15, Su.16	1.2223	0.2548	462
Au.15, Wi.16	2.4307	0.0226	7696
Au.15, Sp.16	0.56152	0.5857	7655
Au.15, Su.16	1.1267	0.2746	7646
Wi.16, Sp.16	2.1428	0.044	462
Wi.16, Su.16	4.5634	0.0025	460
Sp.16, Su.16	2.0666	0.0673	462

Piercer			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	7.1512	0.0022	83
Sp.14, Sp.15	5.5608	**0.0003**	1466
Sp.14, Su.15	1.1647	0.273	179
Sp.14, Au.15	1.5766	0.1323	5244
Sp.14, Wi.16	0.14792	0.8718	179
Sp.14, Sp.16	3.1317	**0.0157**	179
Sp.14, Su.16	0.47511	0.6425	179
Wi.15, Sp.15	1.9302	0.0756	816
Wi.15, Su.15	7.3148	0.0016	210
Wi.15, Au.15	7.251	0.0002	5721
Wi.15, Wi.16	3.0568	**0.0152**	119
Wi.15, Sp.16	13.818	0.002	210
Wi.15, Su.16	7.1673	0.0019	210
Sp.15, Su.15	4.9481	0.0006	3357
Sp.15, Au.15	6.8521	0.0001	9610
Sp.15, Wi.16	2.8504	0.0081	2278
Sp.15, Sp.16	10.264	**0.0001**	3334
Sp.15, Su.16	5.2911	0.0003	3356
Su.15, Au.15	2.5646	0.0167	7585
Su.15, Wi.16	0.62679	0.5601	462
Su.15, Sp.16	5.5681	0.0022	462
Su.15, Su.16	0.69913	0.5086	336
Au.15, Wi.16	0.85062	0.4167	7626
Au.15, Sp.16	0.65012	0.5331	7603
Au.15, Su.16	2.003	0.0578	7656
Wi.16, Sp.16	1.0471	0.3426	460
Wi.16, Su.16	0.35737	0.7237	461
Sp.16, Su.16	4.0362	0.0063	462

Predator

Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	1.2602	0.2422	462
Sp.14, Wi.15	0.21025	0.8446	462
Sp.14, Sp.15	0.80523	0.4316	4325
Sp.14, Su.15	3.3381	0.0094	462
Sp.14, Au.15	1.9068	0.074	7670
Sp.14, Wi.16	0.52814	0.5934	462
Sp.14, Sp.16	0.34844	0.7297	462
Sp.14, Su.16	1.1412	0.2885	462
Su.14, Wi.15	0.70112	0.4907	462
Su.14, Sp.15	0.61213	0.5587	4279
Su.14, Su.15	1.4982	0.172	462
Su.14, Au.15	3.2671	0.0032	7644
Su.14, Wi.16	1.5838	0.1423	460
Su.14, Sp.16	1.4981	0.1828	462
Su.14, Su.16	0.1211	0.8969	461
Wi.15, Sp.15	0.34742	0.7393	4338
Wi.15, Su.15	1.9513	0.0782	462
Wi.15, Au.15	1.5646	0.1282	7736
Wi.15, Wi.16	0.55384	0.6244	462
Wi.15, Sp.16	0.42879	0.7156	461
Wi.15, Su.16	0.60767	0.5567	462
Sp.15, Su.15	2.4902	0.0312	4288
Sp.15, Au.15	2.9608	0.0087	9654
Sp.15, Wi.16	1.2674	0.2277	4272
Sp.15, Sp.16	1.1183	0.2807	4315
Sp.15, Su.16	0.47297	0.6526	4297
Su.15, Au.15	6.1573	0.0004	7671
Su.15, Wi.16	3.4355	0.0113	462
Su.15, Sp.16	3.5103	0.0082	462
Su.15, Su.16	1.6604	0.129	461
Au.15, Wi.16	0.99934	0.3381	7675
Au.15, Sp.16	1.3747	0.1913	7676
Au.15, Su.16	3.1279	0.0045	7648
Wi.16, Sp.16	0.20162	0.8198	461
Wi.16, Su.16	1.479	0.175	462
Sp.16, Su.16	1.3867	0.1857	461

Predator

Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	0.94655	0.3951	462
Sp.14, Wi.15	1.3046	0.2215	462
Sp.14, Sp.15	1.2122	0.2411	4240
Sp.14, Su.15	1.2794	0.2438	462
Sp.14, Au.15	0.50853	0.6059	7541
Sp.14, Wi.16	3.6632	0.0061	462
Sp.14, Sp.16	0.64217	0.5781	462
Sp.14, Su.16	2.1404	0.0586	462
Su.14, Wi.15	2.2113	0.0418	461
Su.14, Sp.15	0.10752	0.9135	4324
Su.14, Su.15	0.30206	0.6921	462
Su.14, Au.15	1.4366	0.1751	7670
Su.14, Wi.16	4.3974	0.002	461
Su.14, Sp.16	0.054387	0.9679	460
Su.14, Su.16	1.0687	0.2702	462
Wi.15, Sp.15	3.0493	0.0146	4264
Wi.15, Su.15	2.5872	0.022	462
Wi.15, Au.15	0.65025	0.5242	7649
Wi.15, Wi.16	0.47089	0.6413	461
Wi.15, Sp.16	1.5125	0.1588	462
Wi.15, Su.16	3.5855	0.0059	462
Sp.15, Su.15	0.52652	0.6385	4279
Sp.15, Au.15	1.7605	0.0923	9694
Sp.15, Wi.16	6.5661	0.0004	4320
Sp.15, Sp.16	0.00639	0.9953	4313
Sp.15, Su.16	1.6016	0.131	4348
Su.15, Au.15	1.7651	0.0922	7647
Su.15, Wi.16	4.8751	0.0028	462
Su.15, Sp.16	0.28367	0.7566	462
Su.15, Su.16	0.76426	0.4448	462
Au.15, Wi.16	2.3498	0.0326	7654
Au.15, Sp.16	1.1531	0.2609	7599
Au.15, Su.16	2.5897	0.0213	7694
Wi.16, Sp.16	2.8161	0.004	462
Wi.16, Su.16	6.2177	0.0027	460
Sp.16, Su.16	0.85561	0.4142	452

Predator

Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	3.46	0.0102	460
Sp.14, Sp.15	0.10787	0.9143	4284
Sp.14, Su.15	2.1623	0.0298	461
Sp.14, Au.15	1.875	0.0818	7622
Sp.14, Wi.16	0.55949	0.6494	462
Sp.14, Sp.16	0.22281	0.8463	462
Sp.14, Su.16	6.2427	0.0022	462
Wi.15, Sp.15	3.2553	0.0076	4298
Wi.15, Su.15	4.1271	0.0017	462
Wi.15, Au.15	5.3927	0.0001	7612
Wi.15, Wi.16	2.9743	**0.0023**	462
Wi.15, Sp.16	6.7687	0.0024	462
Wi.15, Su.16	10.15	0.0025	462
Sp.15, Su.15	2.3826	0.0223	4269
Sp.15, Au.15	1.9042	0.0721	9650
Sp.15, Wi.16	0.51872	0.623	4289
Sp.15, Sp.16	0.3232	0.748	4265
Sp.15, Su.16	6.4593	0.0001	4315
Su.15, Au.15	1.4001	0.179	7627
Su.15, Wi.16	1.5186	0.164	460
Su.15, Sp.16	2.4917	0.0065	462
Su.15, Su.16	2.1274	0.0564	462
Au.15, Wi.16	0.91619	0.3861	7654
Au.15, Sp.16	2.3774	0.0255	7685
Au.15, Su.16	5.4326	0.0006	7669
Wi.16, Sp.16	0.80066	0.658	462
Wi.16, Su.16	4.5155	0.0071	461
Sp.16, Su.16	7.9268	0.0021	462

Parasite			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	2.3807	0.042	462
Sp.14, Wi.15	1.0981	0.3505	462
Sp.14, Sp.15	0.12655	0.8926	4314
Sp.14, Su.15	1.865	0.1025	462
Sp.14, Au.15	0.213	0.8308	7536
Sp.14, Wi.16	2.6204	0.0299	462
Sp.14, Sp.16	0.46478	0.6036	462
Sp.14, Su.16	0.38451	0.7061	462
Su.14, Wi.15	4.6102	0.0046	461
Su.14, Sp.15	2.8318	0.0172	4319
Su.14, Su.15	1.1988	0.2814	462
Su.14, Au.15	2.6264	0.0234	7642
Su.14, Wi.16	7.0055	0.002	462
Su.14, Sp.16	2.9098	0.0193	462
Su.14, Su.16	1.6067	0.0553	462
Wi.15, Sp.15	1.0817	0.3142	4316
Wi.15, Su.15	4.7528	0.0047	462
Wi.15, Au.15	1.5494	0.1442	7645
Wi.15, Wi.16	1.1379	0.0569	462
Wi.15, Sp.16	0.527	0.6636	462
Wi.15, Su.16	1.9932	0.0835	460
Sp.15, Su.15	2.2088	0.0524	4294
Sp.15, Au.15	0.4091	0.6877	9676
Sp.15, Wi.16	2.7509	0.0158	4295
Sp.15, Sp.16	0.41241	0.6949	4303
Sp.15, Su.16	0.57924	0.577	4266
Su.15, Au.15	1.8801	0.082	7638
Su.15, Wi.16	8.4242	0.0017	462
Su.15, Sp.16	2.4712	0.0389	462
Su.15, Su.16	2.1043	0.0561	462
Au.15, Wi.16	3.311	0.003	7628
Au.15, Sp.16	0.79826	0.4308	7599
Au.15, Su.16	0.21829	0.8296	7647
Wi.16, Sp.16	2.0082	0.0622	462
Wi.16, Su.16	4.2453	0.0016	462
Sp.16, Su.16	0.93602	0.3687	462

Parasite			
Seasons	t	P(perm)	Unique perms
Sp.14, Su.14	1.7779	0.1537	462
Sp.14, Wi.15	2.8221	0.0285	460
Sp.14, Sp.15	0.59899	0.5466	4258
Sp.14, Su.15	1.8836	0.1591	462
Sp.14, Au.15	0.50222	0.6213	7665
Sp.14, Wi.16	1.7553	0.1226	462
Sp.14, Sp.16	0.3794	0.6998	461
Sp.14, Su.16	1.9663	0.1504	462
Su.14, Wi.15	8.6821	0.0027	462
Su.14, Sp.15	2.0487	0.0633	4271
Su.14, Su.15	0.36865	0.6988	462
Su.14, Au.15	1.5835	0.1342	7672
Su.14, Wi.16	7.2458	0.0023	462
Su.14, Sp.16	2.7453	0.0203	462
Su.14, Su.16	0.66546	0.4935	462
Wi.15, Sp.15	5.2786	0.001	4252
Wi.15, Su.15	8.9115	0.0028	462
Wi.15, Au.15	4.2397	0.0014	7549
Wi.15, Wi.16	1.7534	0.1198	462
Wi.15, Sp.16	5.0817	0.005	461
Wi.15, Su.16	9.055	0.0023	461
Sp.15, Su.15	2.2309	0.0424	4250
Sp.15, Au.15	0.080997	0.9325	9676
Sp.15, Wi.16	3.6742	0.0043	4313
Sp.15, Sp.16	0.25088	0.7962	4284
Sp.15, Su.16	2.3721	0.0336	4270
Su.15, Au.15	1.7144	0.1035	7555
Su.15, Wi.16	7.4984	0.0023	462
Su.15, Sp.16	2.9719	0.0142	461
Su.15, Su.16	0.30433	0.7583	462
Au.15, Wi.16	2.8627	0.0119	7609
Au.15, Sp.16	0.1281	0.9032	7692
Au.15, Su.16	1.8184	0.0889	7652
Wi.16, Sp.16	3.5467	0.0113	462
Wi.16, Su.16	7.6588	0.0023	462
Sp.16, Su.16	3.1376	0.014	462

Parasite			
Seasons	t	P(perm)	Unique perms
Sp.14, Wi.15	9.0562	0.002	336
Sp.14, Sp.15	5.5217	**0.0004**	3365
Sp.14, Su.15	0.84359	0.3908	336
Sp.14, Au.15	1.278	0.2191	6950
Sp.14, Wi.16	0.55159	0.612	335
Sp.14, Sp.16	2.0599	0.0753	336
Sp.14, Su.16	0.36183	0.7291	336
Wi.15, Sp.15	4.3327	0.0008	4258
Wi.15, Su.15	8.7184	0.0028	462
Wi.15, Au.15	8.9241	0.0001	7647
Wi.15, Wi.16	3.534	**0.0022**	462
Wi.15, Sp.16	15.226	0.0018	460
Wi.15, Su.16	9.5467	0.0021	462
Sp.15, Su.15	4.8147	0.0008	4292
Sp.15, Au.15	6.6196	0.0001	9706
Sp.15, Wi.16	2.1586	0.0438	4265
Sp.15, Sp.16	9.1321	**0.0003**	4295
Sp.15, Su.16	5.4872	0.0004	4235
Su.15, Au.15	2.0216	0.0619	7538
Su.15, Wi.16	0.16998	0.861	461
Su.15, Sp.16	3.4434	0.0106	462
Su.15, Su.16	0.53685	0.5834	461
Au.15, Wi.16	1.5381	0.1443	7659
Au.15, Sp.16	0.098286	0.9286	7625
Au.15, Su.16	1.6169	0.1244	7632
Wi.16, Sp.16	1.3646	0.1603	461
Wi.16, Su.16	0.3981	0.6977	462
Sp.16, Su.16	2.9087	0.0237	462

Appendix 4.26. Summary of sequential tests, obtained from distance-based linear models (DISTLM), seeking relationships between temporal variations in macroinvertebrate univariate metrics and channel morphological variables. Values displayed indicate the proportion of variability explained by each channel morphological variables, and the cumulative of variability explained by the models. * indicates values significant at $P < 0.05$. +/- indicate additions to or subtractions from the model. Correlations were obtained using Spearman's rank correlation (ρ), +/- indicate positive or negative correlations.

Macroinvertebrate community data	Morphological variables	Proportion	Cumulative	Relationship
Total Density				
Sp.14:Sp.15	Woody debris%	0.3563*	0.3563	+
Sp.14:Sp.16	+Gravel%	0.87428*	0.87428	+
Su.15:Su.16	+CV_depth	0.1052	0.1052	
	-CV_depth	0.1052	0	
Total Biomass				
Sp.14:Sp.15	+Marginal plant%	0.1612	0.1612	+
Sp.14:Sp.16	+Marginal plant%	0.64392*	0.64392	+
	+Silt%	0.14844*	0.79236	-
	+Sand%	0.05101	0.84337	-
Su.15:Su.16	+Marginal plant%	0.4689*	0.4689	+
	+Leaf litter%	0.3214*	0.7903	+
Taxa Richness				
Sp.14:Sp.15	+Gravel%	0.0402	0.0402	+
Sp.14:Sp.16	+Gravel%	0.391*	0.391	+
	+Marginal plant%	0.2451*	0.6361	+
Su.15:Su.16	+SWI_biotope,	0.3277*	0.3277	+
Taxa Diversity				
Sp.14:Sp.15	CV_depth	0.7987*	0.7987	+
Sp.14:Sp.16	+Gravel%	0.5821*	0.5821	+
	+Marginal plant%	0.1801*	0.7622	+
Su.15:Su.16	+Marginal plant%	0.4617*	0.4617	+
Evenness				
Sp.14:Sp.15	CV_depth	0.7453*	0.7453	+
Sp.14:Sp.16	SWI_biotope	0.9775*	0.9775	+
Su.15:Su.16	CV_width%	0.2853*	0.2853	+
EPT Richness				
Sp.14:Sp.15	CV_depth	0.3519*	0.3519	+
Sp.14:Sp.16	+Gravels%	0.5151*	0.5151	+
Su.15:Su.16	+ CV_depth	0.07764	0.07764	
	- CV_depth	0.07764	0	
EPT Diversity				
Sp.14:Sp.15	+Gravel%	0.4610*	0.4610	+
	+Marginal plant%	0.3221*	0.7831	+
Sp.14:Sp.16	+Gravels%	0.7769*	0.7769	+
Su.15:Su.16	SWI_biotope	0.2674*	0.2674	+
EPT Count%				
Sp.14:Sp.15	Silt%	0.61488*	0.61488	-
Sp.14:Sp.16	Silt%	0.95956*	0.95956	-
Su.15:Su.16	+ CV_depth	0.061074	0.061074	
	- CV_depth	0.061074	0	
Chironomidae Count%				
Sp.14:Sp.15	SWI_biotope	0.69649*	0.69649	-
Sp.14:Sp.16	Gravel%	0.95169*	0.95169	-

Su.15:Su.16	+ CV_width - CV_width	0.0003 0.0003	0.0003 0	
EPT Biomass% Sp.14:Sp.15	Silt%	0.17534	0.17534	-
Sp.14:Sp.16 Su.15:Su.16	+Gravel% +Leaf litter%	0.3786* 0.2321*	0.3786 0.6107	+ +
	+ CV_depth - CV_depth	0.01385 0.01385	0.01385 0	
Chironomidae Biomass%% Sp.14:Sp.15	CV_width	0.23326	0.23326	-
Sp.14:Sp.16	Gravel%	0.69716*	0.69716	-
Su.15:Su.16	+ CV_depth - CV_depth	0.00020 0.00020	0.00020 0	

Appendix 4.27. Summary of sequential tests, obtained from distance-based linear models (DISTLM), seeking relationships between macroinvertebrate FFGs density and channel morphological variables. Values displayed indicate the proportion of variability explained by each variable, and the cumulative of variability explained by the models. * indicates values significant at P <0.05. +/- indicate additions to or subtractions from the model. Correlations were obtained using Spearman's rank correlation (ρ), +/- indicate positive or negative correlations.

FFGs density	Morphological variables	Proportion	Cumulative	Relationship
Absorber				
Sp.14:Sp.15	+Silt%	0.3600	0.3600	+
Sp.14:Sp.16	+Silt%	0.3903	0.3903	+
	+Wet surface area	0.2757	0.6660	+
Su.15:Su.16	+CV_depth	0.0220	0.0220	
	-CV_depth	0.0220	0	
Deposit-feeder				
Sp.14:Sp.15	+Silt%	0.02513	0.02513	
	-Silt%	0.02513	0	
Sp.14:Sp.16	+CV_depth	0.02806	0.02806	
	-CV_depth	0.02806	0	
Su.15:Su.16	+CV_depth	0.31009*	0.31009	+
Shredder				
Sp.14:Sp.15	+CV_width	0.0948	0.0948	
	-CV_width	0.0948	0	
Sp.14:Sp.16	+Gravel%	0.43042*	0.43042	+
	+Marginal plant%	0.32501*	0.75543	+
	+Leaf litter%	0.19903*	0.95446	+
Su.15:Su.16	+CV_depth	0.22308*	0.22308	+
Scraper				
Sp.14:Sp.15	+CV_width	0.68863*	0.68863	+
Sp.14:Sp.16	+Gravel%	0.94821*	0.94821	+
Su.15:Su.16	+Macroalgae%	0.58112*	0.58112	+
Filter-feeder				
Sp.14:Sp.15	+CV_depth	0.00873	0.00873	
	-CV_depth	0.00873	0	
Sp.14:Sp.16	+SWI_biotope	0.7838*	0.7838	+
Su.15:Su.16	+Cobbles%	0.22945	0.22945	+
Piercer				
Sp.14:Sp.15	+Silt%	0.1464	0.1464	
	-Silt%	0.1464	0	
Sp.14:Sp.16	+CV_width	0.53987*	0.53987	+
Su.15:Su.16	+CV_depth	0.0470	0.0470	
	-CV_depth	0.0470	0	
Predator				
Sp.14:Sp.15	+Gravel%	0.7891*	0.7891	+
Sp.14:Sp.16	+Gravel%	0.88932*	0.88932	+
	+Silt%	0.036585	0.9259	-
Su.15:Su.16	+CV_depth	0.01546	0.01546	
	-CV_depth	0.01546	0	
Parasite				
Sp.14:Sp.15	+Silt%	0.1159	0.1159	
	-Silt%	0.1159	0	
Sp.14:Sp.16	+Silt%	0.1311	0.1311	
	-Silt%	0.1311	0	
Su.15:Su.16	+CV_width	0.01308	0.01308	
	-CV_width	0.01308	0	

Appendix 4.28. Summary of sequential tests, obtained from distance-based linear models (DISTLM), seeking relationships between macroinvertebrate FFGs biomass and channel morphological variables. Values displayed indicate the proportion of variability explained by each metrics, and the cumulative of variability explained by the models. * indicates values significant at P <0.05. +/- indicate additions to or subtractions from the model. Correlations were obtained using Spearman's rank correlation (ρ), +/- indicate positive or negative correlations.

FFGs biomass	Morphological variables	Proportion	Cumulative	Relationship
Absorber				
Sp.14:Sp.15	+Silt%	0.3491*	0.3491	+
Sp.14:Sp.16	+Silt%	0.2712	0.2712	+
	+Tree root%	0.2925	0.5638	-
Su.15:Su.16	+CV_depth	0.1596	0.1596	
	-CV_depth	0.1596	0	
Deposit-feeder				
Sp.14:Sp.15	+Silt%	0.27669	0.27669	+
Sp.14:Sp.16	+Silt%	0.2047	0.2047	
	-Silt%	0.2047	0	
Su.15:Su.16	+CV_depth	0.2343	0.2343	+
Shredder				
Sp.14:Sp.15	+Gravel%	0.4027*	0.4027	+
	+Marginal plant%	0.2601*	0.6628	+
Sp.14:Sp.16	+Leaf litter%	0.9297*	0.9297	+
Su.15:Su.16	+Leaf litter%	0.2152*	0.2152	+
Scraper				
Sp.14:Sp.15	+CV_width	0.2087*	0.2087	+
Sp.14:Sp.16	+Sand%	0.9031*	0.9013	-
Su.15:Su.16	+Magroalgae%	0.3405*	0.3405	+
Filter-feeder				
Sp.14:Sp.15	+Silt%	0.5935*	0.5935	+
Sp.14:Sp.16	+Gravel%	0.2969*	0.2969	+
	+Marginal plant%	0.2206*	0.5175	+
	+Leaf litter	0.1261*	0.6436	+
Su.15:Su.16	+Leaf litter%	0.4146*	0.4146	+
	+Marginal plant%	0.3125*	0.7271	+
Piercer				
Sp.14:Sp.15	+Silt%	0.2477*	0.2477	+
Sp.14:Sp.16	+Gravel%	0.4721*	0.4721	+
	+Marginal plant%	0.0564	0.5285	+
Su.15:Su.16	+CV_depth	0.04467	0.04467	
	-CV_depth	0.04467	0	
Predator				
Sp.14:Sp.15	+Silt%	0.0003	0.0003	
	-Silt%	0.0003	0	
Sp.14:Sp.16	+Silt%	0.010	0.010	
	-Silt%	0.010	0	
Su.15:Su.16	+ Marginal plant %	0.3454*	0.3454	+
	+Sand%	0.1065	0.4519	+
Parasite				
Sp.14:Sp.15	+Silt%	0.6952*	0.6952	+
	+Silt%	0.2937	0.2937	-
Sp.14:Sp.16	+CV_depth	0.0267	0.0267	
Su.15:Su.16	-CV_depth	0.0267	0	

Appendix 4.29. Presence/Absence list of macroinvertebrate taxa recorded according to the study reaches. D, Degraded Reach; R Restored Reach; N, Natural Reach.

	Before restoration						After restoration																				
	2014						2015												2016								
	Spring			Summer			Winter			Spring			Summer			Autumn			Winter			Spring			Summer		
Macroinvertebrate taxa	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N	D	R	N
Gammarus pulex	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Asellus aquaticus	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Asellus meridianus					-												X										
Lymnaea (Radix) peregra		X	X	X	-	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X
Lymnaea glabra					-	X					X			X	X		X	X		X						X	X
Lymnaea stagnalis					-									X			X			X						X	
Lymnaea truncatula	X		X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Valvata piscinalis				X	-																				X		
Valvata macrostoma	X			X	-		X			X			X	X		X			X	X		X			X		
Valvata cristata					-												X			X							
Viviparus fasciatus					-						X			X												X	
Potamopyrgus antipodarum	X		X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Bithynia tentaculata	X	X	X	X	-	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Bithynia leachii	X	X	X	X	-					X		X	X					X				X	X	X	X		
Physa fontinalis					-			X			X							X									
Theodoxus fluviatilis					-												X										
Planorbis contortus	X		X	X	-	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Planorbis corneus					-								X	X		X	X										
Planorbis crista					-									X			X			X						X	
Ancylus fluviatilis	X		X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Ancylus lacustris			X		-				X			X						X			X		X	X			X
Pisidium sp.		X	X	X	-	X	X		X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X
Sphaerium sp.	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Anadonta sp.	X			X	-		X			X			X			X						X			X		
Glossiphonia complanata	X	X	X	X	-	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Glossiphonia heteroclita				X	-																				X		
Theromyzon tessulatum				X	-						X			X			X			X					X		
Helobdella stagnalis		X	X	X	-	X		X			X	X	X	X	X		X	X	X	X			X		X	X	X
Erpobdella octoculata	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Erpobdella testacea	X	X	X		-		X			X		X					X	X		X		X					
Lumbriculidae		X	X	X	-	X	X	X	X		X	X			X		X	X		X	X		X	X	X		X
Lumbricidae		X	X		-	X	X		X		X	X				X	X			X							X

Glossoscolecidae					-			X								X											
Tubificidae	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Nais sp.	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Stylaria lacustris				X	-			X		X			X												X		
Gordius aquaticus					-											X	X										
Polycelis tenuis					-					X	X			X		X	X			X						X	
Polycelis felina	X			X	-					X	X		X	X		X	X			X		X	X		X		
Polycelis nigra					-									X			X										
Dugesia lugubris					-												X			X							
Elmidae			X		-	X		X	X		X	X		X	X		X	X		X	X		X	X		X	X
Scirtidae			X		-							X		X									X	X			
Helodidae		X			-																						
Haliplidae					-	X							X		X	X											X
Dytiscidae			X	X	-			X	X		X	X	X	X	X		X	X		X	X		X	X	X	X	
Hydrophilidae					-	X											X										X
Gyrinidae				X	-	X							X		X	X	X	X							X		X
Muscidae			X		-				X			X					X	X		X	X						
Psychodidae	X	X	X	X	-	X	X	X	X	X		X	X				X			X	X	X		X	X		X
Ptychopteridae			X		-	X						X			X			X			X			X			X
Dixidae					-													X									

Tabanidae			X		-							X												X			
Stratiomyidae					-				X			X												X			
Empididae					-				X			X					X			X				X			
Tipulidae		X	X		-	X	X	X	X		X	X			X		X	X		X	X		X	X			X
Pediciidae		X	X	X	-	X	X	X	X		X	X		X	X		X	X		X	X		X	X	X	X	X
Simuliidae	X	X	X		-	X		X	X	X	X	X		X	X		X	X	X	X	X	X	X	X		X	X
Limoniidae					-												X			X							
Ceratopogonidae	X	X	X	X	-	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
Chironominae	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Prodiamesinae	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Orthocladiinae	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Diamesinae	X	X	X	X	-			X	X	X	X	X	X	X			X	X		X	X	X			X	X	
Tanypodinae	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Tinodes sp.				X	-								X				X								X		
Hydropsyche sp.					-	X															X						X
Hydropsyche siltatay		X	X		-	X			X		X	X			X			X			X		X	X			X
Hydropsyche instabilus			X		-	X		X	X		X	X			X			X			X			X			X
Halesus radiatus.	X	X	X		-			X	X	X	X	X									X	X		X			
Halesus digitatus					-			X	X		X			X	X			X			X			X			
Limnephilus lunatus.	X	X	X	X	-	X		X	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X	X	X

Limnephilus nigriceps	X		X	X	-	X		X	X	X	X	X		X	X		X	X		X	X	X	X	X	X	X	X
Limnephilus flavicornis					-												X			X							
Anabolia nervosa	X	X			-					X				X								X					
Chaetopteryx villosa	X	X	X		-	X		X	X	X	X	X		X	X		X	X		X	X		X	X		X	X
Glyphotaelius pellucidus			X		-	X		X	X			X			X		X	X		X	X		X	X			X
Phacopteryx brevipennis					-	X		X	X					X	X		X			X	X			X			X
Micropterna sp.		X	X		-	X	X	X	X		X	X		X	X		X	X		X	X		X	X		X	X
Potamophylax sp.					-				X					X	X			X			X					X	
Molanna albicans		X			-																						
Mystacides longicornis(azurea)		X	X		-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X
Ceraclea sp.		X	X		-	X			X	X	X	X		X	X		X	X		X	X		X	X		X	X
Athripsodes cinereus					-						X			X			X			X							
Athripsodes aterrimus					-	X		X	X			X		X	X		X	X		X	X					X	X
Crunoecia irrorata		X	X	X	-	X			X		X	X			X			X			X			X	X		X
Lepidostoma hirtum			X		-	X			X		X	X			X			X			X			X			X
Lasiocephala basalis			X		-	X			X		X	X			X		X	X		X	X		X	X			X
Sericostoma personatum	X	X	X		-	X		X	X	X	X	X			X		X	X			X	X	X	X		X	
Agapetus fuscipes		X	X		-	X			X		X	X			X		X	X		X	X		X	X			X
Hydroptilidae					-						X	X		X	X		X	X						X		X	
Plectrocnemia conspersa			X		-	X		X	X	X	X	X		X	X		X	X		X	X			X		X	X

Polycentropus flavomaculatus			X		-	X		X	X		X	X		X	X	X	X	X		X	X		X	X		X	X
Apatania muliebris					-	X									X					X							X
Beraea pullata		X	X		-	X		X	X		X	X			X		X	X		X	X		X	X			X
Silo pallipes			X		-	X	X					X		X	X		X	X		X	X		X	X		X	X
Goera pilosa		X	X		-	X			X			X	X		X	X	X	X		X	X			X			X
Rhyacophila dorsalis					-	X									X												X
Baetis rhodani	X	X	X		-	X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X		X	X
Cloeon dipterum				X	-								X												X		
Procloeon pennulatum					-								X		X		X	X									
Centroptilum luteolum			X		-	X		X	X		X	X		X	X			X			X		X	X			X
Caenis macrura					-												X	X									
Caenis luctuosa	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X
Ephemera vulgata					-										X		X										
Ephemera danica			X		-	X						X			X		X	X		X	X			X			X
Serratella ignita			X	X	-	X			X		X	X	X	X	X			X			X			X	X	X	X
Habrophlebia fusca	X		X	X	-	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
Paraleptophlebia werneri			X		-				X		X	X						X			X			X			
Sialis lutaria	X	X	X	X	-	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Calopteryx virgo		X		X	-	X					X		X	X	X		X	X		X			X		X	X	
Platycnemis pennipes					-																						

Coenagrion sp.	X	X			-					X	X			X		X			X			X				X	
Velia caprai		X			-																						
Sisyra sp					-												X										
Lebirtia porosa	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Hygrobates sp (longu)	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Sperchon sp.	X	X	X	X	-	X			X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X
Diplodontus despiciens			X	X	-	X						X	X	X	X		X	X						X	X	X	X
Limnesia sp	X		X	X	-	X			X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Arrenurus truncatellus				X	-					X			X	X	X	X		X	X				X	X	X		
Mideopsis orbicularis					-																			X			

Appendix 5. Summary of PERMANOVA pair-wise analysis of between reach differences in macroinvertebrate secondary production.

Total Production			Malacostraca		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	21.629	0.0001	D1, N1	12.143	0.0004
D1, R1	1.4914	0.2114	D1, R1	4.8628	0.0077
N1, R1	12.253	0.0003	N1, R1	4.0408	0.0161
D2, N2	24.621	0.0001	D2, N2	21.961	0.0001
D2, R2	6.3609	0.0034	D2, R2	3.8229	0.0189
N2, R2	2.8789	0.0469	N2, R2	2.867	0.0476
D1, D2	0.92144	0.4097	D1, D2	0.7186	0.5102
N1, N2	1.6287	0.1752	N1, N2	1.2992	0.2664
R1, R2	4.4026	0.0126	R1, R2	3.3334	0.0276
Gastropoda			Bivalvia		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	15.438	0.0001	D1, N1	11.886	0.0006
D1, R1	1.3171	0.2644	D1, R1	1.2509	0.2728
N1, R1	4.3206	0.0149	N1, R1	9.0494	0.0003
D2, N2	13.225	0.0005	D2, N2	9.3037	0.0012
D2, R2	4.6257	0.0089	D2, R2	12.527	0.0003
N2, R2	1.4657	0.2171	N2, R2	1.9771	0.1223
D1, D2	0.81582	0.4545	D1, D2	0.52502	0.6232
N1, N2	1.7338	0.1522	N1, N2	0.89777	0.4265
R1, R2	5.491	0.0057	R1, R2	8.0167	0.0008
Hirudinea			Oligochaeta		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	1.587	0.1915	D1, N1	5.783	0.0037
D1, R1	1.9423	0.1221	D1, R1	6.6288	0.0019
N1, R1	0.68146	0.5352	N1, R1	0.7923	0.4731
D2, N2	0.59293	0.5845	D2, N2	4.2166	0.0139
D2, R2	0.092991	0.9332	D2, R2	2.982	0.0383
N2, R2	0.56964	0.6001	N2, R2	2.2727	0.0817
D1, D2	0.55765	0.6118	D1, D2	4.365	0.0143
N1, N2	0.57925	0.5914	N1, N2	2.2528	0.0856
R1, R2	1.9864	0.1154	R1, R2	0.12678	0.9074
Turbellaria			Coleoptera		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	4.7991	0.0078	D1, N1	7.1069	0.0025
D1, R1	0.66485	0.5443	D1, R1	1.8946	0.1375
N1, R1	2.3715	0.0747	N1, R1	1.7425	0.1571
D2, N2	6.8714	0.0024	D2, N2	2.9557	0.0427
D2, R2	3.3876	0.0272	D2, R2	4.6995	0.0108
N2, R2	4.9239	0.0067	N2, R2	1.7078	0.1643
D1, D2	2.7601	0.0504	D1, D2	0.41477	0.7095
N1, N2	75903	0.4873	N1, N2	2.1647	0.099
R1, R2	0.0984	0.924	R1, R2	1.5301	0.203

Diptera			Chironomidae		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	40.378	0.0001	D1, N1	31.867	0.0001
D1, R1	5.0781	0.0074	D1, R1	20.884	0.0001
N1, R1	38.086	0.0001	N1, R1	8.2097	0.0008
D2, N2	28.385	0.0001	D2, N2	5.8928	0.004
D2, R2	2.635	0.0587	D2, R2	9.6608	0.0005
N2, R2	28.148	0.0002	N2, R2	4.846	0.008
D1, D2	0.2782	0.7888	D1, D2	0.41388	0.7062
N1, N2	5.3439	0.0067	N1, N2	1.017	0.3603
R1, R2	3.8206	0.0203	R1, R2	1.1066	0.336
EPT			Megaloptera		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	15.746	0.0001	D1, N1	0.82215	0.4583
D1, R1	6.0171	0.004	D1, R1	1.4097	0.2316
N1, R1	11.069	0.0008	N1, R1	2.1961	0.0939
D2, N2	10.801	0.0005	D2, N2	0.58969	0.5898
D2, R2	19.348	0.0002	D2, R2	1.3116	0.2691
N2, R2	5.7113	0.0041	N2, R2	1.3466	0.2418
D1, D2	0.77631	0.4841	D1, D2	0.68912	0.532
N1, N2	1.2198	0.2867	N1, N2	0.61967	0.5638
R1, R2	7.5839	0.0016	R1, R2	0.83985	0.4568
Odonata			Arachnida		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	2.3406	0.0805	D1, N1	0.69673	0.5246
D1, R1	2.3416	0.0822	D1, R1	4.8325	0.0077
N1, R1	3.5754	0.0222	N1, R1	6.4169	0.003
D2, N2	65.097	0.0001	D2, N2	1.3572	0.238
D2, R2	5.1792	0.0065	D2, R2	13.806	0.0003
N2, R2	5.4911	0.0057	N2, R2	9.3749	0.001
D1, D2	0.97919	0.3839	D1, D2	0.35326	0.7474
N1, N2	1.1263	0.3215	N1, N2	2.6351	0.0604
R1, R2	4.7996	0.0087	R1, R2	2.5646	0.0626
Absorber			Deposit-feeder		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	7.2413	0.0023	D1, N1	9.7744	0.0009
D1, R1	3.2575	0.0308	D1, R1	3.3212	0.0305
N1, R1	0.80539	0.4686	N1, R1	7.9283	0.0015
D2, N2	1.2171	0.2932	D2, N2	4.0254	0.0157
D2, R2	0.84786	0.4413	D2, R2	0.053209	0.9581
N2, R2	1.5421	0.1976	N2, R2	13.651	0.0001
D1, D2	0.42917	0.6914	D1, D2	0.042878	0.9692
N1, N2	0.10432	0.927	N1, N2	4.0044	0.0155
R1, R2	1.8651	0.141	R1, R2	3.3182	0.029

Shredders			Scraper		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	31.26	0.0001	D1, N1	24.686	0.0001
D1, R1	2.4941	0.0641	D1, R1	2.502	0.0685
N1, R1	6.7446	0.003	N1, R1	7.5293	0.0018
D2, N2	20.555	0.0002	D2, N2	21.72	0.0001
D2, R2	5.4489	0.0057	D2, R2	4.8432	0.0109
N2, R2	3.4247	0.0244	N2, R2	2.2709	0.0926
D1, D2	0.21721	0.8437	D1, D2	0.75903	0.4873
N1, N2	0.40325	0.6985	N1, N2	1.7306	0.1559
R1, R2	2.1233	0.0976	R1, R2	2.2388	0.0858
Filter-feeder			Piercer		
Reaches	t	P(MC)	Reaches	t	P(MC)
D1, N1	12.472	0.0002	D1, N1	3.0714	0.0357
D1, R1	7.3847	0.0021	D1, R1	3.3959	0.0296
N1, R1	11.884	0.0006	N1, R1	0.23085	0.8271
D2, N2	5.1845	0.0088	D2, N2	3.627	0.0242
D2, R2	6.6576	0.0024	D2, R2	2.2853	0.0829
N2, R2	0.14792	0.8928	N2, R2	4.3061	0.0116
D1, D2	1.2706	0.2731	D1, D2	0.79022	0.4844
N1, N2	2.0069	0.1083	N1, N2	0.11797	0.9104
R1, R2	11.38	0.0003	R1, R2	5.6732	0.0051
Predator			Parasite		
Groups	t	P(MC)	Groups	t	P(MC)
D1, N1	2.6825	0.056	D1, N1	20.448	0.0001
D1, R1	0.096416	0.9275	D1, R1	21.734	0.0002
N1, R1	1.5031	0.2143	N1, R1	1.0733	0.3389
D2, N2	3.7268	0.0196	D2, N2	4.6025	0.0097
D2, R2	2.5585	0.0446	D2, R2	3.6241	0.0219
N2, R2	0.053066	0.9563	N2, R2	4.5776	0.0098
D1, D2	1.197	0.3003	D1, D2	0.58101	0.5925
N1, N2	1.6463	0.1736	N1, N2	0.74027	0.4908
R1, R2	1.8266	0.1336	R1, R2	6.9467	0.003

References

Addy, S., Cooksley, S., Dodd, N., Waylen, K., Stockan, J., Byg, A. & Holstead, K. (2016) River restoration and biodiversity: Nature-based solutions for restoring rivers in the UK and Republic of Ireland.

Albertson, L.K., Cardinale, B.J., Zeug, S.C., Harrison, L.R., Lenihan, H.S. & Wydzga, M.A. (2011) Impacts of channel reconstruction on invertebrate assemblages in a restored river. *Restoration Ecology,* **19,** 627-638.

Allan, D., Erickson, D. & Fay, J. (1997) The influence of catchment land use on stream integrity across multiple spatial scales. *Freshwater Biology,* **37,** 149-161.

Allan, J.D. (1995) *Stream ecology: structure and function of running waters*. Chapman and Hall, London.

Allan, J.D. (2004) Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, 257-284.

Allan, J.D. & Flecker, A.S. (1993) Biodiversity conservation in running waters. *BioScience,* **43,** 32-43.

Allan, J.D., Yuan, L.L., Black, P., Stockton, T., Davies, P.E., Magierowski, R.H. & Read, S.M. (2012) Investigating the relationships between environmental stressors and stream condition using Bayesian belief networks. *Freshwater Biology,* **57,** 58-73.

Anderson, M., Gorley, R.N. & Clarke, R.K. (2008) *Permanova+ for Primer: Guide to software and statisticl methods*.

Anderson, M.J. & Robinson, J. (2003) Generalized discriminant analysis based on distances. *Australian & New Zealand Journal of Statistics,* **45,** 301-318.

Angradi, T.R. (1999) Fine sediment and macroinvertebrate assemblages in Appalachian streams: a field experiment with biomonitoring applications. *Journal of the North American Benthological Society,* **18,** 49-66.

Antheunisse, A.M., Loeb, R., Lamers, L.P. & Verhoeven, J.T. (2006) Regional differences in nutrient limitation in floodplains of selected European rivers: implications for rehabilitation of characteristic floodplain vegetation. *River Research and Applications,* **22,** 1039-1055.

Armitage, P., Pardo, I. & Brown, A. (1995) Temporal constancy of faunal assemblages in'mesohabitats'—application to management? *Archiv für Hydrobiologie,* **133,** 367-387.

Arnold, C.L. & Gibbons, C.J. (1996) Impervious surface coverage: The emergence of a key environmental indicator. *Journal of the American planning Association,* **62,** 243-258.

Ayres, A., Gerdes, H., Goeller, B., Lago, M., Brouwer, O.S., IVM, J.V., Angelopoulos, N. & Cowx, I. (2014) REFORM D1.4 Inventory of river restoration measures: effects, costs and benefits.

Baillie, B.R. (2011) The physical and biological function of wood in New Zealand's forested stream ecosystems. PhD thesis, University of Waikato, New Zealand.

Baillie, B.R., Garrett, L.G. & Evanson, A.W. (2008) Spatial distribution and influence of large woody debris in an old-growth forest river system, New Zealand. *Forest Ecology and Management,* **256,** 20-27.

Bakker, E., Van Donk, E., Declerck, S., Helmsing, N., Hidding, B. & Nolet, B. (2010) Effect of macrophyte community composition and nutrient enrichment on plant biomass and algal blooms. *Basic and Applied Ecology,* **11,** 432-439.

Barham, P. (2013) Enhancing the River Welland: The Welland Valley Partnership. *Our invitation to support a new vision for the local environment* (ed. P. Barham).

Barlaup, B.T., Gabrielsen, S.E., Skoglund, H. & Wiers, T. (2008) Addition of spawning gravel—a means to restore spawning habitat of atlantic salmon (Salmo salar L.), and Anadromous and resident brown trout (Salmo trutta L.) in regulated rivers. *River Research and Applications,* **24,** 543-550.

Barmuta, L. (2002) Monitoring, survey and experimentation in streams and rivers. *Cambridge University Press, Cambridge, UK*.

Bartley, R. & Rutherfurd, I. (1999) The recovery of geomorphic complexity in disturbed streams: using migrating sand slugs as a model. *Proceedings of the Second Australian Stream Management Conference*, pp. 39-44. Adelaide.

Barton, D.R., Taylor, W.D. & Biette, R. (1985) Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. *North American Journal of Fisheries Management,* **5,** 364-378.

Batalla, R.J. & Vericat, D. (2009) Hydrological and sediment transport dynamics of flushing flows: implications for management in large Mediterranean rivers. *River Research and Applications,* **25,** 297-314.

Baumgärtner, D. & Rothhaupt, K.-O. (2003) Predictive length–dry Mass regressions for freshwater invertebrates in a pre-alpine lake littoral. *International Review of Hydrobiology,* **88,** 453-463.

Bear, E.A., McMahon, T.E. & Zale, A.V. (2007) Comparative thermal requirements of westslope cutthroat trout and rainbow trout: implications for species interactions and development of thermal protection standards. *Transactions of the American Fisheries Society,* **136,** 1113-1121.

Beauger, A., Lair, N., Reyes-Marchant, P. & Peiry, J.-L. (2006) The distribution of macroinvertebrate assemblages in a reach of the River Allier (France), in relation to riverbed characteristics. *Hydrobiologia,* **571,** 63-76.

Becker, A. & Robson, B.J. (2009) Riverine macroinvertebrate assemblages up to 8 years after riparian restoration in a semi-rural catchment in Victoria, Australia. *Marine and Freshwater Research,* **60,** 1309-1316.

Bednarek, A.T. (2001) Undamming rivers: a review of the ecological impacts of dam removal. *Environ Manage,* **27,** 803-814.

Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P. & Pollock, M.M. (2010) Process-based principles for restoring river ecosystems. *BioScience,* **60,** 209-222.

Beisel, J.-N., Usseglio-Polatera, P. & Moreteau, J.-C. (2000) The spatial heterogeneity of a river bottom: a key factor determining macroinvertebrate communities. *Assessing the Ecological Integrity of Running Waters*, pp. 163-171. Springer.

Benke, A.C. (1984) Secondary production of aquatic insects. *The ecology of aquatic insects* (eds V.H. Resh & D.M. Rosenberg), pp. 289-322. Praeger Publishers, New York.

Benke, A.C. (1993) Concepts and patterns of invertebrate production in running waters. *Verhandlungen der Internationalen Vereinigung für theoretische und angewandte Limnologie,* **25,** 15-38.

Benke, A.C., Henry, R.L., Gillespie, D.M. & Hunter, R.J. (1985) Importance of snag habitat for animal production in southeastern streams. *Fisheries,* **10,** 8-13.

Benke, A.C. & Huryn, A.D. (2006) Secondary production of macroinvertebrates. *Methods in stream ecology*, pp. 691-710. Elsevier Academic Press, San Diego, California.

Benke, A.C., Huryn, A.D., Smock, L.A. & Wallace, J.B. (1999) Length-mass relationships for freshwater macroinvertebrates in North America with particular reference to the southeastern United States. *Journal of the North American Benthological Society*, 308-343.

Benke, A.C., Richard, H.F., Stites, D.L., Meyer, J.L. & Edwards, R.T. (1992) Growth of snag-dwelling mayflies in a blackwater river: the influence of temperature and food. *Archiv für Hydrobiologie,* **125,** 63-81.

Benke, A.C. & Wallace, J.B. (2003) Influence of wood on invertebrate communities in streams and rivers.

Bernhardt, E.S., Palmer, M., Allan, J., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C. & Follstad-Shah, J. (2005) Synthesizing U. S. river restoration efforts. *Science(Washington),* **308,** 636-637.

Bernhardt, E.S. & Palmer, M.A. (2011) River restoration: the fuzzy logic of repairing reaches to reverse catchment scale degradation. *Ecological Applications,* **21,** 1926-1931.

Biggs, B.J., Smith, R.A. & Duncan, M.J. (1999) Velocity and sediment disturbance of periphyton in headwater streams: biomass and metabolism. *Journal of the North American Benthological Society*, 222-241.

Biggs, J., Corfield, A., Grøn, P., Hansen, H.O., Walker, D., Whitfield, M. & Williams, P. (1998) Restoration of the rivers Brede, Cole and Skerne: a joint Danish and British EU-LIFE demonstration project, V—short-term impacts on the conservation value of aquatic macroinvertebrate and macrophyte assemblages. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **8,** 241-255.

Bilby, R.E. (1981) Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. *Ecology,* **62,** 1234-1243.

Blackwell, M.S., Maltby, E. & Gerritsen, A. (2006) Ecoflood Guidelines: How to use floodplains for flood risk reduction.

Bolam, S.G. & Eggleton, J.D. (2014) Macrofaunal production and biological traits: Spatial relationships along the UK continental shelf. *Journal of Sea Research,* **88,** 47-58.

Bond, N. & Lake, P. (2003) Characterizing fish–habitat associations in streams as the first step in ecological restoration. *Austral Ecology,* **28,** 611-621.

Boon, P.J. (1988) The impact of river regulation on invertebrate communities in the U.K. *Regulated Rivers: Research & Management,* **2,** 389-409.

Borin, M., Passoni, M., Thiene, M. & Tempesta, T. (2010) Multiple functions of buffer strips in farming areas. *European journal of agronomy,* **32,** 103-111.

Bostelmann, R. (2003) Ecological function of small watercourses.

Boulton, A., Brock, M., Robson, B., Ryder, D., Chambers, J. & Davis, J. (2014) *Australian freshwater ecology: processes and management*. John Wiley & Sons.

Bourassa, N. & Morin, A. (1995) Relationships between size structure of invertebrate assemblages and trophy and substrate composition in streams. *Journal of the North American Benthological Society*, 393-403.

Boyero, L. (2003) The quantification of local substrate heterogeneity in streams and its significance for macroinvertebrate assemblages. *Hydrobiologia,* **499,** 161-168.

Brinkhurst, R.O. (1971) *A guide for the identification of British aquatic Oligochaeta,* 2nd edn. Freshwater Biological Association, Kendal.

Broadmeadow, S. & Nisbet, T. (2004) The effects of riparian forest management on the freshwater environment: a literature review of best management practice. *Hydrology and Earth System Sciences Discussions,* **8,** 286-305.

Brock, M., Smith, R. & Jarman, P. (1999) Drain it, dam it: alteration of water regime in shallow wetlands on the New England Tableland of New South Wales, Australia. *Wetlands Ecology and Management,* **7,** 37-46.

Brooker, M. (1985) The ecological effects of channelization. *The Geographical Journal,* **151,** 63-69.

Brookes, A. (1988) *Channelized rivers: perspectives for environmental management*. Wiley & Sons, Chichester, UK.

Brookes, A. (1990) Restoration and enhancement of engineered river channels: some European experiences. *Regulated Rivers: Research & Management,* **5,** 45-56.

Brookes, A. (1996) River restoration experience in Northern Europe. *River Channel Restoration: Guiding Principles for Sustainable Projects* (eds A. Brookes & F.D. Shields), pp. 233–267. Wiley & Sons, Chichester, UK.

Brookes, A., Gregory, K. & Dawson, F. (1983) An assessment of river channelization in England and Wales. *Science of the Total Environment,* **27,** 97-111.

Brookes, A., Knight, S.S. & Shields, F.D. (1996) Habitat enhancemen. *River Channel Restoration: Guiding Principles for Sustainable Projects* (eds A. Brookes & F.D. Shields), pp. 76-101. Wiley & Sons, Chichester, UK.

Brooks, A. (1995) River channel restoration: theory and practice. *Changing River Channels* (eds A.M. Gurnell & G.E. Petts), pp. 369-388. Wiley & Sons, Chichester, UK.

Brooks, A.P., Gehrke, P.C., Jansen, J.D. & Abbe, T.B. (2004) Experimental reintroduction of woody debris on the Williams River, NSW: geomorphic and ecological responses. *River Research and Applications,* **20,** 513-536.

Brooks, S.S., Palmer, M.A., Cardinale, B.J., Swan, C.M. & Ribblett, S. (2002) Assessing stream ecosystem rehabilitation: Limitations of community structure data. *Restoration Ecology,* **10,** 156-168.

Buffagni, A., Crosa, G.A., Harper, D.M. & Kemp, J.L. (2000) Using macroinvertebrate species assemblages to identify river channel habitat units: an application of the functional habitats concept to a large, unpolluted Italian river (River Ticino, northern Italy). *Hydrobiologia,* **435,** 213-225.

Bunn, S.E. & Arthington, A.H. (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ Manage,* **30,** 492-507.

Bunn, S.E. & Davies, P.M. (2000) Biological processes in running waters and their implications for the assessment of ecological integrity. *Hydrobiologia,* **422,** 61-70.

Bunn, S.E., Davies, P.M. & Winning, M. (2003) Sources of organic carbon supporting the food web of an arid zone floodplain river. *Freshwater Biology,* **48,** 619-635.

Burgherr, P. & Meyer, E.I. (1997) Regression analysis of linear body dimensions vs. dry mass in stream macroinvertebrates. *Archiv für Hydrobiologie,* **139,** 101-112.

Bushaw-Newton, K.L., Hart, D.D., Pizzuto, J.E., Thomson, J.R., Egan, J., Ashley, J.T., Johnson, T.E., Horwitz, R.J., Keeley, M. & Lawrence, J. (2002) An integrative approach towards understanding ecological responses to dam removal: The Manatawny Creek study. Wiley Online Library.

Buss, D.F., Baptista, D.F., Nessimian, J.L. & Egler, M. (2004) Substrate specificity, environmental degradation and disturbance structuring macroinvertebrate assemblages in neotropical streams. *Hydrobiologia,* **518,** 179-188.

Cairns, J. (1991) The status of the theoretical and applied science of restoration ecology. *The Environmental Professional,* **13,** 186–194.

Calow, P. (1975) Length-dry weight relationships in snails: some explanatory models. *Journal of Molluscan Studies,* **41,** 357-375.

Cameron, C.J., Cameron, I.F. & Paterson, C.G. (1979) Contribution of organic shell matter to biomass estimates of unionid bivalves. *Canadian Journal of Zoology,* **57,** 1666-1669.

Castelle, A.J., Johnson, A. & Conolly, C. (1994) Wetland and stream buffer size requirements—a review. *Journal of Environmental Quality,* **23,** 878-882.

Chandler, J. (1970) A biological approach to water quality management. *Water Pollution Control,* **69,** 415-422.

Chapman, D. & Knudsen, E. (1980) Channelization and livestock impacts on salmonid habitat and biomass in western Washington. *Transactions of the American Fisheries Society,* **109,** 357-363.

Chevene, F., Doleadec, S. & Chessel, D. (1994) A fuzzy coding approach for the analysis of long-term ecological data. *Freshwater Biology,* **31,** 295-309.

Chin, A., Gelwick, F., Laurencio, D., Laurencio, L.R., Byars, M.S. & Scoggins, M. (2010) Linking geomorphological and ecological responses in restored urban pool-riffle streams. *Ecological Restoration,* **28,** 460-474.

Chow, T.V. (1959) *Open channel hydraulics*. McGraw-Hill, Kogakusha, Japan.

Church, M. (1995) Geomorphic response to river flow regulation: Case studies and time-scales. *Regulated Rivers: Research & Management,* **11,** 3-22.

Cianciara, S. (1980) Biometric and bioenergetic characterization of the development of Cloeon dipterum (L.). *Polskie archiwum hydrobiologii.= Polish archives of hydrobiology*.

Clark, B. (2011) Does habitat restoration increase macroinvertebrate diversity of urban streams in Perth, Western Australia? PhD thesis, The University of Western Australia.

Clarke, K.R. & Ainsworth, M. (1993) A method of linking multivariate community structure to environmental variables. *Marine Ecology Progress Series***,** 205-219.

Clarke, K.R. & Gorley, R.N. (2015) *PRIMER v7: User manual/tutorial,* 1st edn. PRIMER-E: Plymouth.

Clarke, K.R., Gorley, R.N., Somerfield, P.J. & Warwick, R.M. (2014) *Change in Marine Communities: An approach to statistical analysis and interpretation,* 3rd edn. PRIMER-E: Plymouth.

Clilverd, H.M. (2016) Hydroecological monitoring and modelling of river-floodplain restoration in a UK lowland river meadow. PhD thesis, University College London, UK.

Coe, H.J., Kiffney, P.M., Pess, G.R., Kloehn, K.K. & McHenry, M.L. (2009) Periphyton and invertebrate response to wood placement in large pacific coastal rivers. *River Research and Applications,* **25,** 1025-1035.

Collares-Pereira, M. & Cowx, I. (2004) The role of catchment scale environmental management in freshwater fish conservation. *Fisheries management and Ecology,* **11,** 303-312.

Collier, K.J. & Halliday, J.N. (2000) Macroinvertebrate-wood associations during decay of plantation pine in New Zealand pumice-bed streams: stable habitat or trophic subsidy? *Journal of the North American Benthological Society,* **19,** 94-111.

Comiti, F., Andreoli, A., Mao, L. & Lenzi, M.A. (2008) Wood storage in three mountain streams of the Southern Andes and its hydro-morphological effects. *Earth Surface Processes and Landforms,* **33,** 244-262.

Cook, S.E.K. (1976) Quest for an index of community structure sensitive to water-pollution. *Environmental Pollution,* **11,** 269-288.

Corenblit, D., Steiger, J., Gurnell, A. & Tabacchi, E. (2007) Darwinian origin of landforms. *Earth Surface Processes and Landforms,* **32,** 2070-2073.

Cornish, P. (2001) The effects of roading, harvesting and forest regeneration on streamwater turbidity levels in a moist eucalypt forest. *Forest Ecology and Management,* **152,** 293-312.

Correll, D.L. (2005) Principles of planning and establishment of buffer zones. *Ecological Engineering,* **24,** 433-439.

Cowx, I., Angelopoulos, N., Noble, R., Slawson, D., Buijse, T. & Wolter, C. (2013) Measuring success of river restoration actions using end-points and benchmarking. *D5.1 Measuring river restoration success*.

Cowx, I.G. & Welcomme, R.L. (1998) *Rehabilitation of rivers for fish*. Food & Agriculture Org.

Cranston, P.S. (1982) *A key to the larvae of the British Orthocladiinae (Chironomidae)*. Freshwater Biological Association, Ambleside.

Croft, P.S. (1986) *A key to the major groups of British freshwater invertebrates*. Field Studies Council.

Culp, J.M., Walde, S.J. & Davies, R.W. (1983) Relative importance of substrate particle size and detritus to stream benthic macroinvertebrate microdistribution. *Canadian Journal of Fisheries and Aquatic Sciences,* **40,** 1568-1574.

Cummins, K.W., Wilzbach, M.A., Gates, D.M., Perry, J.B. & Taliaferro, W.B. (1989) Shredders and riparian vegetation. *BioScience,* **39,** 24-30.

Dangles, O. (2002) Aggregation of shredder invertebrates associated with benthic detrital pools in seven headwater forested streams. *Internationale Vereinigung fur Theoretische und Angewandte Limnologie Verhandlungen,* **28,** 910-913.

Davies-Colley, R.J. (1997) Stream channels are narrower in pasture than in forest. *New Zealand Journal of Marine and Freshwater Research,* **31,** 599-608.

De Vaate, A.B., Klink, A.G., Greijdanus-Klaas, M., Jans, L.H., Oosterbaan, J. & Kok, F. (2007) Effects of habitat restoration on the macroinvertebrate fauna in a foreland along the river Waal, the main distributary in the Rhine delta. *River Research and Applications,* **23,** 171-183.

DEFRA (2005) *Making space for water: taking forward a new government strategy for flood and coastal erosion risk management in England*. Department for Environment Food and Rural Affairs: London.

Delong, M.D. & Brusven, M.A. (1998) Macroinvertebrate community structure along the longitudinal gradient of an agriculturally impacted stream. *Environ Manage,* **22,** 445-457.

Demars, B.O.L., Kemp, J.L., Friberg, N., Usseglio-Polatera, P. & Harper, D.M. (2012) Linking biotopes to invertebrates in rivers: Biological traits, taxonomic composition and diversity. *Ecological Indicators,* **23,** 301-311.

DeVries, P. (1997) Riverine salmonid egg burial depths: review of published data and implications for scour studies. *Canadian Journal of Fisheries and Aquatic Sciences,* **54,** 1685-1698.

Dickman, M.D., Peart, M.R. & Yim, W. (2005) Benthic diatoms as indicators of stream sediment concentration in Hong Kong. *International Review of Hydrobiology,* **90,** 412.

Diez, J., Elosegi, A. & Pozo, J. (2001) Woody debris in north Iberian streams: influence of geomorphology, vegetation, and management. *Environ Manage,* **28,** 687-698.

Dixon, S.J., Sear, D.A., Odoni, N.A., Sykes, T. & Lane, S.N. (2016) The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms,* **41,** 997-1008.

Dobson, M., Hildrew, A.G., Ibbotson, A. & Garthwaite, J. (1992) Enhancing litter retention in streams: do altered hydraulics and habitat area confound field experiments? *Freshwater Biology,* **28,** 71-79.
Dobson, M., Pawley, S., Fletcher, M. & Powell, A. (2012) *Guide to freshwater invertebrates*. Freshwater Biological Association.
Dolbeth, M., Cusson, M., Sousa, R. & Pardal, M.A. (2012) Secondary production as a tool for better understanding of aquatic ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences,* **69,** 1230-1253.
Doll, B.A., Grabow, G.L., Hall, K.R., Halley, J., Harman, W.A., Jennings, G.D. & Wise, D.E. (2003) Stream restoration: a natural channel design handbook. *NC Stream Restoration Institute, NC State University*.
Dolph, C.L., Eggert, S.L., Magner, J., Ferrington Jr, L.C. & Vondracek, B. (2015) Reach-scale stream restoration in agricultural streams of southern Minnesota alters structural and functional responses of macroinvertebrates. *Freshwater Science,* **34,** 535-546.
Dosskey, M.G. (2001) Toward quantifying water pollution abatement in response to installing buffers on crop land. *Environ Manage,* **28,** 577-598.
Downes, B.J., Barmuta, L.A., Fairweather, P.G., Faith, D.P., Keough, M.J., Lake, P., Mapstone, B.D. & Quinn, G.P. (2002) *Monitoring ecological impacts: concepts and practice in flowing waters*. Cambridge University Press, UK.
Downes, B.J., Glaister, A. & Lake, P. (1997) Spatial variation in the force required to initiate rock movement in 4 upland streams: implications for estimating disturbance frequencies. *Journal of the North American Benthological Society*, 203-220.
Downes, B.J., Lake, P.S. & Schreiber, E.S.G. (1995) Habitat structure and invertebrate assemblages on stream stones: A multivariate view from the riffle. *Australian Journal of Ecology,* **20,** 502-514.
Downes, B.J., Lake, P.S., Schreiber, E.S.G. & Glaister, A. (1998) Habitat structure and regulation of local species diversity in a stony, upland stream. *Ecological Monographs,* **68,** 237-257.
Downs, P.W. (1995) River channel classification for channel management purposes. *Changing River Channels. John Whiley & Sons Ltd., University of Nottingham, UK*, 347-367.
Doyle, M.W., Stanley, E.H., Orr, C.H., Selle, A.R., Sethi, S.A. & Harbor, J.M. (2005) Stream ecosystem response to small dam removal: lessons from the Heartland. *Geomorphology,* **71,** 227-244.
Ebrahimnezhad, M. & Harper, D.M. (1997) The biological effectiveness of artificial riffles in river rehabilitation. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **7,** 187-197.
Eddy, E.N. & Roman, C.T. (2016) Relationship between epibenthic invertebrate species assemblages and environmental variables in Boston Harbor's intertidal habitat. *Northeastern Naturalist,* **23,** 45-66.
Edington, J.M. & Hildrew, A.G. (1995) *A revised key to the caseless caddis larvae of the British Isles with notes on their ecology*. Freshwater Biological Association.
Edwards, C.J., Griswold, B.L., Tubb, R.A., Weber, E.C. & Woods, L.C. (1984) Mitigating effects of artificial riffles and pools on the fauna of a channelized warmwater stream. *North American Journal of Fisheries Management,* **4,** 194-203.
Edwards, F.K., Lauridsen, R.B., Armand, L., Vincent, H.M. & Jones, I.J. (2009) The relationship between length, mass and preservation time for three species of freshwater leeches (Hirudinea). *Fundamental and Applied Limnology/Archiv für Hydrobiologie,* **173,** 321-327.

Elliott, J.M. (2009) *Freshwater Megaloptera and Neuroptera of Britain and Ireland: keys to adults and larvae, and a review of their ecology*. Freshwater Biological Association (FBA).

Elliott, J.M. & Humpesch, U. (2010) *Mayfly larvae (Ephemeroptera) of Britain and Ireland: keys and a review of their ecology*. Freshwater Biological Association.

Elliott, J.M., Humpesch, U.H. & Macan, T.T. (1988) *Larvae of the British Ephemeroptera: a key with ecological notes*. Freshwater Biological Association.

Elliott, J.M. & Mann, K.H. (1979) *A key to the British freshwater leeches: with notes on their life cycles and ecology*. Freshwater Biological Association.

Entrekin, S.A., Tank, J.L., Rosi-Marshall, E.J., Hoellein, T.J. & Lamberti, G.A. (2009) Response of secondary production by macroinvertebrates to large wood addition in three Michigan streams. *Freshwater Biology,* **54,** 1741-1758.

Environment Agency (2003) River habitat survey in Britain and Ireland field survey guidance manual: version 2003. (ed. E. Agency).

Environment Agency (2013) Weir removal, lowering and modification: A review of best practice Environment Agency, Bristol.

Ernst, A.G., Baldigo, B.P., Mulvihill, C.I. & Vian, M. (2010) Effects of natural-channel-design restoration on habitat quality in Catskill Mountain streams, New York. *Transactions of the American Fisheries Society,* **139,** 468-482.

Ernst, A.G., Warren, D.R. & Baldigo, B.P. (2012) Natural-Channel-Design restorations that changed geomorphology have little effect on macroinvertebrate communities in headwater streams. *Restoration Ecology,* **20,** 532-540.

Erwin, A.C. (2014) Evaluating fish habitat compensation in the Canadian Arctic: Stream habitat attributes and macroinvertebrate assemblages. Master thesis, University of Alberta, Canada.

European Environment Agency (2012) European waters — assessment of status and pressures.

European Union (2000) Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. *The European Parliament and the Council of the European Union: Brussels, Belgium*.

Everard, M. (2012) Why does 'good ecological status' matter? *Water and Environment Journal,* **26,** 165-174.

Extence, C.A., Chadd, R.P., England, J., Dunbar, M.J., Wood, P.J. & Taylor, E.D. (2013) The assessment of fine sediment accumulation in rivers using macroinvertebrate community response. *River Research and Applications,* **29,** 17-55.

Faculty of Public Health (2010) Great outdoors: how our natural health service uses green space to improve wellbeing. Brifing statement.

Fehér, J., Gáspár, J., Veres, K.S., Kiss, A., Austnes, K., Globevnik, L., Kirn, T., Peterlin, M., Stein, U. & Spiteri, C. (2012) Hydromorphological alterations and pressures in European rivers, lakes, transitional and coastal waters: Thematic assessment for EEA Water 2012 Report. European Topic Centre on Inland, Coastal and Marine Waters.

Feld, C.K., Birk, S., Bradley, D.C., Hering, D., Kail, J., Marzin, A., Melcher, A., Nemitz, D., Pedersen, M.L., Pletterbauer, F., Pont, D., Verdonschot, P.F.M. & Friberg, N. (2011) From natural to degraded rivers and back again: a test of restoration ecology theory and practice. *Advances in Ecological Research,* **44,** 119-209.

Fenoglio, S., Bo, T., Agosta, P. & Malacarne, G. (2005) Temporal and spatial patterns of coarse particulate organic matter and macroinvertebrate distribution in a low-order Apennine stream. *Journal of Freshwater Ecology,* **20,** 539-547.

Finlayson, B.L. & McMahon, T.A. (1988) Australia v the world: a comparative analysis of streamflow characteristics. *Fluvial geomorphology of Australia*, 17-40.

Florsheim, J.L. & Mount, J.F. (2002) Restoration of floodplain topography by sand-splay complex formation in response to intentional levee breaches, Lower Cosumnes River, California. *Geomorphology,* **44**, 67-94.

Friberg, N. (2010) Ecological consequences of river channel management. *Handbook of Catchment management*, 77-106.

Friberg, N. (2014) Impacts and indicators of change in lotic ecosystems. *Wiley Interdisciplinary Reviews: Water,* **1**, 513-531.

Friberg, N., Angelopoulos, N.V., Buijse, A.D., Cowx, I.G., Kail, J., Moe, T.F., Moir, H., O'Hare, M.T., Verdonschot, P.F.M. & Wolter, C. (2016) Effective river restoration in the 21st century: From trial and error to novel evidence-based approaches. *Advances in Ecological Research*.

Friberg, N., Baattrup-Pedersen, A., Kristensen, E.A., Kronvang, B., S.E. Larsen, Pedersen, M.L., Skriver, J., Thodsen, H. & Wiberg-Larsen, P. (2013) The River Gelså restoration revisited: Habitat specific assemblages and persistence of the macroinvertebrate community over an 11-year period. *Ecological Engineering,* **66**, 150-157.

Friberg, N., Bonada, N., Bradley, D.C., Dunbar, M.J., Edwards, F.K., Grey, J., Hayes, R.B., Hildrew, A.G., Lamouroux, N. & Trimmer, M. (2011) Biomonitoring of human impacts in freshwater ecosystems: the good, the bad and the ugly. *Advances in Ecological Research,* **44**, 1-68.

Friberg, N., Kronvang, B., Hansen, H.O. & Svenden, L.M. (1998) Long-term, habitat-specific response of a macroinvertebrate community to river restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **8**, 87-99.

Friberg, N., Kronvang, B., Svendsen, L.M., Hansen, H.O. & Nielsen, M.B. (1994) Restoration of a channelized reach of the River Gelså, Denmark: Effects on the macroinvertebrate community. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **4**, 289-296.

Friberg, N., Sandin, L. & Pedersen, M.L. (2009) Assessing the effects of hydromorphological degradation on macroinvertebrate indicators in rivers: examples, constraints, and outlook. *Integrated environmental assessment and management,* **5**, 86-96.

Frissell, C.A., Liss, W.J., Warren, C.E. & Hurley, M.D. (1986) A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environ Manage,* **10**, 199-214.

Galli, J. (1990) *Thermal impacts associated with urbanization and stormwater management best management practices*. Department of Environmental Programs, Metropolitan Washington Council of Governments.

Garcia de Jalón, D., Alonso, C., González del Tango, M., Martinez, V., Gurnell, A., Lorenz, S., Wolter, C., Rinaldi, M., Belletti, B. & Mosselman, E. (2013) REFORM D1.2 Review on pressure effects on hydromorphological variables and ecologically relevant processes. *Project Report REFORM D*.

Gee, J.H.R. (1982) Resource utilization by Gammarus pulex (Amphipoda) in a Cotswold stream: a microdistribution study. *The Journal of Animal Ecology*, 817-831.

Genito, D., Gburek, W.J. & Sharpley, A.N. (2002) Response of stream macroinvertebrates to agricultural land cover in a small watershed. *Journal of Freshwater Ecology,* **17**, 109-119.

Gerhard, M. & Reich, M. (2000) Restoration of streams with large wood: Effects of accumulated and built-in wood on channel morphology, habitat diversity and aquatic fauna. *International Review of Hydrobiology,* **85,** 123-137.

Gippel, C.J. (1995) Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering,* **121,** 388-395.

Gippel, C.J., Finlayson, B.L. & O'Neill, I.C. (1992) *The hydraulic basis of snag management*. Centre for Environmental Applied Hydrology, Department of Civil and Agricultural Engineering, University of Melbourne.

Gippel, C.J., O'neill, I., Finlayson, B.L. & Schnatz, I. (1996) Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers. *Regulated Rivers Research & Management,* **12,** 223-236.

Giustini, M., Miccoli, F., De Luca, G. & Cicolani, B. (2008) Length–weight relationships for some plecoptera and ephemeroptera from a carbonate stream in central Apennine (Italy). *Hydrobiologia,* **605,** 183-191.

Gledhill, T., Sutcliffe, D.W. & Williams, W.D. (1976) *A revised key to the British species of Crustacea: Malacostraca occurring in fresh water: With notes on their ecology and distribution*. Freshwater Biological Association.

Glendell, M., Extence, C., Chadd, R. & Brazier, R.E. (2014) Testing the pressure-specific invertebrate index (PSI) as a tool for determining ecologically relevant targets for reducing sedimentation in streams. *Freshwater Biology,* **59,** 353-367.

Godfrey, A. & Middlebrook, I. (2007) Invertebrates associated with coarse woody debris in streams and rivers in Britain. *British Wildlife,* **18,** 178-183.

Goeller, B. & Wolter, C. (2015) Performance of bottom ramps to mitigate gravel habitat bottlenecks in a channelized lowland river. *Restoration Ecology*.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. & Nathan, R.J. (2004) *Stream hydrology: an introduction for ecologists*. John Wiley & Sons.

Gore, J.A., Crawford, D.J. & Addison, D.S. (1998) An analysis of artificial riffles and enhancement of benthic community diversity by physical habitat simulation (PHABSIM) and direct observation. *Regulated Rivers-Research & Management,* **14,** 69-77.

Gørtz, P. (1998) Effects of stream restoration on the macroinvertebrate community in the River Esrom, Denmark. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **8,** 115-130.

Gosch, N.J.C., Miller, M.L., Dzialowski, A.R., Morris, D.M., Gemeinhardt, T.R. & Bonneau, J.L. (2014) Assessment of Missouri River floodplain invertebrates during historic inundation: implications for river restoration. *Knowledge and Management of Aquatic Ecosystems,* **412,** 1-15.

Grant, G.E., Swanson, F.J. & Wolman, M.G. (1990) Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. *Geological Society of America Bulletin,* **102,** 340-352.

Greenhalgh, M. & Ovenden, D. (2007) *Freshwater Life: Britain and Northern Europe*. Collins.

Greenwood, M.T., Bickerton, M.A., Gurnell, A.M. & Petts, G.E. (1999) Channel changes and invertebrate faunas below Nant-Y-Môch Dam, River Rheidol, Wales, UK: 35 Years On. *River Research and Applications,* **15,** 99-112.

Gregory, K.J. (2006) The human role in changing river channels. *Geomorphology,* **79,** 172-191.

Gregory, S., Boyer, K.L. & Gurnell, A.M. (2003) Ecology and management of wood in world rivers. *International conference of wood in world rivers*. American Fisheries Society, Corvallis, Oregon, USA.

Gregory, S., Li, H. & Li, J. (2002) The conceptual basis for ecological responses to dam removal resource managers face enormous challenges in assessing the consequences of removing large dams from rivers and evaluating management options. *BioScience,* **52,** 713-723.

Gregory, S.V., Swanson, F.J., McKee, W.A. & Cummins, K.W. (1991) An ecosystem perspective of riparian zones. *BioScience,* **41,** 540-551.

Greig, S.M., Sear, D.A. & Carling, P.A. (2005) The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. *Science of the Total Environment,* **344,** 241-258.

Gurnell, A. (2013) Wood in fluvial systems. *Treatise on geomorphology,* **9,** 163-188.

Gurnell, A.M., Gregory, K. & Petts, G.E. (1995) The role of coarse woody debris in forest aquatic habitats: implications for management. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **5,** 143-166.

Haapala, A., Muotka, T. & Laasonen, P. (2003) Distribution of benthic macroinvertebrates and leaf litter in relation to streambed retentivity: implications for headwater stream restoration. *Boreal Environment Research,* **8,** 19-30.

Haase, P., Hering, D., Jähnig, S., Lorenz, A. & Sundermann, A. (2013) The impact of hydromorphological restoration on river ecological status: a comparison of fish, benthic invertebrates, and macrophytes. *Hydrobiologia,* **704,** 475-488.

Hancock, P.J. (2002) Human impacts on the stream–groundwater exchange zone. *Environ Manage,* **29,** 763-781.

Hansen, D.R. (1971) Effects of stream channelization on fishes and bottom fauna in the Little Sioux River, Iowa.

Hansen, H.O., Friberg, N. & Baattrup-Pedersen, A. (1999) Remeandering of three Danish streams: impact on the biota. *Neri Technical Report* (eds N. Friberg & J.D. Carl), pp. 83-88. National Environmental Research Institute.

Harper, D.M. (1995) *River bottom habitats: Biological reality and practical value in river management*. Masarykova Univerzita, Brno.

Harper, D.M. & Everard, M. (1998) Why should the habitat-level approach underpin holistic river survey and management? *Aquatic Conservation: Marine and Freshwater Ecosystems,* **8,** 395-413.

Harper, D.M., Mekotova, J., Hulme, S., White, J. & Hall, J. (1997) Habitat heterogeneity and aquatic invertebrate diversity in floodplain forests. *Global Ecology and Biogeography Letters,* **6,** 275-285.

Harper, D.M., Smith, C., Barham, P. & Howell, R. (1995) The ecological basis for the management of the natural river environment. *The Ecological Basis for River Management* (eds D.M. Harper & A.J.D. Ferguson), pp. 219–238. John Wiley & Sons, Chichester.

Harper, D.M. & Smith, C.D. (1995) Habitats in British rivers: biological reality and practical value in river management. *National Rivers Authority, Anglian Region*.

Harper, D.M., Smith, C.D. & Barham, P.J. (1992) Habitats as the building blocks for river conservation assessment. *River Conservation and Management* (eds P.J. Boon, P. Calow & G.E. Petts), pp. 311-319. John Wiley & Sons Ltd, Chichester, UK.

Harrison, S.S.C., Pretty, J.L., Shepherd, D., Hildrew, A.G., Smith, C. & Hey, R.D. (2004) The effect of instream rehabilitation structures on macroinvertebrates in lowland rivers. *Journal of Applied Ecology,* **41,** 1140-1154.

Hart, D.D., Johnson, T.E., Bushaw-Newton, K.L., Horwitz, R.J., Bednarek, A.T., Charles, D.F., Kreeger, D.A. & Velinsky, D.J. (2002) Dam removal: challenges and opportunities for ecological research and river restoration. *BioScience,* **52,** 669-682.

Harvey, G.L., Clifford, N.J. & Gurnell, A.M. (2008) Towards an ecologically meaningful classification of the flow biotope for river inventory, rehabilitation, design and appraisal purposes. *Journal of Environmental Management,* **88,** 638-650.

Hauer, F. & Resh, V. (1996) Benthic macroinvertebrates. *Methods in stream ecology*, pp. 339-369. Academic Press, San Diego, CA.

Heede, B.H. (1972) Influences of a forest on the hydraulic geometry of two mountain streams. *JAWRA Journal of the American Water Resources Association,* **8,** 523-530.

Heerhartz, S.M., Toft, J.D., Cordell, J.R., Dethier, M.N. & Ogston, A.S. (2016) Shoreline armoring in an estuary constrains wrack-associated invertebrate communities. *Estuaries and Coasts,* **39,** 171-188.

Hendry, K., Cragg-Hine, D., O'Grady, M., Sambrook, H. & Stephen, A. (2003) Management of habitat for rehabilitation and enhancement of salmonid stocks. *Fisheries Research,* **62,** 171-192.

Henley, W., Patterson, M., Neves, R. & Lemly, A.D. (2000) Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. *Reviews in Fisheries Science,* **8,** 125-139.

Herbst, D.B. & Kane, J.M. (2009) Responses of aquatic macroinvertebrates to stream channel reconstruction in a degraded rangeland creek in the Sierra Nevada. *Ecological Restoration,* **27,** 76-88.

Hering, D., Moog, O., Sandin, L. & Verdonschot, P.F. (2004) Overview and application of the AQEM assessment system. *Hydrobiologia,* **516,** 1-20.

Heywood, M.J.T. & Walling, D.E. (2007) The sedimentation of salmonid spawning gravels in the Hampshire Avon catchment, UK: implications for the dissolved oxygen content of intragravel water and embryo survival. *Hydrological Processes,* **21,** 770-788.

Hicks, B.J. (1997) Food webs in forest and pasture streams in the Waikato region, New Zealand: a study based on analyses of stable isotopes of carbon and nitrogen, and fish gut contents. *New Zealand Journal of Marine and Freshwater Research,* **31,** 651-664.

Hilderbrand, R., Watts, A. & Randle, A. (2005) The myths of restoration ecology. *Ecology and Society,* **10**.

Hilderbrand, R.H., Lemly, A.D., Dolloff, C.A. & Harpster, K.L. (1997) Effects of large woody debris placement on stream channels and benthic macroinvertebrates. *Canadian Journal of Fisheries and Aquatic Sciences,* **54,** 931-939.

Hladyz, S., Åbjörnsson, K., Chauvet, E., Dobson, M., Elosegi, A., Ferreira, V., Fleituch, T., Gessner, M.O., Giller, P.S. & Gulis, V. (2011) Stream ecosystem functioning in an agricultural landscape: the importance of terrestrial-aquatic linkages. *Advances in Ecological Research,* **44,** 211-276.

Hobbs, R.J. & Norton, D.A. (1996) Towards a conceptual framework for restoration ecology. *Restoration Ecology,* **4,** 93-110.

Hooijer, A., Klijn, F., Pedroli, G.B.M. & Van Os, A.G. (2004) Towards sustainable flood risk management in the Rhine and Meuse river basins: synopsis of the findings of IRMA-SPONGE. *River Research and Applications,* **20,** 343-357.

Horner, R.R., Booth, D.B., Azous, A. & May, C.W. (1997) Watershed determinants of ecosystem functioning. *Effects of watershed development and management on aquatic ecosystems*, pp. 251-274. ASCE.

Hortle, K. & Lake, P. (1983) Fish of channelized and unchannelized sections of the Bunyip River, Victoria. *Marine and Freshwater Research,* **34,** 441-450.

Hose, G.C., Lim, R.P., Hyne, R.V. & Pablo, F. (2003) Short-term exposure to aqueous endosulfan affects macroinvertebrate assemblages. *Ecotoxicology and Environmental Safety,* **56,** 282-294.

Hrodey, P.J., Kalb, B.J. & Sutton, T.M. (2008) Macroinvertebrate community response to large-woody debris additions in small warmwater streams. *Hydrobiologia,* **605,** 193-207.

Hughes, R.M., Larsen, D.P. & Omernik, J.M. (1986) Regional reference sites: a method for assessing stream potentials. *Environ Manage,* **10,** 629-635.

Huryn, A.D. & Wallace, J.B. (1987) Local geomorphology as a determinant of macrofaunal production in a mountain stream. *Ecology***,** 1932-1942.

Huryn, A.D. & Wallace, J.B. (2000) life history and production of stream insects. *Annu. Rev. Entomol.,* **45,** 83-110.

Hutchinson, G.E. (1959) Homage to Santa Rosalia or why are there so many kinds of animals? *The American Naturalist,* **93,** 145-159.

Hynes, H.B.N. (1970) *The ecology of running waters*. Liverpool University Press Liverpool.

Hynes, H.B.N. (1977) *A key to the adults and nymphs of British stoneflies (Plecoptera) with notes on their ecology and distribution*. Freshwater Biological Association.

Hynes, H.B.N., Macan, T.T. & Williams, W.D. (1960) *A key to the British species of Crustacea: Malacostraca occurring in fresh water: with notes on their ecology and distribution*. Freshwater Biological Association.

Jähnig, S.C., Brabec, K., Buffagni, A., Erba, S., Lorenz, A.W., Ofenböck, T., Verdonschot, P.F. & Hering, D. (2010) A comparative analysis of restoration measures and their effects on hydromorphology and benthic invertebrates in 26 central and southern European rivers. *Journal of Applied Ecology,* **47,** 671-680.

Jähnig, S.C. & Lorenz, A.W. (2008) Substrate-specific macroinvertebrate diversity patterns following stream restoration. *Aquatic Sciences,* **70,** 292-303.

Januschke, K., Jähnig, S.C., Lorenz, A.W. & Hering, D. (2014) Mountain river restoration measures and their succession: Effects on river morphology, local species pool, and functional composition of three organism groups. *Ecological Indicators,* **38,** 243-255.

Jayawardana, J.M.C.K. (2011) Role of riparian vegetation and instream vegetation in macroinvertebrate production in stream restoration. *Stream Restoration: Halting Disturbances, Assisted Recovery and Managed Recovery*, pp. 83-110.

Johnson, L.B., Breneman, D.H. & Richards, C. (2003) Macroinvertebrate community structure and function associated with large wood in low gradient streams. *River Research and Applications,* **19,** 199-218.

Johnson, M.W., Powers, S.P., Hightower, C.L. & Kenworthy, M. (2010) Age, growth, mortality, and diet composition of vermilion snapper from the north-central Gulf of Mexico. *Transactions of the American Fisheries Society,* **139,** 1136-1149.

Johnson, S.L., Rodgers, J.D., Solazzi, M.F. & Nickelson, T.E. (2005) Effects of an increase in large wood on abundance and survival of juvenile salmonids (Oncorhynchus spp.) in an Oregon coastal stream. *Canadian Journal of Fisheries and Aquatic Sciences,* **62,** 412-424.

Jones, J., Duerdoth, C., Collins, A., Naden, P. & Sear, D. (2014) Interactions between diatoms and fine sediment. *Hydrological Processes,* **28,** 1226-1237.

Jones Jr, J.B. & Smock, L.A. (1991) Transport and retention of particulate organic matter in two low-gradient headwater streams. *Journal of the North American Benthological Society,* **10,** 115-126.

Jones, K.L., Poole, G.C., Meyer, J.L., Bumback, W. & Kramer, E.A. (2006) Quantifying expected ecological response to natural resource legislation: a case study of riparian buffers, aquatic habitat, and trout populations. *Ecology and Society,* **11,** 15.

Jowett, I., Richardson, J. & Boubee, J. (2009) Effects of riparian manipulation on stream communities in small streams: two case studies. *New Zealand Journal of Marine and Freshwater Research,* **43,** 763-774.

Jowett, I.G. (1993) A method for objectively identifying pool, run, and riffle habitats from physical measurements. *New Zealand Journal of Marine and Freshwater Research,* **27,** 241-248.

Julien, H. & Bergeron, N. (2006) Effect of fine sediment infiltration during the incubation period on Atlantic salmon (Salmo salar) embryo survival. *Hydrobiologia,* **563,** 61-71.

Jungwirth, M., Moog, O. & Muhar, S. (1993) Effects of river bed restructuring on fish and benthos of a fifth order stream, Melk, Austria. *Regulated Rivers: Research & Management,* **8,** 195-204.

Jungwirth, M., Muhar, S. & Schmutz, S. (2000) Fundamentals of fish ecological integrity and their relation to the extended serial discontinuity concept. *Assessing the Ecological Integrity of Running Waters*, pp. 85-97. Springer.

Jungwirth, M., Muhar, S. & Schmutz, S. (2002) Re-establishing and assessing ecological integrity in riverine landscapes. *Freshwater Biology,* **47,** 867-887.

Kail, J. (2003) Influence of large woody debris on the morphology of six central European streams. *Geomorphology,* **51,** 207-223.

Kail, J., Brabec, K., Poppe, M. & Januschke, K. (2015) The effect of river restoration on fish, macroinvertebrates and aquatic macrophytes: A meta-analysis. *Ecological Indicators,* **58,** 311-321.

Kail, J., Hering, D., Muhar, S., Gerhard, M. & Preis, S. (2007) The use of large wood in stream restoration: experiences from 50 projects in Germany and Austria. *Journal of Applied Ecology,* **44,** 1145-1155.

Kampa, E. & Stein, U. (2012) Factsheets on environmental effectiveness of selected hydro-morphological measures. *Comparative study of pressures and measures in the Major River Basin Management Plans* Ecological Institute, Berlin.

Kanehl, P.D., Lyons, J. & Nelson, J.E. (1997) Changes in the habitat and fish community of the Milwaukee River, Wisconsin, following removal of the Woolen Mills Dam. *North American Journal of Fisheries Management,* **17,** 387-400.

Kedzierski, W.M. & Smock, L.A. (2001) Effects of logging on macroinvertebrate production in a sand-bottomed, low-gradient stream. *Freshwater Biology,* **46,** 821-833.

Keller, E.A. & Swanson, F.J. (1979) Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms,* **4,** 361-380.

Kemp, J.L. (1999) Physical controls on the diversity and distribution of river channel habitats. PhD thesis, University of Leicester, UK.

Kemp, J.L., Harper, D.M. & Crosa, G.A. (1999) Use of 'functional habitats' to link ecology with morphology and hydrology in river rehabilitation. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **9,** 159-178.

Kemp, J.L., Harper, D.M. & Crosa, G.A. (2000) The habitat-scale ecohydraulics of rivers. *Ecological Engineering,* **16,** 17–29.

Killeen, I.J., Aldridge, D. & Oliver, G. (2004) *Freshwater bivalves of Britain and Ireland*. Field Studies Council, Preston Montfort/National Museums of Wales.

Klein, L.R., Clayton, S.R., Alldredge, J.R. & Goodwin, P. (2007) Long-term monitoring and evaluation of the Lower Red River meadow restoration project, Idaho, USA. *Restoration Ecology,* **15,** 223-239.

Koebel, J.W., Bousquin, S.G. & Colee, J. (2014) Interim responses of benthic and snag-dwelling macroinvertebrates to reestablished flow and habitat structure in the Kissimmee River, Florida, USA. *Restoration Ecology,* **22,** 409-417.

Kondolf, G.M. (1997) PROFILE: hungry water: effects of dams and gravel mining on river channels. *Environ Manage,* **21,** 533-551.

Kondolf, G.M. (2006) River restoration and meanders. *Ecology and Society,* **11,** 42.

Korsu, K. (2004) Response of benthic invertebrates to disturbance from stream restoration: the importance of bryophytes. *Hydrobiologia,* **523,** 37-45.

Kreutzweiser, D.P., Capell, S.S. & Good, K.P. (2005) Effects of fine sediment inputs from a logging road on stream insect communities: a large-scale experimental approach in a Canadian headwater stream. *Aquatic Ecology,* **39,** 55-66.

Kroes, D.E. & Hupp, C.R. (2010) The effect of channelization on floodplain sediment deposition and subsidence along the Pocomoke River, Maryland. Wiley Online Library.

Kronvang, B., Svendsen, L., Brookes, A., Fisher, K., Møller, B., Ottosen, O., Newson, M. & Sear, D. (1998) Restoration of the rivers Brede, Cole and Skerne: a joint Danish and British EU-LIFE demonstration project, III—channel morphology, hydrodynamics and transport of sediment and nutrients. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **8,** 209-222.

Laasonen, P., Muotka, T. & Kivijärvi, I. (1998) Recovery of macroinvertebrate communities from stream habitat restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **8,** 101-113.

Laeser, S.R., Baxter, C.V. & Fausch, K.D. (2005) Riparian vegetation loss, stream channelization, and web-weaving spiders in northern Japan. *Ecological Research,* **20,** 646-651.

Lake, P. & Marchant, R. (1990) Australian upland streams: ecological degradation and possible restoration. *Proceedings of the Ecological Society of Australia*, pp. 79-91.

Lancaster, J. & Belyea, L.R. (1997) Nested hierarchies and scale-dependence of mechanisms of flow refugium use. *Journal of the North American Benthological Society*, 221-238.

Lancaster, J., Buffin-belanger, T., Reid, I. & Rice, S. (2006) Flow-and substratum-mediated movement by a stream insect. *Freshwater Biology,* **51,** 1053-1069.

Landwehr, K. & Rhoads, B.L. (2003) Depositional response of a headwater stream to channelization, east central Illinois, USA. *River Research and Applications,* **19,** 77-100.

Larsen, S., Vaughan, I.P. & Ormerod, S.J. (2009) Scale-dependent effects of fine sediments on temperate headwater invertebrates. *Freshwater Biology,* **54,** 203-219.

Larson, M.G., Booth, D.B. & Morley, S.A. (2001) Effectiveness of large woody debris in stream rehabilitation projects in urban basins. *Ecological Engineering,* **18,** 211-226.

Leal, C.C. (2012) The effects of restored aquatic large woody debris structures on invertebrate populations in the Napa River. Master thesis, San Jose State University, USA.

Lemly, A.D. & Hilderbrand, R.H. (2000) Influence of large woody debris on stream insect communities and benthic detritus. *Hydrobiologia,* **421,** 179-185.

Lenat, D.R. & Crawford, J.K. (1994) Effects of land use on water quality and aquatic biota of three North Carolina Piedmont streams. *Hydrobiologia,* **294,** 185-199.

Leonard, A.W., Hyne, R.V., Lim, R.P. & Chapman, J.C. (1999) Effect of endosulfan runoff from cotton fields on macroinvertebrates in the Namoi River. *Ecotoxicology and Environmental Safety,* **42,** 125-134.

Lepori, F., Gaul, D., Palm, D. & Malmqvist, B. (2006) Food-web responses to restoration of channel heterogeneity in boreal streams. *Canadian Journal of Fisheries and Aquatic Sciences,* **63,** 2478-2486.

Lepori, F., Palm, D., Brannas, E. & Malmqvist, B. (2005) Does restoration of structural heterogeneity in streams enhance fish and macroinvertebrate diversity? *Ecological Applications,* **15,** 2060-2071.

Lester, R.E. & Boulton, A.J. (2008) Rehabilitating agricultural streams in Australia with wood: a review. *Environ Manage,* **42,** 310-326.

Lester, R.E., Wright, W. & Jones-Lennon, M. (2007) Does adding wood to agricultural streams enhance biodiversity? An experimental approach. *Marine and Freshwater Research,* **58,** 687-698.

Levell, A. & Chang, H. (2008) Monitoring the channel process of a stream restoration project in an urbanizing watershed: a case study of Kelley Creek, Oregon, USA. *River Research and Applications,* **24,** 169-182.

Lorenz, A.W., Jahnig, S.C. & Hering, D. (2009) Re-meandering German lowland streams: qualitative and quantitative effects of restoration measures on hydromorphology and macroinvertebrates. *Environ Manage,* **44,** 745-754.

Louhi, P., Mykrä, H., Paavola, R., Huusko, A., Vehanen, T., Mäki-Petäys, A. & Muotka, T. (2011) Twenty years of stream restoration in Finland: little response by benthic macroinvertebrate communities. *Ecological Applications,* **21,** 1950-1961.

Lugthart, G.J. & Wallace, J.B. (1992) Effects of disturbance on benthic functional structure and production in mountain streams. *Journal of the North American Benthological Society,* **11,** 138-164.

Luke, S.H., Luckai, N.J., Burke, J.M. & Prepas, E.E. (2007) Riparian areas in the Canadian boreal forest and linkages with water quality in streams. *Environmental Reviews,* **15,** 79-97.

Macan, T.T. & Cooper, R.D. (1977) *A key to the British fresh-and brackish-water gastropods: with notes on their ecology*. Freshwater Biological Association.

Mackie, J.K., Chester, E.T., Matthews, T.G. & Robson, B.J. (2013) Macroinvertebrate response to environmental flows in headwater streams in western Victoria, Australia. *Ecological Engineering,* **53,** 100-105.

Mainstone, C. & Wheeldon, J. (2016) The physical restoration of English rivers with special designations for wildlife: from concepts to strategic planning and implementation. *Freshwater Reviews,* **8,** 1-25.

Mainstone, C.P. & Holmes, N.T.H. (2010) Embedding a strategic approach to river restoration in operational management processes — experiences in England. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **20,** S82-S95.

Maloney, K.O., Dodd, H.R., Butler, S.E. & Wahl, D.H. (2008) Changes in macroinvertebrate and fish assemblages in a medium-sized river following a breach of a low-head dam. *Freshwater Biology,* **53,** 1055-1068.

Maltby, E., Ormerod, S., Acreman, M., Blackwell, M., Durance, I., Everard, M., Morris, J., Spray, C., Biggs, J. & Boon, P. (2011) Freshwaters–openwaters, wetlands and floodplains. *UK National Ecosystem Assesessment*, pp. 295-360. Cambridge, UK.

Mann, K.H. & Watson, E. (1954) *A key to the British freshwater leeches with notes on their ecology*. Freshwater Biological Association, Ambleside.

Maohua, M., Tarmi, S. & Helenius, J. (2002) Revisiting the species–area relationship in a semi-natural habitat: floral richness in agricultural buffer zones in Finland. *Agriculture, ecosystems & environment,* **89,** 137-148.

Matthaei, C.D., Guggelberger, C. & Huber, H. (2003) Local disturbance history affects patchiness of benthic river algae. *Freshwater Biology,* **48,** 1514-1526.

Matthaei, C.D. & Townsend, C.R. (2000) Long-term effects of local disturbance history on mobile stream invertebrates. *Oecologia,* **125,** 119-126.

Matthaei, C.D., Werthmüller, D. & Frutiger, A. (1997) Invertebrate recovery from a bed-moving spate: the role of drift versus movements inside or over the substratum. *Archiv für Hydrobiologie,* **140,** 221-235.

Maxted, J.R., Evans, B.F. & Scarsbrook, M.R. (2003) Development of standard protocols for macroinvertebrate assessment of soft-bottomed streams in New Zealand. *New Zealand Journal of Marine and Freshwater Research,* **37,** 793-807.

McBride, M., Hession, W.C. & Rizzo, D.M. (2008) Riparian reforestation and channel change: A case study of two small tributaries to Sleepers River, northeastern Vermont, USA. *Geomorphology,* **102,** 445-459.

McCarthy, D.T. (1985) The adverse effects of channelization and their amelioration. *Habitat Modification and Freshwater Fisheries – Proceedings of a Symposium of the European Inland Fisheries Advisory Commission(ed. J.S.Alabaster). Butterworths, London, UK*, 83–98.

McClurg, S.E., Petty, J.T., Mazik, P.M. & Clayton, J.L. (2007) Stream ecosystem response to limestone treatment in acid impacted watersheds of the Allegheny Plateau. *Ecological Applications,* **17,** 1087-1104.

McManamay, R.A., Orth, D.J. & Dolloff, C.A. (2013) Macroinvertebrate community responses to gravel addition in a southeastern regulated river. *Southeastern Naturalist,* **12,** 599-618.

Merritt, R.W. & Cummins, K.W. (1996) *An introduction to the aquatic insects of North America*. Kendall Hunt pubblication commpany, Dubuque, Iowa, USA.

Meyer, E.I. (1989) The relationship between body length parameters and dry mass in running water invertebrates. *Archiv für Hydrobiologie,* **117,** 191-203.

Meyer, E.I., Niepagenkemper, O., Molls, F. & Spänhoff, B. (2008) An experimental assessment of the effectiveness of gravel cleaning operations in improving hyporheic water quality in potential salmonid spawning areas. *River Research and Applications,* **24,** 119-131.

Miller, S.W., Budy, P. & Schmidt, J.C. (2010) Quantifying macroinvertebrate responses to in-stream habitat restoration: applications of meta-analysis to river restoration. *Restoration Ecology,* **18,** 8-19.

Milner, A.M. (1996) System Recovery. *River Restoration* (eds P. Calow & G.E. Petts), pp. 205-226. Blackwell Science Ltd, Oxford.

Mitsch, W.J. & Jørgensen, S.E. (2003) Ecological engineering: A field whose time has come. *Ecological Engineering,* **20,** 363-377.

Moerke, A.H., Gerard, K.J., Latimore, J.A., Hellenthal, R.A. & Lamberti, G.A. (2004) Restoration of an Indiana, USA, stream: bridging the gap between basic and applied lotic ecology. *Journal of the North American Benthological Society,* **23,** 647-660.

Moerke, A.H. & Lamberti, G.A. (2003) Responses in fish community structure to restoration of two Indiana streams. *North American Journal of Fisheries Management,* **23,** 748-759.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M. & Pess, G. (1995) Pool spacing in forest channels. *Water Resourse Research,* **31,** 1097-1105.

Montgomery, D.R., Collins, B.D., Buffington, J.M. & Abbe, T.B. (2003) Geomorphic effects of wood in rivers. *American Fisheries Society Symposium 37*. Bethesda, Australia.

Morandi, B., Piégay, H., Lamouroux, N. & Vaudor, L. (2014) How is success or failure in river restoration projects evaluated? Feedback from French restoration projects. *Journal of Environmental Management,* **137,** 178-188.

Morin, A. (1997) Empirical models predicting population abundance and productivity in lotic systems. *Journal of the North American Benthological Society,* **16,** 319-337.

Morin, A. & Bourassa, N. (1992) Modèles empiriques de la production annuelle et du rapport P/B d'inverte'bre's benthiques d'eau courante.

Morin, A. & Dumont, P. (1994) A simple model to estimate growth rate of lotic insect larvae and its value for estimating population and community production. *Journal of the North American Benthological Society*, 357-367.

Mosley, M.P. (1981) The influence of organic debris on channel morphology and bedload transport in a New Zealand forest stream. *Earth Surface Processes and Landforms,* **6,** 571-579.

Moss, B. (2010) headwater streams and rivers. *Ecology of Freshwaters: A View for the Twenty-first Century*, pp. 89-125. Blackwell Publishing Ltd., UK.

Mossop, B. & Bradford, M.J. (2004) Importance of large woody debris for juvenile chinook salmon habitat in small boreal forest streams in the upper Yukon River basin, Canada. *Canadian Journal of Forest Research,* **34,** 1955-1966.

Mueller, M., Pander, J. & Geist, J. (2014) The ecological value of stream restoration measures: An evaluation on ecosystem and target species scales. *Ecological Engineering,* **62,** 129-139.

Muhar, S., Januschke, K., Kail, J., Poppe, M., Schmutz, S., Hering, D. & Buijse, A. (2015) Evaluating good-practice cases for river restoration across Europe: context, methodological framework, selected results and recommendations. *Hydrobiologia*, 1-17.

Muhar, S., Schmutz, S. & Jungwirth, M. (1995) River restoration concepts—goals and perspectives. *The Importance of Aquatic-Terrestrial Ecotones for Freshwater Fish*, pp. 183-194. Springer.

Muhar, S., Unfer, G., Schmutz, S., Jungwirth, M., Egger, G. & Angermann, K. (2004) Assessing river restoration programmes: habitat conditions, fish fauna and vegetation as indicators for the possibilities and constraints of river restoration. *Proceedings of 5th International Symposium on Ecohydraulics. Aquatic Habitats: analysis and restoration*, pp. 300-305.

Muotka, T. & Laasonen, P. (2002) Ecosystem recovery in restored headwater streams: the role of enhanced leaf retention. *Journal of Applied Ecology,* **39,** 145-156.

Muotka, T., Paavola, R., Haapala, A., Novikmec, M. & Laasonen, P. (2002) Long-term recovery of stream habitat structure and benthic invertebrate communities from in-stream restoration. *Biological Conservation,* **105,** 243-253.

Myers, T.J. & Swanson, S. (1991) Aquatic habitat condition index, stream type, and livestock bank damage in Northern Nevada. Wiley Online Library.

Myers, T.J. & Swanson, S. (1996) Long-term aquatic habitat restoration: Mahogany Creek, Nevada, as a case study. *Journal of the American Water Resources Association,* **32,** 241-252.

Naiman, R.J. (1992) Balancing sustainability and environmental change. *Watershed management*. Springer Science & Business Media.

Naiman, R.J. & Décamps, H. (1997) The ecology of interfaces: riparian zones. *Annual Review of Ecology and Systematics*, 621-658.
Nakamura, F. & Yamada, H. (2005) Effects of pasture development on the ecological functions of riparian forests in Hokkaido in northern Japan. *Ecological Engineering,* **24,** 539-550.
Nakano, D. & Nakamura, F. (2008) The significance of meandering channel morphology on the diversity and abundance of macroinvertebrates in a lowland river in Japan. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **18,** 780-798.
National Research Council (1992) *Restoration of aquatic ecosystems:: Science, technology, and public policy*. National Academy Press, Washington, D.C.
Negishi, J.N. & Richardson, J.S. (2003) Responses of organic matter and macroinvertebrates to placements of boulder clusters in a small stream of southwestern British Columbia, Canada. *Canadian Journal of Fisheries and Aquatic Sciences,* **60,** 247-258.
Newson, M.D., Harper, D.M., Padmore, C.L., Kemp, J.L. & Vogel, B. (1998) A cost-effective approach for linking habitats, flow types and species requirements. *Aquatic Conservation-Marine and Freshwater Ecosystems,* **8,** 431-446.
Nilsson, C. & Svedmark, M. (2002) Basic principles and ecological consequences of changing water regimes: riparian plant communities. *Environ Manage,* **30,** 468-480.
Niyogi, D.K., Simon, K.S. & Townsend, C.R. (2003) Breakdown of tussock grass in streams along a gradient of agricultural development in New Zealand. *Freshwater Biology,* **48,** 1698-1708.
Norman, D.K. (1998) Reclamation of flood-plain sand and gravel pits as off-channel salmon habitat. *Washington Geology,* **26,** 21-28.
Northington, R.M., Benfield, E.F., Schoenholtz, S.H., Timpano, A.J., Webster, J.R. & Zipper, C. (2011) An assessment of structural attributes and ecosystem function in restored Virginia coalfield streams. *Hydrobiologia,* **671,** 51-63.
Northington, R.M. & Hershey, A.E. (2006) Effects of stream restoration and wastewater treatment plant effluent on fish communities in urban streams. *Freshwater Biology,* **51,** 1959-1973.
Opperman, J.J. & Merenlender, A.M. (2004) The effectiveness of riparian restoration for improving instream fish habitat in four hardwood-dominated California streams. *North American Journal of Fisheries Management,* **24,** 822-834.
Ormerod, S. (2004) A golden age of river restoration science? *Aquatic Conservation: Marine and Freshwater Ecosystems,* **14,** 543-549.
Ormerod, S.J. (2003) Restoration in applied ecology: Editor's introduction. *Journal of Applied Ecology,* **40,** 44-50.
Orzetti, L.L., Jones, R.C. & Murphy, R.F. (2010) Stream condition in Piedmont streams with restored riparian buffers in the Chesapeake Bay watershed. Wiley Online Library.
Osborne, L.L. & Kovacic, D.A. (1993) Riparian vegetated buffer strips in water-quality restoration and stream management. *Freshwater Biology,* **29,** 243-258.
Padmore, C.L. (1997) Physical biotopes in representative river channels: identification, hydraulic characterisation and application. PhD thesis, Newcastle University, UK.
Paillex, A., Castella, E., zu Ermgassen, P.S. & Aldridge, D.C. (2015) Testing predictions of changes in alien and native macroinvertebrate communities and their interaction after the restoration of a large river floodplain (French Rhône). *Freshwater Biology,* **60,** 1162-1175.

Palmer, M.A., Allan, J.D., Meyer, J. & Bernhardt, E.S. (2007) River restoration in the twenty-first century: data and experiential knowledge to inform future efforts. *Restoration Ecology,* **15,** 472-481.

Palmer, M.A., Ambrose, R.F. & Poff, N.L. (1997) Ecological theory and community restoration ecology. *Restoration Ecology,* **5,** 291-300.

Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C.N., Follstad Shah, J., Galat, D.L., Loss, S.G., Goodwin, P., Hart, D.D., Hassett, B., Jenkinson, R., Kondolf, G.M., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L. & Sudduth, E. (2005) Standards for ecologically successful river restoration. *Journal of Applied Ecology,* **42,** 208-217.

Palmer, M.A., Hakenkamp, C.C. & Nelson-Baker, K. (1997) Ecological heterogeneity in streams: why variance matters. *Journal of the North American Benthological Society,* **16,** 189-202.

Palmer, M.A., Hondula, K.L. & Koch, B.J. (2014) Ecological restoration of streams and rivers: Shifting strategies and shifting goals. *Annual Review of Ecology, Evolution, and Systematics,* **45,** 247-269.

Palmer, M.A., Menninger, H.L. & Bernhardt, E. (2010) River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? *Freshwater Biology,* **55,** 205-222.

Pan, B.Z., Wang, Z.Y. & Xu, M.Z. (2012) Macroinvertebrates in abandoned channels: assemblage characteristics and their indications for channel management. *River Research and Applications,* **28,** 1149-1160.

Parkyn, S.M., Davies-Colley, R.J., Halliday, N.J., Costley, K.J. & Croker, G.F. (2003) Planted riparian buffer zones in New Zealand: do they live up to expectations? *Restoration Ecology,* **11,** 436-447.

Parkyn, S.M. & Smith, B.J. (2011) Dispersal constraints for stream invertebrates: setting realistic timescales for biodiversity restoration. *Environ Manage,* **48,** 602-614.

Paul, A.J. & Post, J.R. (2001) Spatial distribution of native and nonnative salmonids in streams of the eastern slopes of the Canadian Rocky Mountains. *Transactions of the American Fisheries Society,* **130,** 417-430.

Pedersen, M.L. (2009) Effects of channelisation, riparian structure and catchment area on physical habitats in small lowland streams. *Fundamental and Applied Limnology/Archiv für Hydrobiologie,* **174,** 89-99.

Pedersen, M.L. & Friberg, N. (2007) Two lowland stream riffles – linkages between physical habitats and macroinvertebrates across multiple spatial scales. *Aquatic Ecology,* **41,** 475-490.

Pedersen, M.L. & Friberg, N. (2009) Influence of disturbance on habitats and biological communities in lowland streams. *Fundamental and Applied Limnology / Archiv für Hydrobiologie,* **174,** 27-41.

Pedersen, M.L., Friberg, N., Skriver, J., Baattrup-Pedersen, A. & Larsen, S.E. (2007) Restoration of Skjern River and its valley—Short-term effects on river habitats, macrophytes and macroinvertebrates. *Ecological Engineering,* **30,** 145-156.

Pedersen, M.L., Kristensen, E.A., Kronvang, B. & Thodsen, H. (2009) Ecological effects of re-introduction of salmonid spawning gravel in lowland Danish streams. *River Research and Applications,* **25,** 626-638.

Pedersen, M.L., Kristensen, K.K. & Friberg, N. (2014) Re-meandering of lowland streams: will disobeying the laws of geomorphology have ecological consequences? *PloS one,* **9**.

Pedersen, T.C.M., Baattrup-Pedersen, A. & Madsen, T.O.M.V. (2006) Effects of stream restoration and management on plant communities in lowland streams. *Freshwater Biology,* **51,** 161-179.
Pedraza, G.X., Giraldo, L.P. & Chará, J.D. (2008) Effect of restoration of riparian corridors on the biotic and abiotic characteristics of streams in Cattle Ranching areas of La Vieja River catchment in Colombia. *Zootecnia Tropical,* **26,** 179-182.
Pedroli, B., de Blust, G., van Looy, K. & van Rooij, S. (2002) Setting targets in strategies for river restoration. *Landscape Ecology,* **17,** 5-18.
Penczak, T. (1995) Effects of removal and regeneration of bankside vegetation on fish population dynamics in the Warta River, Poland. *Hydrobiologia,* **303,** 207-210.
Pennak, R.W. & Van Gerpen, E.D. (1947) Bottom fauna production and physical nature of the substrate in a northern Colorado trout stream. *Ecology,* **28,** 42-48.
Perkins, D.M., Reiss, J., Yvon-Durocher, G. & Woodward, G. (2010) Global change and food webs in running waters. *Hydrobiologia,* **657,** 181-198.
Pescott, O. & Wentworth, J. (2011) Natural flood management. POST Note 396. Parliamentary Office of Science and Technology, London.
Pess, G., Liermann, M., McHenry, M., Peters, R. & Bennett, T. (2012) Juvenile salmon response to the placement of engineered log jams (ELJs) in the Elwha River, Washington State, USA. *River Research and Applications,* **28,** 872-881.
Petersen, R., Petersen, L. & Lacoursiere, J. (1992) A building-block model for stream restoration. John Wiley and Sons, New York.
Petts, G.E. (1984) *Impounded rivers: perspectives for ecological management*. john Wiley.
Petts, G.E. & Calow, P. (1996) River restoration. Selected extracts from the Rivers handbook.
Petty, J.T., Gingerich, G., Anderson, J.T. & Ziemkiewicz, P.F. (2013) Ecological function of constructed perennial stream channels on reclaimed surface coal mines. *Hydrobiologia,* **720,** 39-53.
Pilotto, F., Harvey, G.L., Wharton, G. & Pusch, M.T. (2016) Simple large wood structures promote hydromorphological heterogeneity and benthic macroinvertebrate diversity in low-gradient rivers. *Aquatic Sciences*, 1-12.
Poepperl, R. (1998) Biomass determination of aquatic invertebrates in the Northern German lowland using the relationship between body length and dry mass. *Faunistisch-Ökologische Mitteilungen,* **7,** 379-386.
Poole, G.C. & Berman, C.H. (2001) An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. *Environ Manage,* **27,** 787-802.
Poppe, M., Kail, J., Aroviita, J., Stelmaszczyk, M., Giełczewski, M. & Muhar, S. (2015) Assessing restoration effects on hydromorphology in European mid-sized rivers by key hydromorphological parameters. *Hydrobiologia,* **769,** 21-40.
Possingham, H.P. (2012) How can we sell evaluating, analyzing and synthesizing to young scientists? *Animal Conservation,* **15,** 229-230.
Potter, K.W. (1991) Hydrological impacts of changing land management practices in a moderate-sized agricultural catchment. *Water Resources Research,* **27,** 845-855.
Pretty, J.L. & Dobson, M. (2004) The response of macroinvertebrates to artificially enhanced detritus levels in plantation streams. *Hydrology and Earth System Sciences Discussions,* **8,** 550-559.

Pretty, J.L., Harrison, S.S.C., Shepherd, D.J., Smith, C., Hildrew, A.G. & Hey, R.D. (2003) River rehabilitation and fish populations: assessing the benefit of instream structures. *Journal of Applied Ecology,* **40,** 251-265.

Pringle, C. (2003) What is hydrologic connectivity and why is it ecologically important? *Hydrological Processes,* **17,** 2685-2689.

Prosser, I., Rustomji, P., Young, B., Moran, C. & Hughes, A. (2001) *Constructing river basin sediment budgets for the National Land and Water Resources Audit*. CSIRO Land and Water Canberra.

Purcell, A.H., Friedrich, C. & Resh, V.H. (2002) An assessment of a small urban stream restoration project in Northern California. *Restoration Ecology,* **10,** 685-694.

Quinn, J.M., Cooper, A.B., Davies-Colley, R.J., Rutherford, J.C. & Williamson, R.B. (1997) Land use effects on habitat, water quality, periphyton, and benthic invertebrates in Waikato, New Zealand, hill-country streams. *New Zealand Journal of Marine and Freshwater Research,* **31,** 579-597.

Quinn, J.M., Croker, G.F., Smith, B.J. & Bellingham, M.A. (2009) Integrated catchment management effects on flow, habitat, instream vegetation and macroinvertebrates in Waikato, New Zealand, hill-country streams. *New Zealand Journal of Marine and Freshwater Research,* **43,** 775-802.

Quinn, J.M. & Hickey, C.W. (1990) Characterisation and classification of benthic invertebrate communities in 88 New Zealand rivers in relation to environmental factors. *New Zealand Journal of Marine and Freshwater Research,* **24,** 387-409.

Quinn, J.M., Williamson, R.B., Smith, R.K. & Vickers, M.L. (1992) Effects of riparian grazing and channelisation on streams in Southland, New Zealand. 2. Benthic invertebrates. *New Zealand Journal of Marine and Freshwater Research,* **26,** 259-273.

Quinn, J.W. & Kwak, T.J. (2000) Use of rehabilitated habitat by brown trout and rainbow trout in an Ozark tailwater river. *North American Journal of Fisheries Management,* **20,** 737-751.

Rabeni, C.F., Doisy, K.E. & Galat, D.L. (2002) Testing the biological basis of a stream habitat classification using benthic invertebrates. *Ecological Applications,* **12,** 782-796.

Rabení, C.F., Doisy, K.E. & Zweig, L.D. (2005) Stream invertebrate community functional responses to deposited sediment. *Aquatic Sciences-Research Across Boundaries,* **67,** 395-402.

Raven, E.K., Lane, S.N., Ferguson, R.I. & Bracken, L.J. (2009) The spatial and temporal patterns of aggradation in a temperate, upland, gravel-bed river. *Earth Surface Processes and Landforms,* **34,** 1181-1197.

Raven, P.J., Holmes, N.T.H., Dawson, F.H., Fox, P.J.A., Everard, M., Fozzard, I.R. & Rouen, K.J. (1998) River habitat quality: the physical character of rivers and streams in the UK and Isle of Man. Environment Agency, Bristol UK.

Reice, S.R. (1980) The role of substratum in benthic macroinvertebrate microdistribution and litter decomposition in a woodland stream. *Ecology,* **61,** 580-590.

Reichert, P., Langhans, S.D., Lienert, J. & Schuwirth, N. (2015) The conceptual foundation of environmental decision support. *Journal of Environmental Management,* **154,** 316-332.

Reily, P.W. & Johnson, W.C. (1982) The effects of altered hydrologic regime on tree growth along the Missouri River in North Dakota. *Canadian Journal of Botany,* **60,** 2410-2423.

Renöfält, B., Lejon, A.G., Jonsson, M. & Nilsson, C. (2013) Long-term taxon-specific responses of macroinvertebrates to dam removal in a mid-sized Swedish stream. *River Research and Applications,* **29,** 1082-1089.

Rhoads, B.L. (1990) The impact of stream channelization on the geomorphic stability of an arid-region river. *National Geographic Research,* **6,** 157-177.
Richards, C., Cernera, P.J., Ramey, M.P. & Reiser, D.W. (1992) Development of off-channel habitats for use by juvenile chinook salmon. *North American Journal of Fisheries Management,* **12,** 721-727.
Richards, C., Host, G.E. & Arthur, J.W. (1993) Identification of predominant environmental factors structuring stream macroinvertebrate communities within a large agricultural catchment. *Freshwater Biology,* **29,** 285-294.
Richmond, A.D. & Fauseh, K.D. (1995) Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences,* **52,** 1789-1802.
Rinaldi, M., Wyżga, B. & Surian, N. (2005) Sediment mining in alluvial channels: physical effects and management perspectives. *River Research and Applications,* **21,** 805-828.
Rios-Touma, B., Prescott, C., Axtell, S. & Kondolf, G.M. (2015) Habitat restoration in the context of watershed prioritization: the ecological performance of urban stream restoration projects in Portland, Oregon. *River Research and Applications,* **31,** 755-766.
Robertson, A., Bunn, S., Boon, P.I. & Walker, K.F. (1999) Sources, sinks and transformations of organic carbon in Australian floodplain rivers. *Marine and Freshwater Research,* **50,** 813-829.
Robertson, A. & Rowling, R. (2000) Effects of livestock on riparian zone vegetation in an Australian dryland river. *Regulated Rivers: Research & Management,* **16,** 527-541.
Roeding, C.E. & Smock, L.A. (1989) Ecology of macroinvertebrate shredders in a low-gradient sandy-bottomed stream. *Journal of the North American Benthological Society,* **8,** 149-161.
Roni, P. & Beechie, T. (2013) *Stream and watershed restoration: A guide to restoring riverine processes and habitats*. Wiley-Blackwell.
Roni, P., Bennett, T., Morley, S., Pess, G.R., Hanson, K., Slyke, D.V. & Olmstead, P. (2006a) Rehabilitation of bedrock stream channels: the effects of boulder weir placement on aquatic habitat and biota. *River Research and Applications,* **22,** 967-980.
Roni, P., Hanson, K. & Beechie, T. (2008) Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. *North American Journal of Fisheries Management,* **28,** 856-890.
Roni, P., Morley, S.A., Garcia, P., Detrick, C., King, D. & Beamer, E. (2006b) Coho salmon smolt production from constructed and natural floodplain habitats. *Transactions of the American Fisheries Society,* **135,** 1398-1408.
Roni, P. & Quimby, E. (2005) *Monitoring stream and watershed restoration*. CABI.
Roni, P. & Quinn, T.P. (2001) Effects of wood placement on movements of trout and juvenile coho salmon in natural and artificial stream channels. *Transactions of the American Fisheries Society,* **130,** 675-685.
Rosgen, D.L. (1994) A classification of natural rivers. *Catena,* **22,** 169-199.
Rosgen, D.L. (1996) *Applied river morphology*. Wildland Hydrology, Colorado.
Rosi-Marshall, E.J., Moerke, A.H. & Lamberti, G.A. (2006) Ecological responses to trout habitat rehabilitation in a northern Michigan stream. *Environ Manage,* **38,** 99-107.
Ross, D.H. & Wallace, J.B. (1983) Longitudinal patterns of production, food consumption, and seston utilization by net-spinning caddisflies (Trichoptera) in a Southern Appalachian Stream (USA). *Holarctic Ecology,* **6,** 270-284.

RRC (2011) Practical river restoration appraisal guidance for monitoring options (PRAGMO). *The River Restoration Centre*.
Rubin, J.F., Glimsäter, C. & Jarvi, T. (2004) Characteristics and rehabilitation of the spawning habitats of the sea trout, Salmo trutta, in Gotland (Sweden). *Fisheries management and Ecology,* **11,** 15-22.
Rutherford, J.C., Marsh, N.A., Davies, P.M. & Bunn, S.E. (2004) Effects of patchy shade on stream water temperature: how quickly do small streams heat and cool? *Marine and Freshwater Research,* **55,** 737-748.
Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B. & Kinzig, A. (2000) Global biodiversity scenarios for the year 2100. *Science,* **287,** 1770-1774.
Sarriquet, P.-E., Bordenave, P. & Marmonier, P. (2007) Effects of bottom sediment restoration on interstitial habitat characteristics and benthic macroinvertebrate assemblages in a headwater stream. *River Research and Applications,* **23,** 815-828.
Schiff, R., Benoit, G. & Macbroom, J. (2011) Evaluating stream restoration: a case study from two partially developed 4th order Connecticut, USA streams and evaluation monitoring strategies. *River Research and Applications,* **27,** 431-460.
Schneider, K.N. & Winemiller, K.O. (2008) Structural complexity of woody debris patches influences fish and macroinvertebrate species richness in a temperate floodplain-river system. *Hydrobiologia,* **610,** 235-244.
Schultz, R., Collettil, J., Isenhart, T., Simpkins, W., Mize, C. & Thompson, M. (1995) Design and placement of a multi-species riparian buffer strip system. *Agroforestry Systems,* **29,** 201-226.
Scrimgeour, G., Jones, N. & Tonn, W. (2013) Benthic macroinvertebrate response to habitat restoration in a constructed Arctic stream. *River Research and Applications,* **29,** 352-365.
Sear, D.A., Briggs, A. & Brookes, A. (1998) A preliminary analysis of the morphological adjustment within and downstream of a lowland river subject to river restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **8,** 167-183.
Selego, S.M., Rose, C.L., Merovich, G.T., Welsh, S.A. & Anderson, J.T. (2011) Community-level response of fishes and aquatic macroinvertebrates to stream restoration in a third-order tributary of the Potomac River, USA. *International Journal of Ecology,* **2012**.
Selvakumar, A., O'Connor, T.P. & Struck, S.D. (2010) Role of stream restoration on improving benthic macroinvertebrates and in-stream water quality in an urban watershed: Case study. *Journal of Environmental Engineering-Asce,* **136,** 127-139.
Selvakumar, A., O'Connor, T.P. & Struck, S.D. (2009) Role of stream restoration on improving benthic macroinvertebrates and in-stream water quality in an urban watershed: case study. *Journal of Environmental Engineering,* **136,** 127-139.
Senate, U.S. (1972) Federal water pollution control act.
Shannon, C.E. & Weaver, W. (1949) *The mathematical theory of communication*. University of Illinois Press, Urbana, USA.
Shields, F.D., Cooper, C., Knight, S.S. & Moore, M. (2003a) Stream corridor restoration research: a long and winding road. *Ecological Engineering,* **20,** 441-454.
Shields, F.D., Knight, S.S. & Cooper, C.M. (1994) Effects of channel incision on base flow stream habitats and fishes. *Environ Manage,* **18,** 43-57.

Shields, F.D., Knight, S.S., Morin, N. & Blank, J. (2003b) Response of fishes and aquatic habitats to sand-bed stream restoration using large woody debris. *The Interactions between Sediments and Water*, pp. 251-257. Springer.

Smith, B. & Chadwick, M.A. (2014) Litter decomposition in highly urbanized rivers: influence of restoration on ecosystem function. *Fundamental and Applied Limnology,* **185,** 7-18.

Smith, B., Clifford, N.J. & Mant, J. (2014) The changing nature of river restoration. *Wiley Interdisciplinary Reviews: Water,* **1,** 249-261.

Smith, C.D., Harper, D.M. & Barham, P.J. (1990) Engineering operations and invertebrates: linking hydrology with ecology. *River Research and Applications,* **5,** 89-96.

Smith, C.D., Harper, D.M. & Barham, P.J. (1991) Physical environment for river invertebrate communities. *Project Report, National River Authority (Anglian Region), Operational Investigation A13-38A*.

Smock, L.A. (1980) Relationships between body size and biomass of aquatic insects. *Freshwater Biology,* **10,** 375-383.

Smock, L.A., Gilinsky, E. & Stoneburner, D.L. (1985) Macroinvertebrate production in a southeastern United States blackwater stream. *Ecology,* **66,** 1491-1503.

Smock, L.A., Metzler, G.M. & Gladden, J.E. (1989) Role of debris dams in the structure and functioning of low-gradient headwater streams. *Ecology,* **70,** 764-775.

Snyder, C., Young, J., Villella, R. & Lemarie, D. (2003) Influences of upland and riparian land use patterns on stream biotic integrity. *Landscape Ecology,* **18,** 647-664.

Soar, C.D. & Williamson, W. (1925) *The British Hydracarina, Volume I*. The Ray Society, London.

Soar, C.D. & Williamson, W. (1927) *The British Hydracarina, Volume II*. The Ray Society, London.

Soar, C.D. & Williamson, W. (1929) *The British Hydracarina, Volume III*. The Ray Society, London.

Society for Ecological Restoration (2016).

Solheim, A.L., Austnes, K., Peterlin, M., Kodeš, V., Filippi, R., Semerádová, S., Prchalová, H., Künitzer, A., Spiteri, C., Prins, T. & Collins, R.P. (2012) Ecological and chemical status and pressures in European waters: Thematic assessment for EEA Water 2012 Report.

Soulsby, C., Youngson, A., Moir, H. & Malcolm, I. (2001) Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment. *Science of the Total Environment,* **265,** 295-307.

Southwood, T. (1977) Habitat, the templet for ecological strategies? *The Journal of Animal Ecology***,** 337-365.

Sovell, L.A., Vondracek, B., Frost, J.A. & Mumford, K.G. (2000) Impacts of rotational grazing and riparian buffers on physicochemical and biological characteristics of Southeastern Minnesota, USA, streams. *Environ Manage,* **26,** 629-641.

Spänhoff, B., Riss, W., Jäkel, P., Dakkak, N. & Meyer, E.I. (2006) Effects of an experimental enrichment of instream habitat heterogeneity on the stream bed morphology and chironomid community of a straightened section in a sandy lowland stream. *Environ Manage,* **37,** 247-257.

Sparks, R.E. (1995) Need for ecosystem management of large rivers and their floodplains. *BioScience,* **45,** 168-182.

Sponseller, R.A., Benfield, E.F. & Valett, H.M. (2001) Relationships between land use, spatial scale and stream macroinvertebrate communities. *Freshwater Biology,* **46,** 1409-1424.

Stanford, J.A. & Ward, J.V. (1983) Insect species diversity as a function of environmental variability and disturbance in stream systems. *Stream Ecology: Application and Testing* *of General Ecological Theory* (eds J.R. Barnes & G.W. Minshall), pp. 265-278. Springer US, Boston, MA.

Stauffer, J., Goldstein, R. & Newman, R. (2000) Relationship of wooded riparian zones and runoff potential to fish community composition in agricultural streams. *Canadian Journal of Fisheries and Aquatic Sciences,* **57,** 307-316.

Stranko, S.A., Hilderbrand, R.H. & Palmer, M.A. (2012) Comparing the fish and benthic macroinvertebrate diversity of restored urban streams to reference streams. *Restoration Ecology,* **20,** 747-755.

Sudduth, E.B. & Meyer, J.L. (2006) Effects of bioengineered streambank stabilization on bank habitat and macroinvertebrates in urban streams. *Environ Manage,* **38,** 218-226.

Sundermann, A., Antons, C., Cron, N., Lorenz, A.W., Hering, D. & Haase, P. (2011) Hydromorphological restoration of running waters: Effects on benthic invertebrate assemblages. *Freshwater Biology,* **56,** 1689-1702.

Sundermann, A., Stoll, S. & Haase, P. (2011) River restoration success depends on the species pool of the immediate surroundings. *Ecological Applications,* **21,** 1962-1971.

Sutton, A.J., Fisher, T.R. & Gustafson, A.B. (2010) Effects of restored stream buffers on water quality in non-tidal streams in the Choptank River basin. *Water, Air, and Soil Pollution,* **208,** 101-118.

Tachet, H., Richoux, P., Bournaud, M. & Usseglio-Polatera, P. (2010) *Invertébrés d'eau douce: systématique, biologie, écologie*. CNRS éditions Paris.

Testa, S., Douglas Shields, F. & Cooper, C.M. (2011) Macroinvertebrate response to stream restoration by large wood addition. *Ecohydrology,* **4,** 631-643.

Thomas, H. & Nisbet, T. (2007) An assessment of the impact of floodplain woodland on flood flows. *Water and Environment Journal,* **21,** 114-126.

Thompson, M. (2015) The effect of large woody debris restoration on stream ecosystems. PhD thesis PhD, University College London, UK.

Thompson, R. & Parkinson, S. (2011) Assessing the local effects of riparian restoration on urban streams. *New Zealand Journal of Marine and Freshwater Research,* **45,** 625-636.

Thomson, J.R., Hart, D.D., Charles, D.F., Nightengale, T.L. & Winter, D.M. (2005) Effects of removal of a small dam on downstream macroinvertebrate and algal assemblages in a Pennsylvania stream. *Journal of the North American Benthological Society,* **24,** 192-207.

Thorp, J.H. & Covich, A.P. (2001) An overview of freshwater habitats. *Ecology and classification of North American freshwater invertebrates*, pp. 19-41. Academic Press, San Diego, California, USA.

Tikkanen, P., Laasonen, P., Muotka, T., Huhta, A. & Kuusela, K. (1994) Short-term recovery of benthos following disturbance from stream habitat rehabilitation. *Hydrobiologia,* **273,** 121-130.

Tilman, D., Kilham, S.S. & Kilham, P. (1982) Phytoplankton community ecology: the role of limiting nutrients. *Annual Review of Ecology and Systematics***,** 349-372.

Timm, H. (2003) Typology and classification of freshwaters in Estonia: preliminary results using shallow-water macroinvertebrates. *How to Assess and Monitor Ecological Quality in Freshwaters***,** 164œ169.

Tockner, K., Pennetzdorfer, D., Reiner, N., Schiemer, F. & Ward, J. (1999) Hydrological connectivity, and the exchange of organic matter and nutrients in a dynamic river–floodplain system (Danube, Austria). *Freshwater Biology,* **41,** 521-535.

Tolkamp, H.H. (1980) Organism-substrate relationships in lowland streams. Landbouwhogeschool Wageningen.

Towers, D.J., Henderson, I.M. & Veltman, C.J. (1994) Predicting dry weight of New Zealand aquatic macroinvertebrates from linear dimensions. *New Zealand Journal of Marine and Freshwater Research,* **28,** 159-166.

Townsend, C.R. & Hildrew, A.G. (1994) Species traits in relation to a habitat templet for river systems. *Freshwater Biology,* **31,** 265-275.

Triska, F.J. & Cromack Jr, K. (1980) The role of wood debris in forests and streams. *Forests: fresh perspectives from ecosystem analysis. Oregon State University Press, Corvallis, Oregon, USA***,** 171-190.

Tszydel, M., Grzybkowska, M. & Kruk, A. (2009) Influence of dam removal on trichopteran assemblages in the lowland Drzewiczka River, Poland. *Hydrobiologia,* **630,** 75-89.

Tullos, D.D., Penrose, D.L., Jennings, G.D. & Cope, W.G. (2009) Analysis of functional traits in reconfigured channels: implications for the bioassessment and disturbance of river restoration. *Journal of the North American Benthological Society,* **28,** 80-92.

Usseglio-Polatera, P., Bournaud, M., Richoux, P. & Tachet, H. (2000) Biomonitoring through biological traits of benthic macroinvertebrates: how to use species trait databases? *Hydrobiologia,* **422-423,** 153-162.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. & Cushing, C.E. (1980) The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences,* **37,** 130-137.

Vaughan, I., Diamond, M., Gurnell, A., Hall, K., Jenkins, A., Milner, N., Naylor, L., Sear, D., Woodward, G. & Ormerod, S. (2009) Integrating ecology with hydromorphology: a priority for river science and management. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **19,** 113-125.

Verdonschot, R.C.M., Kail, J., McKie, B.G. & Verdonschot, P.F.M. (2015) The role of benthic microhabitats in determining the effects of hydromorphological river restoration on macroinvertebrates. *Hydrobiologia,* **769,** 55-66.

Violin, C.R., Cada, P., Sudduth, E.B., Hassett, B.A., Penrose, D.L. & Bernhardt, E.S. (2011) Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems. *Ecological Applications,* **21,** 1932-1949.

Vitousek, P.M., Mooney, H.A., Lubchenco, J. & Melillo, J.M. (1997) Human domination of Earth's ecosystems. *Science,* **277,** 494-499.

Wadeson, R. (1994) A geomorphological approach to the identification and classification of instream flow environments. *Southern African Journal of Aquatic Science,* **20,** 38-61.

Wallace, I.D. (2006) *Simple key to caddis larvae*. AIDGAP Field Studies Council.

Wallace, I.D., Wallace, B. & Philipson, G.N. (1990) *A key to the case-bearing caddis larvae of Britain and Ireland*. The freshwater Biological Association, Cumbria, UK.

Wallace, J.B. (1990) Recovery of lotic macroinvertebrate communities from disturbance. *Environ Manage,* **14,** 605-620.

Wallace, J.B., Webster, J.R. & Meyer, J.L. (1995) Influence of log additions on physical and biotic characteristics of a mountain stream. *Canadian Journal of Fisheries and Aquatic Sciences,* **52,** 2120-2137.

Walter, R.C. & Merritts, D.J. (2008) Natural streams and the legacy of water-powered mills. *Science,* **319,** 299-304.

Wang, L., Lyons, J., Kanehl, P. & Gatti, R. (1997) Influences of watershed land use on habitat quality and biotic integrity in Wisconsin streams. *Fisheries,* **22,** 6-12.

Ward, J.V. & Stanford, J.A. (1979) *The ecology of regulated streams*. Plenum Press, New York.

Waringer, J. & Graf, W. (2013) Key and bibliography of the genera of European Trichoptera larvae. *Zootaxa,* **3640,** 101-151.

Waters, T.F. (1979) Influence of benthos life history upon the estimation of secondary production. *Journal of the Fisheries Research Board of Canada,* **36,** 1425-1430.

Webb, A.A. & Erskine, W.D. (2003) Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream: Tonghi Creek, southeastern Australia. *Geomorphology,* **51,** 109-126.

Welland Rivers Trust (2014) Welland for People and Wildlife Newsletter.

Welland Rivers Trust (2015) People and Wildlife Project.

Wenger, S. (1999) A review of the scientific literature on riparian buffer width, extent and vegetation.

Wenzel, F., Meyer, E. & Schwoerbel, J. (1990) Morphometry and biomass determination of dominant mayfly larvae (Ephemeroptera) in running waters. *Archiv für Hydrobiologie,* **118,** 31-46.

Wheaton, J.M., Pasternack, G.B. & Merz, J.E. (2004) Spawning habitat rehabilitation-I. Conceptual approach and methods. *International Journal of River Basin Management,* **2,** 3-20.

White, J.C., Hill, M.J., Bickerton, M.A. & Wood, P.J. (2017) Macroinvertebrate taxonomic and functional trait compositions within lotic habitats affected by river restoration practices. *Environ Manage*, 1-13.

WHO (2005) Ecosystems and human well-being: Health Synthesis: A Report of the Millennium Ecosystem Assessment. Island Press, Washington, DC.

Wilcove, D.S., Rothstein, D., Dubow, J., Phillips, A. & Losos, E. (1998) Quantifying threats to imperiled species in the United States. *BioScience,* **48,** 607-615.

Williams, D.D. & Moore, K.A. (1986) Microhabitat selection by a stream-dwelling amphipod: a muitivariate analysis approach. *Freshwater Biology,* **16,** 115-122.

Williams, D.D. & Williamce, N.E. (1993) The upstream/downstream movement paradox of lotic invertebrates: quantitative evidence from a Welsh mountain stream. *Freshwater Biology,* **30,** 199-218.

Williamson, R.B., Smith, R.K. & Quinn, J.M. (1992) Effects of riparian grazing and channelisation on streams in Southland, New Zealand. 1. Channel form and stability. *New Zealand Journal of Marine and Freshwater Research,* **26,** 241-258.

Wing, M.G. & Skaugset, A. (2002) Relationships of channel characteristics, land ownership, and land use patterns to large woody debris in western Oregon streams. *Canadian Journal of Fisheries and Aquatic Sciences,* **59,** 796-807.

Winking, C. (2015) Ecological evaluation of restored former sewage channels in the urbanised Emscher catchment. PhD thesis PhD, Universität Duisburg-Essen, Germany.

Winterbottom, S.J. (2000) Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. *Geomorphology,* **34,** 195-208.

Wishart, D., Warburton, J. & Bracken, L. (2008) Gravel extraction and planform change in a wandering gravel-bed river: The River Wear, Northern England. *Geomorphology,* **94,** 131-152.

Wolter, C., Lorenz, S., Scheunig, S., Lehmann, N., Schomaker, C., Nastase, A., García de Jalón, D., Marzin, A., Lorenz, A. & Kraková, M. (2013) REFORM D 1.3 Review on ecological response to hydromorphological degradation and restoration. *Project Report REFORM D,* **1**.

Wondzell, S.M., LaNier, J., Haggerty, R., Woodsmith, R.D. & Edwards, R.T. (2009) Changes in hyporheic exchange flow following experimental wood removal in a small, low-gradient stream. *Water Resources Research,* **45**.

Wood, P.J. & Armitage, P.D. (1997) Biological effects of fine sediment in the lotic environment. *Environ Manage,* **21,** 203-217.

Wood, P.J., Armitage, P.D., Hill, M.J., Mathers, K.L. & Millett, J. (2016) Faunal response to fine sediment deposition in urban rivers. *River Science: Research and Management for the 21st Century* (ed. D.J. Gilvear, Greenwood, M. T., Thomas, M. C., Wood, P. J.). John Wiley and Sons Chichester.

Worrall, T.P. (2012) The influence of hydromorphology on instream ecology in lowland rivers. PhD thesis, Loghborough University, UK.

Wortley, L., Hero, J.M. & Howes, M. (2013) Evaluating ecological restoration success: a review of the literature. *Restoration Ecology,* **21,** 537-543.

Wu, J., Cheng, S., Li, Z., Guo, W., Zhong, F. & Yin, D. (2013) Case study on rehabilitation of a polluted urban water body in Yangtze River basin. *Environmental Science and Pollution Research,* **20,** 7038-7045.

Wyżga, B. (2001) Impact of the channelization-induced incision of the Skawa and Wisłoka Rivers, southern Poland, on the conditions of overbank deposition. *Regulated Rivers: Research & Management,* **17,** 85-100.

Yoder, C.O., Miltner, R.J. & White, D. (1999) Assessing the status of aquatic life designated uses in urban and suburban watersheds. *Proc. Natl. Conf. Retrofit Opportunities for Water Resour. Prot. Urban Environ*, pp. 16-28.

Zweig, L.D. & Rabeni, C.F. (2001) Biomonitoring for deposited sediment using benthic invertebrates: a test on 4 Missouri streams. *Journal of the North American Benthological Society,* **20,** 643-657.