**Supplementary material**

**A spatially distributed Clark’s unit hydrograph based hybrid hydrologic model (Distributed-Clark)**

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**Table S1.** Manning’s *n* values for NLCD classifications.

|  |  |  |
| --- | --- | --- |
| NLCD Value | Class | Manning's *n* |
| 11 | Open Water | 0.030 |
| 21 | Developed, Open Space | 0.015 |
| 22 | Developed, Low Intensity | 0.015 |
| 23 | Developed, Medium Intensity | 0.015 |
| 24 | Developed High Intensity | 0.012 |
| 31 | Barren Land (Rock/Sand/Clay) | 0.020 |
| 41 | Deciduous Forest | 0.120 |
| 42 | Evergreen Forest | 0.120 |
| 43 | Mixed Forest | 0.120 |
| 52 | Shrub/Scrub | 0.075 |
| 71 | Grassland/Herbaceous | 0.035 |
| 81 | Pasture/Hay | 0.040 |
| 82 | Cultivated Crops | 0.035 |
| 90 | Woody Wetlands | 0.085 |
| 95 | Emergent Herbaceous Wetlands | 0.075 |

**Table S2.** SCS CN values for NLCD classifications.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| NLCD Value | Class | Hydrologic Soil Group | | | | Imperviousness  (%) |
| A | B | C | D |
| 11 | Open Water | 98 | 98 | 98 | 98 | - |
| 21 | Developed, Open Space | 45 | 65 | 76 | 82 | 10 |
| 22 | Developed, Low Intensity | 60 | 74 | 82 | 86 | 35 |
| 23 | Developed, Medium Intensity | 77 | 85 | 90 | 92 | 65 |
| 24 | Developed High Intensity | 92 | 94 | 96 | 96 | 90 |
| 31 | Barren Land (Rock/Sand/Clay) | 77 | 86 | 91 | 94 | - |
| 41 | Deciduous Forest | 36 | 60 | 73 | 79 | - |
| 42 | Evergreen Forest | 30 | 55 | 70 | 77 | - |
| 43 | Mixed Forest | 30 | 55 | 70 | 77 | - |
| 52 | Shrub/Scrub | 35 | 56 | 70 | 77 | - |
| 71 | Grassland/Herbaceous | 30 | 58 | 71 | 78 | - |
| 81 | Pasture/Hay | 49 | 69 | 79 | 84 | - |
| 82 | Cultivated Crops | 62 | 71 | 78 | 81 | - |
| 90 | Woody Wetlands | 45 | 66 | 77 | 83 | - |
| 95 | Emergent Herbaceous Wetlands | 49 | 69 | 79 | 84 | - |

**Table S3.** Statistical result comparisons of model calibration and validation for spatially distributed and averaged rainfall data simulation (Illinois River). In the row headers, Dist. indicates distributed, Avg. indicates averaged, [D1] and [D2] indicate Distributed-Clark, [H] indicates HEC-HMS, and Diff. indicates differences from averaged output (‘-’ means ‘reduction’ in time to peak). Statistics are for the period of model simulation (for direct runoff), not the total storm event duration.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Storm Events (#) [model] | | Direct Runoff | | | | Streamflow | | | | |
| *E*NS | *R*2 | PBIAS (%) | Total  (mm) | *E*NS | *R*2 | PBIAS (%) | Peak flow (m3/s)  [time, hour] | Total  (mm) |
| 1 | Dist.[D1] | 0.93 | 0.93 | -0.03 | 46.2 | 0.93 | 0.93 | -0.03 | 658.2 [66] | 56.4 |
| Avg.[D2] | 0.95 | 0.95 | -0.09 | 46.2 | 0.95 | 0.95 | -0.07 | 680.7 [66] | 56.4 |
| Diff. | -0.02 | -0.02 | 0.06 | - | -0.02 | -0.02 | 0.04 | -22.5 [-] | - |
| Avg.[H] | 0.86 | 0.86 | 0.08 | 46.2 | 0.86 | 0.86 | 0.06 | 592.2 [65] | 56.4 |
| Diff. | 0.07 | 0.07 | -0.11 | - | 0.07 | 0.07 | -0.09 | 66.0 [1] | - |
| 2 | Dist.[D1] | 0.84 | 0.85 | -0.04 | 28.9 | 0.84 | 0.85 | -0.03 | 487.9 [62] | 34.1 |
| Avg.[D2] | 0.80 | 0.82 | -0.04 | 28.9 | 0.80 | 0.82 | -0.03 | 475.5 [62] | 34.1 |
| Diff. | 0.04 | 0.03 | - | - | 0.04 | 0.03 | - | 12.4 [-] | - |
| Avg.[H] | 0.64 | 0.66 | 0.12 | 28.9 | 0.64 | 0.66 | 0.10 | 434.3 [60] | 34.1 |
| Diff. | 0.20 | 0.19 | -0.16 | - | 0.20 | 0.19 | -0.13 | 53.6 [2] | - |
| 3 | Dist.[D1] | 0.79 | 0.79 | 0.08 | 5.6 | 0.78 | 0.79 | 0.00 | 138.8 [57] | 14.6 |
| Avg.[D2] | 0.76 | 0.77 | 0.05 | 5.6 | 0.75 | 0.76 | -0.01 | 137.2 [57] | 14.6 |
| Diff. | 0.03 | 0.02 | 0.03 | - | 0.03 | 0.03 | 0.01 | 1.6 [-] | - |
| Avg.[H] | 0.54 | 0.54 | -0.11 | 5.6 | 0.52 | 0.52 | -0.08 | 131.2 [56] | 14.6 |
| Diff. | 0.25 | 0.25 | 0.19 | - | 0.26 | 0.27 | 0.08 | 7.6 [1] | - |
| 4 | Dist.[D1] | 0.58 | 0.62 | -0.10 | 6.4 | 0.58 | 0.62 | -0.05 | 129.9 [86] | 13.8 |
| Avg.[D2] | 0.55 | 0.60 | -0.15 | 6.4 | 0.55 | 0.59 | -0.07 | 128.4 [86] | 13.8 |
| Diff. | 0.03 | 0.02 | 0.05 | - | 0.03 | 0.03 | 0.02 | 1.5 [-] | - |
| Avg.[H] | 0.41 | 0.47 | 0.16 | 6.4 | 0.41 | 0.47 | 0.08 | 119.3 [84] | 13.8 |
| Diff. | 0.17 | 0.15 | -0.26 | - | 0.17 | 0.15 | -0.13 | 10.6 [2] | - |
| 5 | Dist.[D1] | 0.70 | 0.74 | 0.13 | 23.3 | 0.70 | 0.74 | 0.12 | 367.6 [68] | 24.8 |
| Avg.[D2] | 0.68 | 0.72 | 0.13 | 23.3 | 0.68 | 0.72 | 0.12 | 364.0 [68] | 24.8 |
| Diff. | 0.02 | 0.02 | - | - | 0.02 | 0.02 | - | 3.6 [-] | - |
| Avg.[H] | 0.60 | 0.63 | 0.50 | 23.3 | 0.60 | 0.63 | 0.47 | 328.6 [69] | 24.8 |
| Diff. | 0.10 | 0.11 | -0.37 | - | 0.10 | 0.11 | -0.35 | 39.0 [-1] | - |
| 6 | Dist.[D1] | 0.79 | 0.82 | 0.01 | 30.0 | 0.79 | 0.82 | 0.01 | 369.8 [77] | 33.9 |
| Avg.[D2] | 0.75 | 0.80 | 0.01 | 30.0 | 0.75 | 0.80 | 0.01 | 368.6 [77] | 33.9 |
| Diff. | 0.04 | 0.02 | - | - | 0.04 | 0.02 | - | 1.2 [-] | - |
| Avg.[H] | 0.32 | 0.47 | 0.13 | 30.0 | 0.32 | 0.47 | 0.11 | 348.5 [73] | 33.9 |
| Diff. | 0.47 | 0.35 | -0.12 | - | 0.47 | 0.35 | -0.10 | 21.3 [4] | - |

**Table S4.** Statistical result comparisons of model calibration and validation for spatially distributed and averaged rainfall data simulation (Elk River). In the row headers, Dist. indicates distributed, Avg. indicates averaged, [D1] and [D2] indicate Distributed-Clark, [H] indicates HEC-HMS, and Diff. indicates differences from averaged output (‘-’ means ‘reduction’ in time to peak). Statistics are for the period of model simulation (for direct runoff), not the total storm event duration.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Storm Events (#) [model] | | Direct Runoff | | | | Streamflow | | | | |
| *E*NS | *R*2 | PBIAS (%) | Total  (mm) | *E*NS | *R*2 | PBIAS (%) | Peak flow (m3/s)  [time, hour] | Total  (mm) |
| 1 | Dist.[D1] | 0.84 | 0.84 | -1.10 | 15.1 | 0.95 | 0.95 | -0.31 | 836.5 [53] | 54.3 |
| Avg.[D2] | 0.84 | 0.84 | -0.89 | 15.1 | 0.95 | 0.95 | -0.25 | 835.9 [53] | 54.3 |
| Diff. | - | - | -0.21 | - | - | - | -0.06 | 0.6 [-] | - |
| Avg.[H] | 0.88 | 0.89 | -0.88 | 15.1 | 0.96 | 0.96 | -0.24 | 800.2 [52] | 54.3 |
| Diff. | -0.04 | -0.05 | -0.22 | - | -0.01 | -0.01 | -0.07 | 36.3 [1] | - |
| 2 | Dist.[D1] | 0.81 | 0.81 | -1.55 | 5.0 | 0.94 | 0.95 | -0.37 | 225.6 [70] | 21.2 |
| Avg.[D2] | 0.83 | 0.83 | -2.08 | 5.0 | 0.95 | 0.95 | -0.50 | 229.3 [69] | 21.2 |
| Diff. | -0.02 | -0.02 | 0.53 | - | -0.01 | - | 0.13 | -3.7 [1] | - |
| Avg.[H] | 0.88 | 0.88 | -1.70 | 5.0 | 0.96 | 0.97 | -0.41 | 236.1 [68] | 21.2 |
| Diff. | -0.07 | -0.07 | 0.15 | - | -0.02 | -0.02 | 0.04 | -10.5 [2] | - |
| 3 | Dist.[D1] | 0.93 | 0.93 | -0.31 | 12.9 | 0.97 | 0.97 | -0.09 | 828.1 [26] | 44.0 |
| Avg.[D2] | 0.88 | 0.89 | -0.41 | 12.9 | 0.95 | 0.96 | -0.12 | 751.3 [26] | 44.0 |
| Diff. | 0.05 | 0.04 | 0.10 | - | 0.02 | 0.01 | 0.03 | 76.8 [-] | - |
| Avg.[H] | 0.79 | 0.81 | -0.23 | 12.9 | 0.92 | 0.93 | -0.07 | 710.9 [30] | 44.0 |
| Diff. | 0.14 | 0.12 | -0.08 | - | 0.05 | 0.04 | -0.02 | 117.2 [-4] | - |
| 4 | Dist.[D1] | 0.86 | 0.89 | -3.08 | 8.8 | 0.95 | 0.96 | -0.78 | 569.1 [38] | 35.7 |
| Avg.[D2] | 0.91 | 0.91 | -2.93 | 8.8 | 0.96 | 0.96 | -0.74 | 502.1 [38] | 35.7 |
| Diff. | -0.05 | -0.02 | -0.15 | - | -0.01 | - | -0.04 | 67.0 [-] | - |
| Avg.[H] | 0.86 | 0.86 | -2.58 | 8.8 | 0.95 | 0.95 | -0.65 | 461.9 [44] | 35.7 |
| Diff. | - | 0.03 | -0.50 | - | - | 0.01 | -0.13 | 107.2 [-6] | - |
| 5 | Dist.[D1] | 0.71 | 0.71 | -1.44 | 4.8 | 0.91 | 0.91 | -0.32 | 245.9 [53] | 22.1 |
| Avg.[D2] | 0.96 | 0.97 | -1.55 | 4.8 | 0.99 | 0.99 | -0.34 | 253.2 [48] | 22.1 |
| Diff. | -0.25 | -0.26 | 0.11 | - | -0.08 | -0.08 | 0.02 | -7.3 [5] | - |
| Avg.[H] | 0.71 | 0.73 | -0.86 | 4.8 | 0.91 | 0.93 | -0.19 | 217.1 [53] | 22.1 |
| Diff. | - | -0.02 | -0.58 | - | - | -0.02 | -0.13 | 28.8 [-] | - |
| 6 | Dist.[D1] | 0.85 | 0.86 | -1.38 | 2.7 | 0.95 | 0.96 | -0.31 | 124.5 [51] | 11.8 |
| Avg.[D2] | 0.69 | 0.70 | -1.08 | 2.7 | 0.89 | 0.91 | -0.24 | 130.2 [54] | 11.8 |
| Diff. | 0.16 | 0.16 | -0.30 | - | 0.06 | 0.05 | -0.07 | -5.7 [-3] | - |
| Avg.[H] | 0.24 | 0.25 | -0.62 | 2.7 | 0.74 | 0.75 | -0.14 | 106.6 [60] | 11.8 |
| Diff. | 0.61 | 0.61 | -0.76 | - | 0.21 | 0.21 | -0.17 | 17.9 [-9] | - |

**Table S5.** Statistical result comparisons of model calibration and validation for spatially distributed and averaged rainfall data simulation (Silver Creek). In the row headers, Dist. indicates distributed, Avg. indicates averaged, [D1] and [D2] indicate Distributed-Clark, [H] indicates HEC-HMS, and Diff. indicates differences from averaged output (‘-’ means ‘reduction’ in time to peak). Statistics are for the period of model simulation (for direct runoff), not the total storm event duration.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Storm Events (#) [model] | | Direct Runoff | | | | Streamflow | | | | |
| *E*NS | *R*2 | PBIAS (%) | Total  (mm) | *E*NS | *R*2 | PBIAS (%) | Peak flow (m3/s)  [time, hour] | Total  (mm) |
| 1 | Dist.[D1] | 0.83 | 0.86 | -0.67 | 10.1 | 0.96 | 0.97 | -0.22 | 99.3 [57] | 30.8 |
| Avg.[D2] | 0.77 | 0.79 | -0.47 | 10.1 | 0.94 | 0.96 | -0.15 | 97.8 [57] | 30.8 |
| Diff. | 0.06 | 0.07 | -0.20 | - | 0.02 | 0.01 | -0.07 | 1.5 [-] | - |
| Avg.[H] | 0.86 | 0.90 | 0.02 | 10.1 | 0.96 | 0.97 | 0.00 | 101.1 [57] | 30.8 |
| Diff. | -0.03 | -0.04 | -0.69 | - | - | - | -0.22 | -1.8 [-] | - |
| 2 | Dist.[D1] | 0.88 | 0.89 | -0.68 | 23.7 | 0.98 | 0.98 | -0.20 | 220.1 [59] | 79.9 |
| Avg.[D2] | 0.88 | 0.89 | -0.29 | 23.7 | 0.98 | 0.98 | -0.09 | 219.7 [59] | 79.9 |
| Diff. | - | - | -0.39 | - | - | - | -0.11 | 0.4 [-] | - |
| Avg.[H] | 0.75 | 0.75 | -0.09 | 23.7 | 0.95 | 0.95 | -0.03 | 229.7 [55] | 79.9 |
| Diff. | 0.13 | 0.14 | -0.59 | - | 0.03 | 0.03 | -0.17 | -9.6 [4] | - |
| 3 | Dist.[D1] | 0.87 | 0.89 | -0.78 | 16.4 | 0.97 | 0.97 | -0.24 | 151.4 [53] | 55.0 |
| Avg.[D2] | 0.80 | 0.81 | -0.84 | 16.4 | 0.96 | 0.96 | -0.25 | 155.6 [48] | 55.0 |
| Diff. | 0.07 | 0.08 | 0.06 | - | 0.01 | 0.01 | 0.01 | -4.2 [5] | - |
| Avg.[H] | 0.75 | 0.76 | -0.69 | 16.4 | 0.95 | 0.95 | -0.21 | 158.9 [48] | 55.0 |
| Diff. | 0.12 | 0.13 | -0.09 | - | 0.02 | 0.02 | -0.03 | -7.5 [5] | - |
| 4 | Dist.[D1] | 0.85 | 0.92 | -0.06 | 11.9 | 0.96 | 0.97 | -0.02 | 118.4 [39] | 37.7 |
| Avg.[D2] | 0.79 | 0.82 | -0.13 | 11.9 | 0.95 | 0.95 | -0.04 | 122.0 [39] | 37.7 |
| Diff. | 0.06 | 0.10 | 0.07 | - | 0.01 | 0.02 | 0.02 | -3.6 [-] | - |
| Avg.[H] | 0.72 | 0.75 | -0.17 | 11.9 | 0.93 | 0.93 | -0.06 | 124.7 [38] | 37.7 |
| Diff. | 0.13 | 0.17 | 0.11 | - | 0.03 | 0.04 | 0.04 | -6.3 [1] | - |
| 5 | Dist.[D1] | 0.75 | 0.76 | -0.39 | 14.4 | 0.94 | 0.94 | -0.12 | 143.3 [47] | 48.2 |
| Avg.[D2] | 0.75 | 0.76 | -0.39 | 14.4 | 0.94 | 0.94 | -0.12 | 143.3 [47] | 48.2 |
| Diff. | - | - | - | - | - | - | - | - [-] | - |
| Avg.[H] | 0.67 | 0.67 | -0.42 | 14.4 | 0.92 | 0.92 | -0.13 | 147.3 [47] | 48.2 |
| Diff. | 0.08 | 0.09 | 0.03 | - | 0.02 | 0.02 | 0.01 | -4.0 [-] | - |
| 6 | Dist.[D1] | 0.65 | 0.71 | -0.38 | 6.4 | 0.88 | 0.88 | -0.11 | 74.7 [36] | 21.1 |
| Avg.[D2] | 0.48 | 0.48 | -0.43 | 6.4 | 0.82 | 0.82 | -0.13 | 77.6 [35] | 21.1 |
| Diff. | 0.17 | 0.23 | 0.05 | - | 0.06 | 0.06 | 0.02 | -2.9 [1] | - |
| Avg.[H] | 0.39 | 0.39 | -0.10 | 6.4 | 0.79 | 0.80 | -0.03 | 79.1 [35] | 21.1 |
| Diff. | 0.26 | 0.32 | -0.28 | - | 0.09 | 0.08 | -0.08 | -4.4 [1] | - |

**Table S6.** Statistical result comparisons of model calibration and validation for spatially distributed and averaged rainfall data simulation (Muscatatuck River). In the row headers, Dist. indicates distributed, Avg. indicates averaged, [D1] and [D2] indicate Distributed-Clark, [H] indicates HEC-HMS, and Diff. indicates differences from averaged output (‘-’ means ‘reduction’ in time to peak). Statistics are for the period of model simulation (for direct runoff), not the total storm event duration.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Storm Events (#) [model] | | Direct Runoff | | | | Streamflow | | | | |
| *E*NS | *R*2 | PBIAS (%) | Total  (mm) | *E*NS | *R*2 | PBIAS (%) | Peak flow (m3/s)  [time, hour] | Total  (mm) |
| 1 | Dist.[D1] | 0.96 | 0.97 | -1.30 | 27.8 | 0.98 | 0.99 | -0.65 | 426.9 [32] | 55.8 |
| Avg.[D2] | 0.95 | 0.97 | -1.38 | 27.8 | 0.98 | 0.99 | -0.69 | 433.6 [33] | 55.8 |
| Diff. | 0.01 | - | 0.08 | - | - | - | 0.04 | -6.7 [-1] | - |
| Avg.[H] | 0.97 | 0.97 | -1.03 | 27.8 | 0.99 | 0.99 | -0.51 | 408.2 [33] | 55.8 |
| Diff. | -0.01 | - | -0.27 | - | -0.01 | - | -0.14 | 18.7 [-1] | - |
| 2 | Dist.[D1] | 0.91 | 0.92 | -1.62 | 9.0 | 0.95 | 0.95 | -0.83 | 133.8 [51] | 17.5 |
| Avg.[D2] | 0.86 | 0.90 | -2.02 | 9.0 | 0.92 | 0.94 | -1.04 | 139.2 [51] | 17.5 |
| Diff. | 0.05 | 0.02 | 0.40 | - | 0.03 | 0.01 | 0.21 | -5.4 [-] | - |
| Avg.[H] | 0.92 | 0.93 | -1.69 | 9.0 | 0.96 | 0.96 | -0.87 | 127.1 [51] | 17.5 |
| Diff. | -0.01 | -0.01 | 0.07 | - | -0.01 | -0.01 | 0.04 | 6.7 [-] | - |
| 3 | Dist.[D1] | 0.96 | 0.96 | -4.72 | 41.1 | 0.98 | 0.98 | -2.57 | 562.6 [52] | 76.7 |
| Avg.[D2] | 0.96 | 0.96 | -4.75 | 41.1 | 0.98 | 0.98 | -2.58 | 592.0 [51] | 76.7 |
| Diff. | - | - | 0.03 | - | - | - | 0.01 | -29.4 [1] | - |
| Avg.[H] | 0.96 | 0.97 | -4.39 | 41.1 | 0.98 | 0.98 | -2.39 | 535.7 [51] | 76.7 |
| Diff. | - | -0.01 | -0.33 | - | - | - | -0.18 | 26.9 [1] | - |
| 4 | Dist.[D1] | 0.98 | 0.98 | -0.09 | 11.7 | 0.99 | 0.99 | -0.04 | 218.2 [26] | 22.8 |
| Avg.[D2] | 0.98 | 0.98 | -0.13 | 11.7 | 0.99 | 0.99 | -0.07 | 210.6 [27] | 22.8 |
| Diff. | - | - | 0.04 | - | - | - | 0.03 | 7.6 [-1] | - |
| Avg.[H] | 0.87 | 0.88 | 0.15 | 11.7 | 0.94 | 0.95 | 0.08 | 222.2 [28] | 22.8 |
| Diff. | 0.11 | 0.10 | -0.24 | - | 0.05 | 0.04 | -0.12 | -4.0 [-2] | - |
| 5 | Dist.[D1] | 0.98 | 0.98 | -0.49 | 21.3 | 0.99 | 0.99 | -0.24 | 364.5 [40] | 42.5 |
| Avg.[D2] | 0.97 | 0.97 | -0.48 | 21.3 | 0.99 | 0.99 | -0.24 | 368.7 [41] | 42.5 |
| Diff. | 0.01 | 0.01 | -0.01 | - | - | - | - | -4.2 [-1] | - |
| Avg.[H] | 0.98 | 0.98 | -0.50 | 21.3 | 0.99 | 0.99 | -0.25 | 345.0 [40] | 42.5 |
| Diff. | - | - | 0.01 | - | - | - | 0.01 | 19.5 [-] | - |
| 6 | Dist.[D1] | 0.87 | 0.91 | -0.25 | 13.1 | 0.95 | 0.95 | -0.13 | 213.5 [28] | 26.0 |
| Avg.[D2] | 0.89 | 0.93 | -0.15 | 13.1 | 0.95 | 0.96 | -0.08 | 214.6 [28] | 26.0 |
| Diff. | -0.02 | -0.02 | -0.10 | - | - | -0.01 | -0.05 | -1.1 [-] | - |
| Avg.[H] | 0.80 | 0.83 | 0.04 | 13.1 | 0.92 | 0.92 | 0.02 | 192.5 [28] | 26.0 |
| Diff. | 0.07 | 0.08 | -0.29 | - | 0.03 | 0.03 | -0.15 | 21.0 [-] | - |