Computational approach to improving efficiency of river discharge measurement

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Abstract

In this work we propose a simple computational scheme with the pragmatic purpose of augmenting the efficiency of river discharge measurements. Observing the functional form of the velocity profile versus depth, applying polynomial regression for each vertical, and finally interpolating between the verticals, we arrive at a continuous approximation for the velocity across the entire vertical section, which turns out to be rather robust to removal of individual measurement points. In particular, numerical data analysis shows that the number of measurements can be significantly reduced without a significant loss of precision of the discharge estimate. This procedure has been tested on the data obtained experimentally on Exu, Capibaribe and Ipojuca rivers, in the state of Pernambuco, northeast of Brazil, with different stream flow patterns demonstrating multiple local velocity maxima on and below the surface.

Keywords: discharge measurement, numerical procedure, optimization, area-velocity method

1. Introduction

Measurement of discharge of rivers and open channels represents a fundamental ingredient for diverse studies on environmental impact, such as propagation of pollutants released by urban centers and factories (West and Woesik, 2001; Muller-Wohlfeil et al., 2003), and degradation of river basins through soil erosion and transport (sediment production) (Edwards and Glusson, 1999; Horowitz, 2003). The area-velocity method is the current standard adopted by the international community for river discharge measurement. This procedure, standardized by the International Standards Organization (ISO) norm ISO 748 (2007) on the international level, involves measurement of velocity at various verticals of a river cross section, at different depths for each vertical, and is based on the pioneering works of Buchann and Somers (1969) and Rantz (1982).

Generally speaking, a relatively large number of measurements is necessary for estimating discharge, representing a difficult and costly task. In practice, river discharge measurements are often performed at a given site (gauging station) for various values of the water level, in order to synthesize the so called rating curves (phenomenological discharge dependence on level, or stage), which are then used for analyzing and modeling the river hydraulic behavior.

The uncertainty of the final discharge estimate depends on the equipment used, but also on the strategy employed, with the basic rule: the more measurements made, the better the result. The uncertainty of the final discharge estimate should be calculated using the prescription defined in the accompanying standard ISO 1088 (2007), wherefrom it follows that increasing density of measurement (with the same equipment) in both horizontal and vertical directions leads to the decrease in uncertainty.

The conflicting goals of minimizing the uncertainty and minimizing the cost often lead to difficult decisions regarding planning the experiment, in particular in developing countries where resources are scarce. It is therefore not uncommon in the literature to find studies that do not follow to the letter the recommendations of the standard ISO 748 (2007), as well as those that do not perform uncertainty calculations as per recommendations of ISO 1088 (2007).

A line of research with notable contributions to

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augmenting the efficiency of discharge measurements, based on entropy maximization formalism, has been carried outover the last couple of decades (Chiu, 1987, 1989; Chiu and Murray, 1992; Chiu and Said, 1995; Chiu and Tung, 2002; Moramarco and Singh, 2010; Moramarco et al., 2011, 2013, 2014). The model with this formalism specifies the cross sectional velocity distribution in open channels in two dimensions using a curvilinear coordinate system, depending on the cross section geometry, and captures well the velocity profile with a unique maximum located at or below the surface (caused by the proximity of lateral walls in narrow channels, or secondary currents), as well as the details of the velocity profile close to the river bed, affected by sediment transport (Chiu, 1989). On the other hand, this model requires as many as six parameters in the two dimensional case, which are rather difficult to estimate. Besides, a recent study using massive historical data for four gauged stations in the upper Tiber River basin in central Italy (Moramarco et al., 2004) demonstrates that the two dimensional maximum entropy model does not always reproduce well the phenomenological velocity profile observations (in particular at verticals close to the river banks), and instead proposes an application of the one dimensional (single vertical velocity profile) maximum entropy model through a second order polynomial fit along the horizontal direction (see Moramarco et al. (2004) for details). Also, while the two dimensional maximum entropy approach is able to explain single humped velocity profiles caused by the bank proximity in narrow channels (where a single velocity maximum is observed below the surface), it does not apply to situations where multiple local velocity maxima are observed, as may be the case in the presence of large boulders or river bifurcation in the proximity of the river cross section under study.

In the current work we propose an alternative, simple and pragmatic, albeit computationally intensive technique, that is found to be rather versatile and is able to capture multiple velocity maxima at or below the surface. We believe that the current approach may help diminish the cost benefit ratio of discharge measurements, which may be found helpful in the cases where the resources are stretched. While it is certainly to be expected that in the hopefully not too distant future low cost automated measurement equipment will become readily available, the current abundance of affordable but powerful computer hardware makes us believe that the approach proposed here may be useful for years to come. In this spirit, we also provide software implementing the method proposed in this work, available for (free) download Stosic et al. (2016).

In what follows, we first describe the methodology, then we present the results and discuss the implications of our approach, and finally we draw the conclusions.

2. Methodology

We begin this section by briefly reviewing the well-known area-velocity method, together with the standard approach to determining the uncertainty of measurement results.

2.1. The area-velocity method

The international standard ISO 748 (2007), based on works of Buchann and Somers (1969) and Rantz (1982) defines the area-velocity method for measurement of discharge Q of a river as the sum of partial discharge values q_i defined as products of average velocity $\overline{v_i}$ and respective areas A_i of multiple vertical polygonal segments ($i = 1, \ldots, N$) comprising the river cross section (as shown schematically in Fig. 1)

$$Q = \sum_{i=1}^{N} q_i = \sum_{i=1}^{N} A_i \, \overline{v_i} \quad . \tag{1}$$

The choice of the number of vertical segments depends on the river width, where any one segment should not contribute with more than 5% of the total flux, insofar as possible, and should in no case exceed 10%.

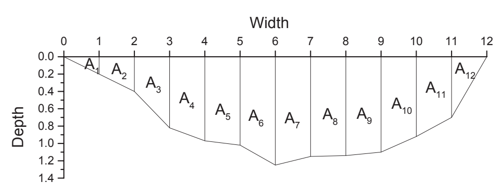


Figure 1: Schematic representation of a river cross section, divided in twelve vertical polygonal segments, with areas $A_1, A_2, \ldots, A_{12}$.

Areas A_i ($i = 1, \ldots N$) of the individual vertical segments are approximated by trapezoids, calculated as the product of the width of the segment multiplied by the average depth (arithmetic average of the depth at the lateral sides).

Finally, the average velocity $\overline{v_i}$ of each segment is determined using multiple velocity measurements at different depths, where the one, two and three point methods seem to be the most common in practice.

2.2. Uncertainty estimate

Discharge estimate using the area-velocity method involves measurement of width b_i and depth d_i of vertical segments (verticals) $i = 1, \ldots, m$, as well as velocity at multiple points at each vertical, and the uncertainty of this estimate depends on the combination of uncertainties of the individual components. The ISO 1088 (2007) standard provides recommendations for calculating the uncertainty using the formula

$$u(Q)^2 = u_m^2 + u_s^2 + \frac{\sum_{i=1}^{m} (b_i d_i \, \overline{v_i})^2 \, u_i^2}{\sum_{i=1}^{m} (b_i d_i \, \overline{v_i})^2} \quad , \tag{2}$$

with

$$u_i^2 = u_{b,i}^2 + u_{d,i}^2 + u_{p,i}^2 + \frac{1}{n_i}\left(u_{c,i}^2 + u_{e,i}^2\right) \quad ,$$

where $u(Q)$ is the relative standard uncertainty of the estimated discharge Q (confidence level 68%), u_m is the relative uncertainty due to the limited number of verticals m, u_s is the relative uncertainty due to calibration errors (of the current-meter, width measurement instrument, and depth sounding instrument), $u_{b,i}$ and $u_{d,i}$ are the relative (percentage) standard uncertainties in the width and depth measurements of vertical i, while $u_{p,i}$ represents the uncertainty associated with determining the mean velocity $\overline{v_i}$ corresponding to the discrete limited number n_i of depths at which velocity measurements are made at vertical i, $u_{c,i}$ represents the uncertainty in point velocity at a particular depth along vertical i due to variable responsiveness of the current-meter, and $u_{e,i}$ the uncertainty in point velocity at a particular depth along vertical i due to velocity fluctuations (pulsations) in the stream.

Finally, the expanded uncertainty for the coverage factor k is given by $U_k(Q) = k\,u(Q)$, where e.g. for $k = 2$ the confidence interval corresponds to 95% and for $k = 3$ the confidence interval corresponds to 99%.

The above description in fact represents a rather succinct overview of the uncertainty estimate procedure prescribed by ISO 1088 (2007) standard, which goes on to suggest a precise recipe (on the basis of massive phenomenological studies) on how to estimate the individual uncertainty components in the informative Annex G.

2.3. Numerical interpolation

In order to introduce the numerical interpolation scheme proposed in this work, consider a virtual mechanical system for fluid flow in the z direction, with the (x, y) cross-section represented by the union of the actual observed cross-section profile, and its reflection

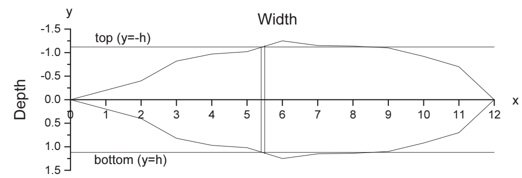


Figure 2: Schematic representation of a virtual fluid flow system obtained by the union of the actual observed river profile, and its reflection about the surface line. The flow direction z is perpendicular to the plane of the figure.

(mirror image) about the x axis (the surface line), as shown schematically in Fig. 2.

By construction, the velocity flow profile of this virtual system should be symmetric about the $x = 0$ axis with zero velocity at the bottom ($y = h$) and top ($y = -h$), and therefore, for the velocity profile at a given vertical x (having depth $h(x)$) one may postulate the general polynomial functional form

$$v(x, y) = a(x) + b(x)(y - h(x))^2 + c(x)(y - h(x))^4, \tag{3}$$

where only even powers of the distance $d(x) \equiv y - h(x)$ from the $y = 0$ axis (surface) have been included because of symmetry. One may then perform polynomial regression using measured data points for each vertical x_i to find the corresponding coefficients a_i, b_i and c_i.

The motivation for the current virtual image scheme and postulating functional form (3) comes from the solution of the Navier-Stokes equations for the elementary case of constant laminar flow between infinite parallel plates. In the case of constant laminar flow in the direction x of uncompressible fluid with viscosity μ, under constant pressure gradient $g \equiv \partial p / \partial x$, positioning the coordinate system at the central vertical position between the plates one arrives at the solution

$$v(x) = \frac{g}{2\mu}(y^2 - h^2) \tag{4}$$

where h is the distance from the origin to each of the plates, in the vertical y direction. Since the factor in front of parentheses on the right hand side of (4) is constant, the velocity profile is described by a simple quadratic curve, where velocity is zero at the plates ($y = \pm h$), and assumes maximum value at the center between the plates ($y = 0$). Equation (3) represents a generalization of (4) assuming that the *functional form* of the velocity profile should be polynomial in the y direction and symmetric about the central position, as it seems unlikely that the velocity profile would turn e.g. exponential, in contrast to quadratic for the highly simplified case of parallel plates.

The advantage of the current virtual image artifact is that already a single velocity measurement point (together with depth information at a given vertical, corresponding to zero velocity) yields sufficient information for estimating the velocity profile when velocity maximum is found on the surface, while only two velocity measurements on a vertical, together with depth information, are sufficient for estimating the velocity profile when the velocity maximum is found below the surface. More precisely, if only a single measurement is available at vertical i of depth h_i, first an additional point is added with zero velocity at h_i (bottom), next these two points are reflected about the $y = 0$ axis representing their "negative depth" mirror images, and finally the resulting set of a total of 4 points is used in polynomial regression using equation (3) with $c_i = 0$ (a two parameter model is sufficient for a single maximum at the surface) to determine parameters a_i and b_i, yielding the velocity profile estimate.

In a more general case when a total of n measurements are available at vertical i of depth h_i, first an additional point is added with zero velocity at h_i (bottom), next all the $n + 1$ points are reflected to negative depths (bottom is reflected to top), and finally the resulting set of a total of $2(n + 1)$ points is used in the polynomial regression.

An empirical example is shown in Fig. 3a for three measurements of velocity (0.71m/s at depth 0.23m, 0.47m/s at 0.69m and 0.24m/s at 0.92m) at a vertical 1.15m deep. Regression to a second degree polynomial (setting $c = 0$) performed for all the points yields $a = 0.735$ and $b = -0.564$, while regression using a single point closest to the surface and the depth information yields $a = 0.739$ and $b = -0.559$, the two curves being hardly distinguishable from each other on the scale of the graph.

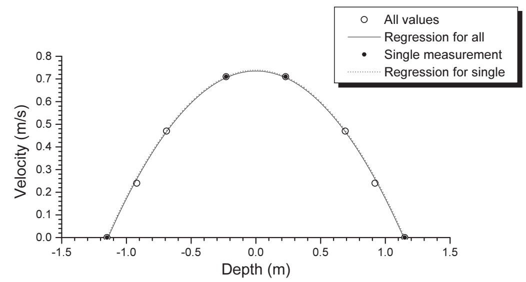
Results of this procedure for $n = 5$ velocity measurements when velocity maximum was found below the surface are shown in Fig. 3b together with a fourth degree polynomial fit using equation (3). In Fig. 3b the error bars corresponding to point velocity measurements are also depicted, together with the upper and lower bound regression polynomials represented by dotted lines. The uncertainty of an individual point velocity measurement at a particular depth j along vertical i is given by

$$u_{p,ij}^2 = u_s^2 + u_{c,ij}^2 + u_{e,ij}^2 \tag{5}$$

where u_s is the relative uncertainty due to calibration errors of the current-meter, $u_{c,ij}$ represents the uncertainty in point velocity due to variable responsiveness of the current-meter, and $u_{e,ij}$ the uncertainty in point velocity at a particular depth along vertical i due to velocity fluctuations (pulsations) in the stream. The lower and the upper bound polynomial estimates correspond to the uncertainty of the coefficients a, b and c in equation (3).

In what follows, this procedure is implemented for every vertical where measurements were made, and then interpolation between the verticals is performed to yield the full cross-section velocity profile, from which the discharge estimate is finally extracted. For interpolating between the verticals we use linear interpolation of the regression coefficients between the verticals.

a)



b)

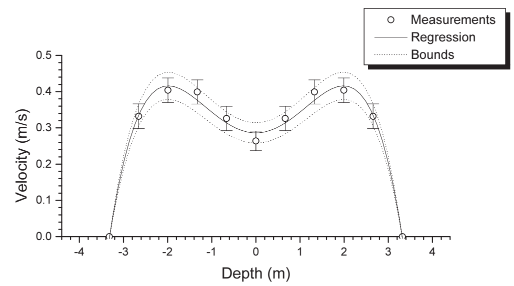


Figure 3: Polynomial regression using equation (3) for a) three measurement points with the velocity maximum on the surface, and b) five measurement points with the velocity maximum below the surface, together with the zero velocity point at the bottom, and their reflections (see text for details).

3. Results and discussion

The data used in this work were collected on River Exu in April 2008, River Ipojuca in June 2009, and River Capibaribe in August 2009, all three situated in the state of Pernambuco in northeast Brazil, as part of a larger prospective phenomenological study (Cunha, 2010). The measurements were performed with a standard current meter at several depths for each vertical section (as prescribed by ISO 748 (2007)). The three rivers under study represent examples of a single and multiple velocity maxima, on and below the surface.

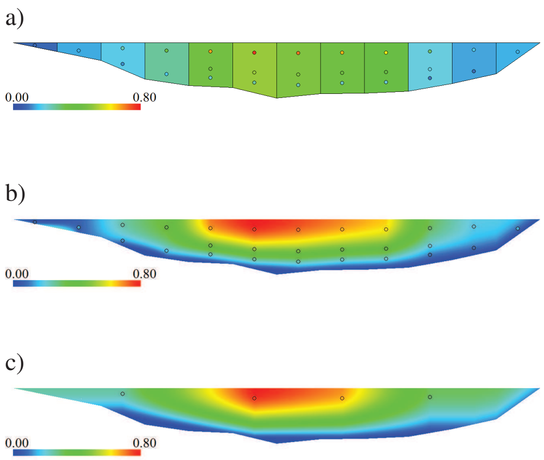


Figure 4: Velocity profiles for the River Exu data collected in the morning of April 14, 2008, using the a) standard area-velocity method, and vertical polynomial regression with linear interpolation between the verticals using b) all the 27 available measurement points, and c) using only 4 measurement points. Velocity profile is color coded according to the color bars. The polygonal segments (color coded to average velocity) in a) are 1m wide, and the depth is to scale.

In Fig. 4 we present the velocity profiles obtained through the standard area-velocity method for the River Exu, for a total of 27 measurement points at 12 vertical segments corresponding to a single velocity maximum on the surface, together with the proposed polynomial regression numerical scheme with linear interpolation between the verticals.

It is seen from Fig. 4b that the proposed numerical procedure provides a rather realistic, smooth velocity profile. It was found while experimenting with the measured data points that the current method is rather robust with respect to the removal of experimental data points. To corroborate this finding, in Fig. 4c we also display the velocity profiles obtained using *only 4 points* from the original measured dataset, where some of the verticals have been omitted altogether. Comparing Fig. 4b where all the 27 measurement points were used in the proposed numerical procedure, and Fig. 5c where only 4 measurements were used, it follows that substantial savings may be made without significant loss of accuracy. The reader is invited to experiment with his/her own data, using our program implementing a friendly graphical user interface Stosic et al. (2016).

In Fig. 5 and Fig. 6 we present the velocity profiles for the measurements on River Ipojuca and on River Capibaribe, which present multiple local velocity maxima located on and below the surface, therefore representing a situation not amenable to the maximum entropy formalism (Chiu, 1987, 1989; Chiu and Murray, 1992; Chiu and Said, 1995; Chiu and Tung, 2002; Moramarco and Singh, 2010; Moramarco et al., 2011, 2013,

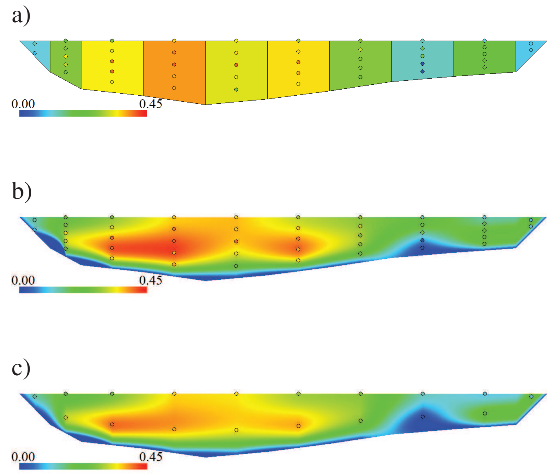


Figure 5: Velocity profiles for River Ipojuca data collected on June 2, 2009, using the a) standard area-velocity method, and vertical polynomial regression with linear interpolation between the verticals using b) all the 44 available measurement points, and c) using only 18 measurement points. The polygonal segments depicted in a) are 2m wide at the edges, and 4m wide in the interior, while the depth is to scale.

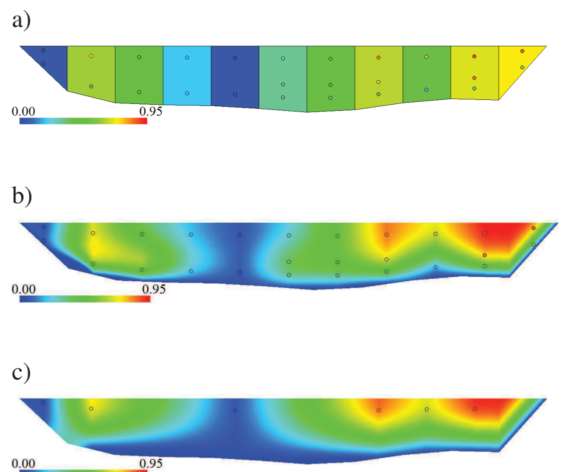


Figure 6: Velocity profiles for River Capibaribe data collected on August 6, 2009, using the a) standard area-velocity method, and vertical polynomial regression with linear interpolation between the verticals using b) all the 26 available measurement points, and c) using only 6 measurement points. The polygonal segments depicted in a) are 1m wide, and the depth is to scale.

2014). As before, the standard area-velocity method is presented together with the proposed polynomial regression numerical scheme with linear interpolation between the verticals. Along with the interpolations using the full set of measurements, calculations using a subset of data points are also presented, demonstrating the robustness of the proposed interpolation approach to the removal of data points. In the case of River Ipojuca where velocity maxima are located below the surface we have used at most two (out of five available) data points for each vertical, and in the case of River Capibaribe with multiple velocity maxima located on the surface we have used only a single data point for each vertical, where some of the verticals have been omitted.

Again a rather realistic cross sectional velocity profile is observed in both cases, in spite of rather complicated phenomenological velocity profiles with multiple distinct streamflows, where in the case of the River Capibaribe one of the velocity maxima is located very close to the right bank. This complicated velocity profile behavior stems mostly from the presence of weeds on the bottom in the case of River Ipojuca, and the geometry of the River Capibaribe with large boulders immediately before, and a bifurcation with a sharp bend to the right after the place of measurement.

To corroborate quantitatively the observed robustness of the proposed numerical interpolation scheme with regard to removal of measurement points, we compare in Table 1 the area-velocity discharge results with the discharge estimates obtained using the interpolation scheme with all the data points, and with the reduced number of points.

Table 1: Discharge calculation results (in m^3/s) for rivers Exu, Ipojuca and Capibaribe, using the standard area-velocity method Q_{av}, and the proposed numerical interpolation scheme using all the available measurements Q_{na} as well as a reduced number of measurement points Q_{nr}. The number of verticals is denoted by N_v, the total number of measurements is N_m, and the reduced number of points used for the NR approximation is N_r, while the uncertainty of the corresponding estimates (standard deviation, in m^3/s) is represented by σ_{av}, σ_{na} and σ_{nr}, respectively.

River	N_v	N_m	Q_{av}	σ_{av}	Q_{na}	σ_{na}	N_r	Q_{nr}	σ_{nr}
Exu	12	27	3.29	0.21	3.33	0.18	4	3.35	0.16
Ipojuca	10	44	28.3	1.69	25.1	1.33	18	23.8	1.25
Capibaribe	11	26	5.00	0.32	4.76	0.24	6	4.10	0.22

The uncertainty estimates σ_{av} (confidence level 68%) for the area velocity calculations were obtained using recommendations of the ISO 1088 (2007) standard, with the details outlined in the informative Annex G. To calculate the absolute standard uncertainties σ_{na} and σ_{nr} of the interpolation discharge estimates Q_{na} and Q_{nr} in Table 1, respectively, first interpolation was performed using upper and lower bounds for the individual point velocity measurements (obtained using equation (5) with recommendations from Annex G of ISO 1088 (2007) standard) in each case. In addition to the relative uncertainty $\sigma_p = (Q_{max} - Q_{min})/2Q$ obtained in this way, stemming from the individual point velocity measurement uncertainties, the spacing of interpolation grid was also taken into account. More precisely, while the proposed interpolation scheme may be implemented with arbitrary precision, we have found empirically that the choice of the grid with 1000-2000 spacings along the horizontal river span (corresponding to the resolution of modern day monitor screens) produces variation of not more than 1% of the interpolation estimate. Therefore, the absolute standard uncertainties σ_{na} and σ_{nr} in Table 1 were calculated from the relative uncertainty $u = \sqrt{u_p^2 + u_g^2}$, where we have taken $u_g = 0.01$ for the relative uncertainty stemming from the choice of grid spacing.

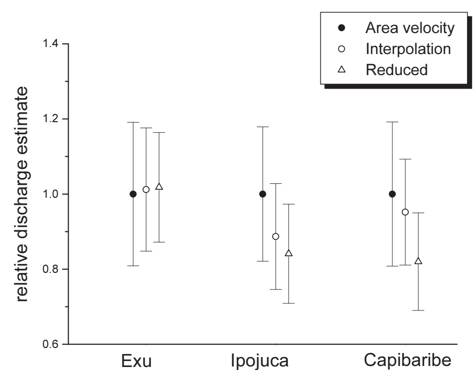


Figure 7: Relative discharge estimates for numerical interpolation using all points Q_{na}/Q_{av}, and interpolation using the reduced number of points Q_{nr}/Q_{av}, with error bars corresponding to coverage factor $k = 3$ (99% confidence interval).

The relative discharge estimates together with error bars are shown in Fig. 7, where it is seen that the error bars for all the calculations (area velocity, numerical interpolation using all measurements, and interpolation using a reduced number of measurements) strongly overlap for the coverage factor $k = 3$ (99% confidence interval). It therefore follows that application of the numerical procedure proposed in this work may lead to substantial savings (with the results falling within uncertainty estimates of the 99% confidence interval of the area-velocity standard), which may be of fundamental importance in countries under development, where resources are often scarce. Moreover, the current approach is conceptually simpler than the entropy maximization approach (Chiu, 1987, 1989; Chiu and Murray, 1992; Chiu and Said, 1995; Chiu and Tung, 2002; Moramarco and Singh, 2010; Moramarco et al., 2011, 2013, 2014), and turns out more flexible for describing stream flows with multiple local velocity maxima, at and below the surface.

4. Conclusions

In this work we propose a numerical procedure, consisting of two distinct steps: i) polynomial regression of data for every vertical, and ii) linear interpolation of the resultant polynomial coefficients between the verticals.

The proposed procedure turns out to be rather robust to the removal of measurement data points, where in the current experimental setup of River Exu, roughly 15% of data points as prescribed by the ISO 748 (2007) standard are found to be sufficient for determining the discharge within 68% uncertainty bounds ($\pm\sigma$) calculated according to standard ISO 1088 (2007). In the case of measurements on River Capibaribe with multiple local velocity maxima below the surface, reducing the number of measurements from 44 to 18 still yields a rather realistic velocity profile, while for the measurements on River Ipojuca with three local velocity maxima on the surface, reducing the number of measurements from 26 to 6 also yields a realistic velocity profile, both within 99% uncertainty bounds ($\pm 3\sigma$) as per standard ISO 1088 (2007).

The numerical interpolation method proposed in this work should be further tested in different situations, such as wider and/or deeper rivers, and waterbeds with multiple shallow and deep sections. Also, stringent criteria should be established for the positioning of the reduced set of measurements that yield a satisfactory result in different situations. An application of Monte Carlo Markov Chain method for establishing the optimum number of measurements and their positions has been proposed and tested for the case of velocity maxima on the surface Stosic et al. (2012), however, testing the validity of this approach and establishing stringent critera for more general cases requires a massive body of experimental data. We therefore encourage researchers to download and experiment with the user friendly software implementing the numerical approach proposed in this work Stosic et al. (2016).

Acknowledgments

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