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Considering sampling strategy and cross-section complexity for estimating the uncertainty of discharge measurements using the velocity-area method

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S U M M A R Y

Streamflow time series provide baseline data for many hydrological investigations. Errors in the data mainly occur through uncertainty in gauging (measurement uncertainty) and uncertainty in the determination of the stage-discharge relationship based on gaugings (rating curve uncertainty). As the velocity-area method is the measurement technique typically used for gaugings, it is fundamental to estimate its level of uncertainty. Different methods are available in the literature (*ISO* 748, $Q+$, *IVE*), all with their own limitations and drawbacks. Among the terms forming the combined relative uncertainty in measured discharge, the uncertainty component relating to the limited number of verticals often includes a large part of the relative uncertainty. It should therefore be estimated carefully. In *ISO* 748 standard, proposed values of this uncertainty component only depend on the number of verticals without considering their distribution with respect to the depth and velocity cross-sectional profiles. The $Q+$ method is sensitive to a user-defined parameter while it is questionable whether the *IVE* method is applicable to stream-gaugings performed with a limited number of verticals. To address the limitations of existing methods, this paper presents a new methodology, called FLow Analog UnceRtainty Estimation (Flaure), to estimate the uncertainty component relating to the limited number of verticals. High-resolution reference gaugings (with 31 and more verticals) are used to assess the uncertainty component through a statistical analysis. Instead of subsampling purely randomly the verticals of these reference stream-gaugings, a subsampling method is developed in a way that mimicks the behavior of a hydrometric technician. A sampling quality index (SQI) is suggested and appears to be a more explanatory variable than the number of verticals. This index takes into account the spacing between verticals and the variation of unit flow between two verticals. To compute the uncertainty component for any routine gauging, the four most similar gaugings among the reference stream-gaugings dataset are selected using an analog approach, where analogy includes both riverbed shape and flow distribution complexity. This new method was applied to 3185 stream-gaugings with various flow conditions and compared with the other methods (*ISO* 748, *IVE*, $Q+$ with a simple automated parametrization). Results show that Flaure is overall consistent with the $Q+$ method but not with *ISO* 748 and *IVE* methods, which produce clearly overestimated uncertainties for discharge measurements with less than 15 verticals. The Flaure approach therefore appears to be a consistent method. An advantage is the explicit link made between the estimation of cross-sectional interpolation errors and the study of high-resolution reference gaugings.

1. Introduction

Hydrometric data are essential for many hydrological issues such as calibration of hydrological models, flood forecasting and warning (using hydrological modeling), engineering design (of dam or dyke for example) and policy decisions related to water

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resource management. For day-to-day power production operations including safety issues and water resource management, the *Division Technique Générale* (DTG) of *Électricité de France* (EDF) operates a hydrometric network. It includes about 300 hydrometric stations mainly spread on the mountainous regions of France (Alps, Pyrénées and Massif Central).

With such important issues, data quality must be ensured and at least evaluated. Some authors have investigated the sources of errors in discharge river measurement (McMillan et al., 2012) but, to date, uncertainty estimation is rarely associated with streamflow data.

Commonly, the streamflow records are based on continuous water level measurements converted by a stage-discharge relationship (called rating curve). Stream-gaugings at many different levels of flow are needed to plot a rating curve and to check the stability of the channel controls. For instance, in case of erosion or deposition processes, the channel of the stream may induce a change and a new rating curve has to be developed.

Stream-gaugings have several functions such as the regulatory supervision (e.g. controlling minimum instream flow), the construction of the stage-discharge relationship and the rating curve validation (in case of geometric instability of the channel).

To meet all these functions, stream discharge measurements are not complete if the associated uncertainty is not provided. Uncertainties in stream-gaugings should then be propagated for estimating the uncertainty associated with stage discharge relationships (Petersen-Øverleir and Reitan, 2009; McMillan et al., 2010; Morlot et al., 2014; Le Coz et al., 2014). In hydrometry a confidence level of 95% for uncertainty intervals is typically used (assuming a normal distribution for uncertainty) (see the Hydrometric Uncertainty Guidance: ISO, 2007b). The main difficulty in estimating uncertainty lies in the lack of streamflow reference data and in the natural time and space variability of river flows and beds.

The two main gauging techniques are the exploration of the velocity field by Doppler profilers (ADCP) or by the velocity-area method using current-meters (WMO, 2010) and the tracer dilution (not discussed in the paper). The river discharge, Q, is estimated by integrating the normal flow velocities, v, and depths through the area A of a cross-section (Herschy, 1993) according to Eq. (1) as follows:

$$Q = \int_A v \mathrm{d}A \qquad (1)$$

Incomplete methods such as surface velocity measurement using hand-held Surface Velocity Radar (SVR) (Corato et al., 2011), Large-Scale Particle Image Velocimetry (LSPIV) (Hauet et al., 2008) or floats can also be applied to measure river discharge during floods. In such cases the field velocity is only explored in a partial way.

Although the ADCP technique is expanding rapidly, a significant proportion of the discharge measurements are still performed using the velocity-area method with a current-meter (in 2013, about 30% of EDF-DTG measurements).

The velocity field is sampled using a number m of verticals distributed across the river, where the vertical velocity profile is sampled by a current-meter at n_i different depths.

Velocity measurements are performed with mechanical, electromagnetic or acoustic Doppler current-meters. The mid-section method is often used by hydrological services to compute discharge Q as:

$$Q = \sum_{i=1}^{m} Q_i = Q_0 + Q_{m+1} + \sum_{i=1}^{m} B_i D_i V_i, \qquad (2)$$

where Q_i, B_i and D_i denote the discharges, widths and depths of each subsection (or panel) i respectively. V_i are the mean normal-to-section velocities computed by integrating the vertical velocity profile. Q_0 and Q_{m+1} correspond to partial discharges near each bank where the subsection velocity is determined by extrapolation. The alternative mean-section approach is not discussed in this study, since it does not produce significant differences in discharge computations.

There are a lot of sources of uncertainties in gaugings (e.g. Carter and Anderson, 1963; Pelletier, 1988; Sauer and Meyer, 1992) but the uncertainty of the velocity-area method heavily depends on the strategy of point measurement sampling and especially on the number m and positions of verticals used to best describe the cross-section complexity.

Most of the computed uncertainty usually stems from the term u_m, due to the limited number of verticals (Le Coz et al., 2012). It must therefore be correctly computed. To address the limitations of existing uncertainty estimation methods (see Section 2), this paper presents a new methodology, called FLow Analog UnceRtainty Estimation (FLAURE), to estimate the u_m uncertainty component. A set of high-resolution gaugings (presented in Section 3.1) is subsampled (Section 3.2). Realistic stream-gaugings with any given number of verticals are produced (Section 3.2) and lead to a new estimation of u_m component depending on a sampling quality index (Section 3.4). In order to take into account cross-sectional complexity, the u_m component is estimated with the four most similar stream-gaugings selected among reference measurements (Section 3.5). To evaluate the new uncertainty methodology (FLAURE) and compare it with *ISO* 748, $Q+$ and *IVE* methods, uncertainties are computed using a set of 3185 routine stream-gaugings (see Section 4.2). A focus on three test cases is also presented in Section 4.3. Section 5 summarizes the conclusions and perspectives of this work.

2. Overview of uncertainty estimation methods

2.1. General guidelines for sampling the cross-section

It is hard to establish universal rules concerning the spacing between verticals and between points along each vertical. In France, these choices are left to the hydrometric technician considering his expertise and regarding bed geometry and flow distribution. During flood conditions it is advisable to reduce the number of point measurements due to potential flow variations and particularly for safety reasons. In all possible measuring situations these choices should lead to the most accurate and the most cost-efficient representation of reality. Some hydrometric technicians recommend that verticals should be regularly spaced but their positions should preferably depend on the transverse variation in bed geometry and flow distribution. Their positions should minimize the partial discharge, which means that more verticals must be placed where flow is higher (recommends that each Q_i should not exceed 10% of the total discharge ISO, 2009). The more the space between verticals is, the more the relative importance of a vertical in total flow is increased.

It is also judicious to place verticals as close as possible to the edges in order to minimize extrapolation and riverbank coefficients effects.

Various requirements can be found in *ISO* 748 standard (ISO, 2009) or other guidelines (e.g. Herschy, 1993; Forray et al., 1998; WMO, 2010). These general rules are applied in internal operating procedures by EDF-DTG hydrometric service.

It is very important to notice here that all these requirements must be followed. The estimation of uncertainty does not take into