Flow Measurement and Instrumentation 48 (2016) 42–50

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Uncertainty of discharge estimation in high-grade Andean streams

Brian García Parra [a], Luis Eduardo Peña Rojas [a,*], Miguel Barrios [b], Juan Camilo Múnera Estrada [a]

[a] Research Group GMAE, Universidad de Ibagué, Colombia
[b] Faculty of Forest Engineering, Universidad del Tolima, Colombia

ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form
22 December 2015
Accepted 13 February 2016
Available online 14 February 2016

Keywords:
Hydrometrics
Discharge estimation
Uncertainty
Area-velocity method
Saline dilution tracer

ABSTRACT

Hydrologic measurements in high-grade Andean streams involve challenges for discharge estimation, caused by its torrential behavior and high flow variability. Since data collected on field are essential to describe the specific hydraulic characteristics of a stream, it is necessary to consider criteria such as the ease of implementation, economic factors and accuracy. In this study, discharge estimation were performed and compared by using the area-velocity method, and a saline dilution tracer method. This analysis allowed determining the best alternative for discharge estimation with a reduced uncertainty. The analysis was carried out in three tropical watersheds whose main streams are natural high-graded with mean depths between 0.1 and 0.5 m. To this end, 104 discharge observations were performed in control cross-sections of the Combeima, Las Perlas and Ambala rivers, part of the Combeima River and Chipalo River basins in the Colombian Andes. In the studied streams, the area-velocity method had an uncertainty of 14.35% greater than that calculated for the discharge estimations using the saline tracer, this result differ from uncertainty values reported by other authors for both approaches. This work represents a contribution to the improvement of discharge estimation for the construction of rating curves and the calibration of hydrological models, specifically in watersheds with high-grade streams.

1. Introduction

During the execution of projects related to water resources or integrated management of natural risks, it is necessary to rely on hydrometric information that allows determining the behavior of a given stream at a control point in a given watershed. Therefore, it is important to identify observation methodologies with an adequate accuracy to obtain rating curves for depth versus discharge, depth versus cross sectional area and depth versus velocity [5,6]. By achieving the greatest accuracy in discharge estimation, it will be possible to achieve better calibrations and validations of hydrological and hydraulic models. The practical application of error measurement and uncertainty estimation will contribute to a greater accuracy in the estimation of water supply, water resource management, and the estimation of flood levels for the protection of communities against heavy rains and flash floods.

The discharge estimation methodology includes error quantification and uncertainty estimation [7], which have been studied for some years by international institutions [16]. However, these considerations have rarely been applied to the particular conditions of Colombian rivers. Therefore, this paper presents the analysis of errors in discharge estimation using the method of area-velocity with a current meter [1] and the method of saline dilution slug [17] in order to identify the approach that renders the greatest accuracy and least uncertainty. It is expected that error propagation in the construction of rating curves will decrease as a result [2]. Rating curves show a hysteresis phenomenon, however, this analysis is not considered in this paper.

The study was carried out in the Combeima and Chipalo River basins, more specifically in the Combeima main stream, and Las Perlas and Ambalá creeks, which are all located in the province of Tolima, Colombia. One-hundred and four discharge estimations were conducted to quantify the accuracy and estimate the uncertainty, following Herschy [7] methodology. The hypothesis of this study is that discharge estimation in high-grade and low-depth surface streams has a lower uncertainty with the tracer method reported by Zellweger et al. [20] than the current meter method reported by Herschy [7]. The results obtained were used to determine error and uncertainty of field observations and perform comparisons between both methods.

* Corresponding author.
E-mail addresses: gp.brian@hotmail.com (B. García Parra), luis.pena@unibague.edu.co (L.E. Peña Rojas), mibarrios@ut.edu.co (M. Barrios), jmunera@cta.org.co (J.C. Múnera Estrada).

http://dx.doi.org/10.1016/j.flowmeasinst.2016.02.005

2. Materials and methods

2.1. Study area

The behavior of Colombian Andean streams is highly influenced by bimodal rainfall patterns, these streams present high variability in minimum, average and maximum discharges. Combeima and Chipalo rivers are located in the Colombian Andes, South America (Fig. 1, Table 1). Ambalá Creek drains an area of 10.06 km^2 to Chipalo River. It is located on the north side of Ibagué city, between 2880 and 1000 m above sea level (masl) with an average grade of 16.19% and frequent occurrence of flash floods.

Combeima watershed has an area of 278.37 km^2 and is located between 5150 and 700 masl. Las Perlas Creek is one of the main tributaries of Combeima River and joins it at 2300 masl. Floods at the observation sites in Combeima River and Las Perlas Creek are moderate and do not result in extensive floodplains because of their high stream grades (stream slope Combeima River 12.6% and 13.0% for Las Perlas Creek). The selected streams represent the average characteristics of Colombian Andean catchments and thus are suitable to assess the uncertainty in discharge estimation in high grade streams, some of which are important for urban water supply and flood risk management.

2.2. Equipment

Discharge estimations were conducted with a current meter (OSS-PC1, Pygmy Hydrological Services, Warwick Farm, Australia) with a velocity measurement range between 0.025 m/s and 8 m/s, a resolution of ±0.001 m and measurement error of ±1%. Discharge estimations with saline tracer were performed with a portable conductivity meter (HACH hq14d, Loveland, CO), with a reported precision of 0.5%.

2.3. Area–velocity method

Discharge estimations with the current meter were performed following the approach of the World Meteorological Organization ([16]). This approach is the Area (A)–Velocity (V) method, and establishes that the distribution of velocities in natural streams varies depending on the streambed configuration and thus the cross-section must be broken up in discrete vertical sub-sections. Therefore, variables that affect the estimation of uncertainty in discharge estimation with current meter include mean velocity in each vertical sub-section (V_m), cross-section width (b), depth of each vertical sub-section (d), measured vertical sub-sections in the control cross-section (i), and the number of vertical sub-sections (n) [5,6].

Table 1
Gauging stations.

Gauging station	Basin	Latitude N	Longitude W	Elevation m
Combeima River	Combeima	4° 33′37.2″	75° 19′48.2″	2355
Las Perlas Creek	Combeima	4° 33′53.6″	75° 19′47.7″	2315
Ambalá Creek	Chipalo	3° 28′23.76″	74° 13′21.82″	1179

Relationships between mean discharge and depths ($d < 1$ m) have been developed for the Combeima River, and Las Perlas and Ambalá creeks; therefore, the mean velocity in each vertical subsection was determined with the one-point approach, as presented in Eq. (1) [12]

$$Vm = V_{0.6} \tag{1}$$

where Vm is mean velocity and $V_{0.6}$ is the velocity at 60% of the mean depth. Partial discharge in the vertical subsection is computed according to Eq. (2)

$$q(i, i+1) = \left(\frac{Vm(i) + Vm(i+1)}{2}\right)\left(\frac{d(i) + d(i+1)}{2}\right) b(i, i+1) \tag{2}$$

For the extreme subsections, the expression is simplified as shown in Eq. (3)

$$q(i, i+1) = \left(\frac{Vm(i+1)}{2}\right)\left(\frac{d(i+1)}{2}\right) b(i, i+1) \tag{3}$$

Discharge is computed using Eq. (4)

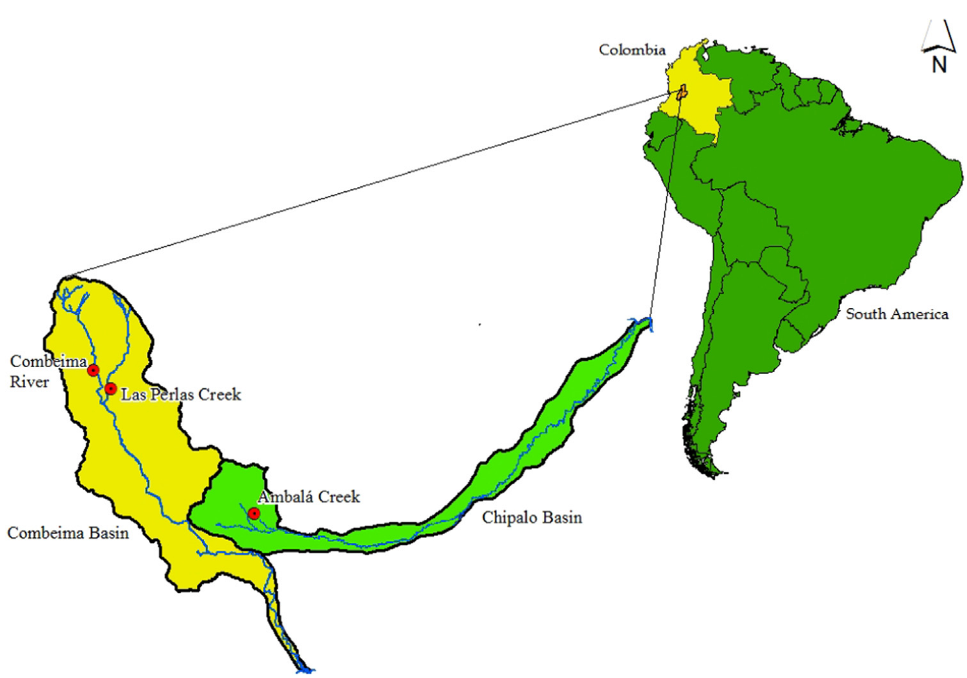

Fig. 1. Location of study area.

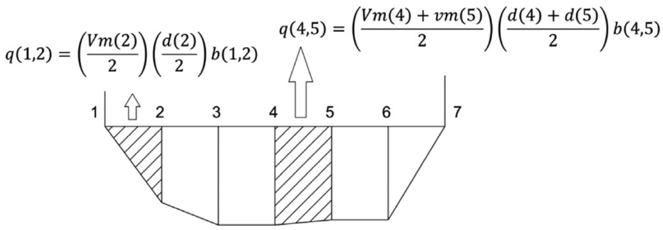

Fig. 2. Discharge computation using the area-velocity method.

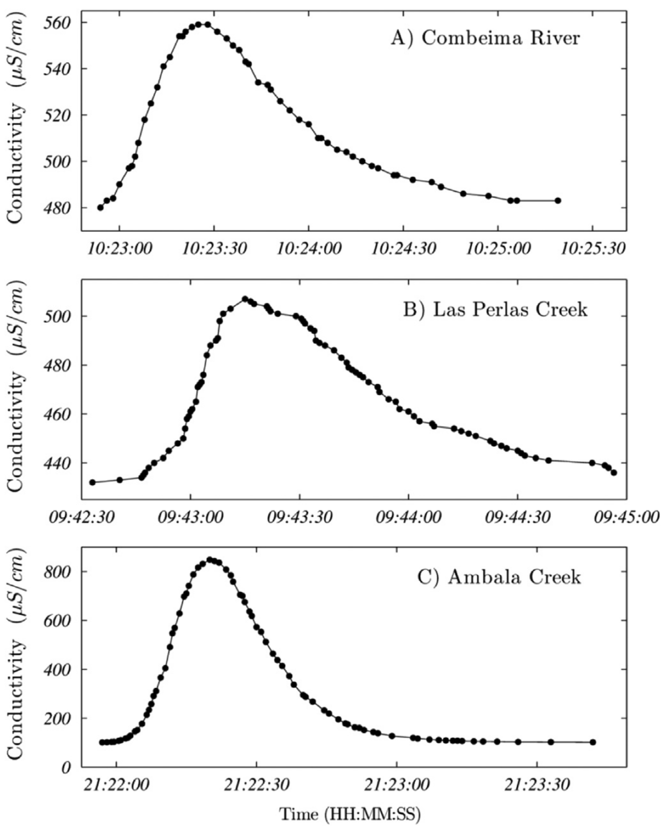

Fig. 3. Example of Electrical conductivity variation on time at each gaging point a) For a discharge of 2.534 m^3/s at Combeima river gaging point b) For a discharge of 0.6472 m^3/s at Las Perlas gaging point c) For a discharge of 0.0286 m^3/s at Ambalá gaging point.

$$Q = \sum_{i=1}^{n-1}\left(\frac{Vm(i+1)}{2}\right)\left(\frac{d(i+1)}{2}\right)b(i,\ i+1) \tag{4}$$

where i is the vertical subsection, q is partial discharge, Vm is the mean velocity in the subsection, d is the subsection depth, and n is the number of vertical subsections (Fig. 2).

According to Eq. (4), the uncertainty in the discharge estimation with the current meter has an inversely proportional ratio to the number of vertical subsections considered [7]. Depending on the width and depth of the cross-section, the operator defined the number of subsections to work based on international guidelines that establish that the width of each subsection (b_i) should be less than 1/20 of the cross-section width (b), and that the partial discharge in each subsection should be less than 10% of the total discharge [12].

2.4. Uncertainty of the area–velocity method

Often, uncertainty of the information collected in discharge estimation of Colombian natural and man-made streams is not carefully analyzed. When it comes to the design and operation of hydrological and hydraulic projects it is crucial having highly accurate estimations. This is made possible by determining and recording the measurement error and by estimating uncertainty [7].

Error measurement cannot be accurately determined in a surface stream [5,6]. However, it is possible to quantify the magnitude of the error, i.e., the measurement uncertainty, through an individual analysis based on statistical approaches. Since the sources of uncertainty of discharge estimation are associated to the measurement of the cross-section width, depth, point velocity and velocity of each vertical subsection [5] it is possible to classify uncertainty as systemic and random.

Systemic uncertainty is associated with the calibration of the measuring equipment; assuming that it is constant, uncertainty can be estimated using international reference values [13]. Systemic errors also include the calibration of the equipment used to measure the cross-section width and depth. A constant value of 1% [14] has been consistently used in discharge estimations performed since the 1970s [8].

Random uncertainty is more complex because of its dependence on the vertical subsections in which a cross-section needs to be divided to measure velocity. The error magnitude varies when several discharge observations are performed consecutively, and it is only possible to reduce it by replicating the velocity measurements in identical conditions, which is challenging and not practical in most natural surface streams [14]. To estimate uncertainty, the number of vertical subsections (m), the number of measured velocities in each vertical subsection, random errors in the equipment exposure time, measured velocity, and the width and depth of each vertical subsection need to be considered, since b_i and d_i, are related to the handling of the instrument by the current meter operator.

Estimated uncertainty in discharge estimation, combining systemic and random errors, results in a reliability of 95% and a cover factor of 2 [11]. Uncertainty is computed using Eq. (5):

$$u^2(Q) = u_s^2 + u_m^2 + \frac{1}{m}\left[u^2(B) + u^2(D) + u_p^2 + \frac{1}{n}\left[u_c^2 + u_e^2\right]\right] \tag{5}$$

where $u^2(Q)$ is the discharge uncertainty, u_s are systemic errors, u_m are errors related to the number of vertical subsections, m is the number of vertical subsections measured in the cross-section, $u(B)$ is the random uncertainty in the width measurement, $u(D)$ is the random uncertainty in the depth measurement, u_p is the uncertainty related to the number of velocities measured in each vertical subsection, n is the number of mean velocities per vertical subsection, u_c is the random uncertainty related to the point velocity measured in the vertical subsection, and u_e is the random uncertainty related to the exposure time of the instrument. Values for each of these variables are tabulated in the standard ISO-748 [13].

2.5. Saline Tracer Method

High-grade, natural surface streams, like Combeima River, usually have low depths, which makes easier performing discharge estimations with a current meter by wading. However, this is a time-consuming endeavor and, in a typical day, no more than three estimations are usually conducted. This results in high costs for data acquisition, which are directly proportional to the monitoring area and the amount of required measurements. Moreover, the morphology of high-grade streams results in abrupt grade changes, irregularities of the streambed, and turbulence pockets, which in turn result in variations of velocity distributions and effects on the discharge estimation accuracy. In some occasions, the stream depths are very low to allow the measurement of velocities at different depths in the same vertical subsection, so that an

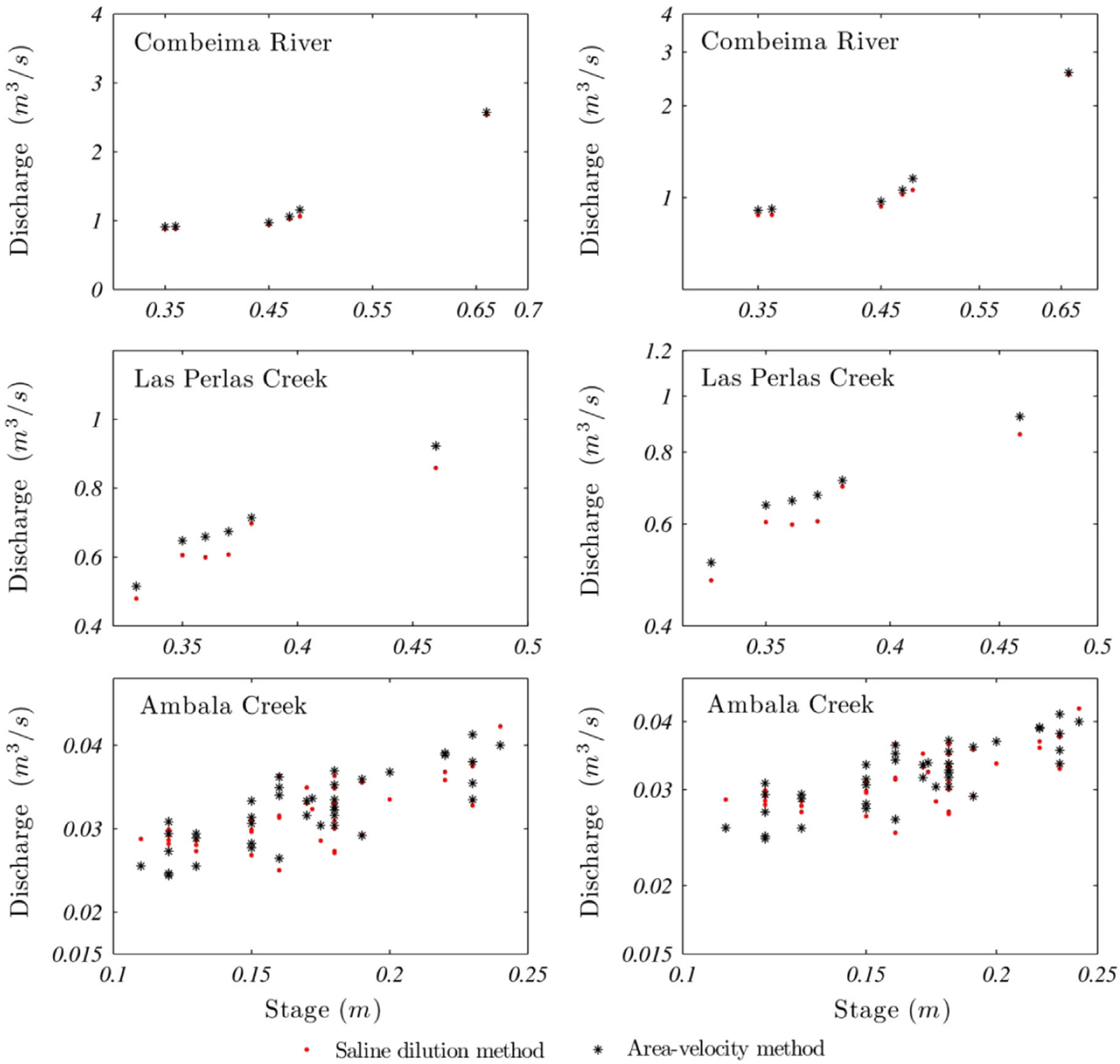

Fig. 4. Discharge estimations. Left: Arithmetic scale, Right: Log–Log scale.

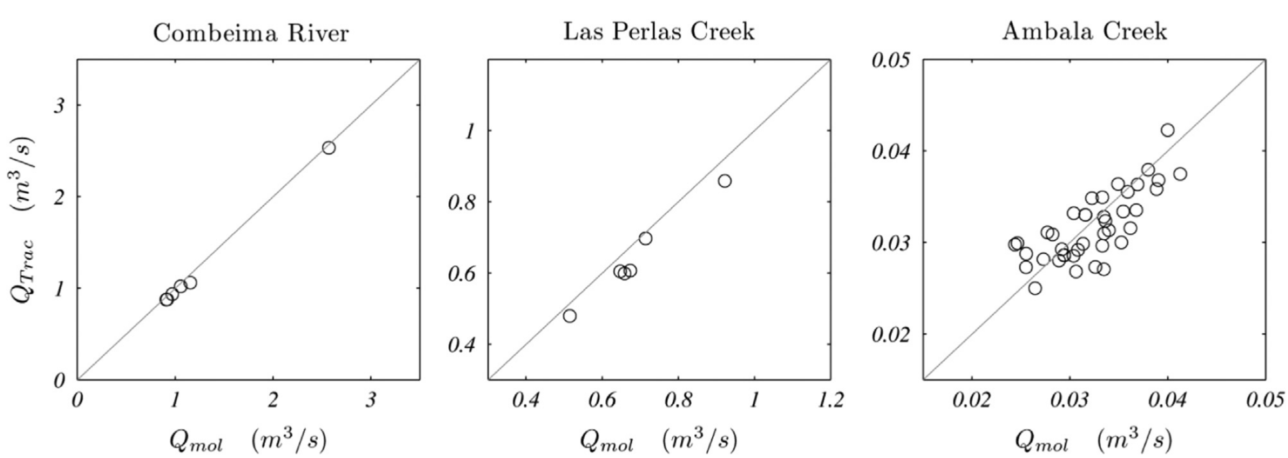

Fig. 5. Scatter plots of discharge obtained by area-velocity method against Saline Tracer Method.

accurate velocity distribution map can be obtained [15].

It is therefore important exploring discharge estimation approaches that result in reduced errors and uncertainty, while at the same time, with low costs and easy to apply on field. This led to the implementation of discharge estimation with a chemical tracer. The method is based on the continuity principle, or mass balance, and uses salt as a tracer, which meets the requirements for a chemical tracer [18] and is also cost-effective and easy to acquire [4].

The Saline Tracer Method consists in applying upstream of the control section a saline dilution with a known volume and measuring the change in electrical conductivity in the control section.

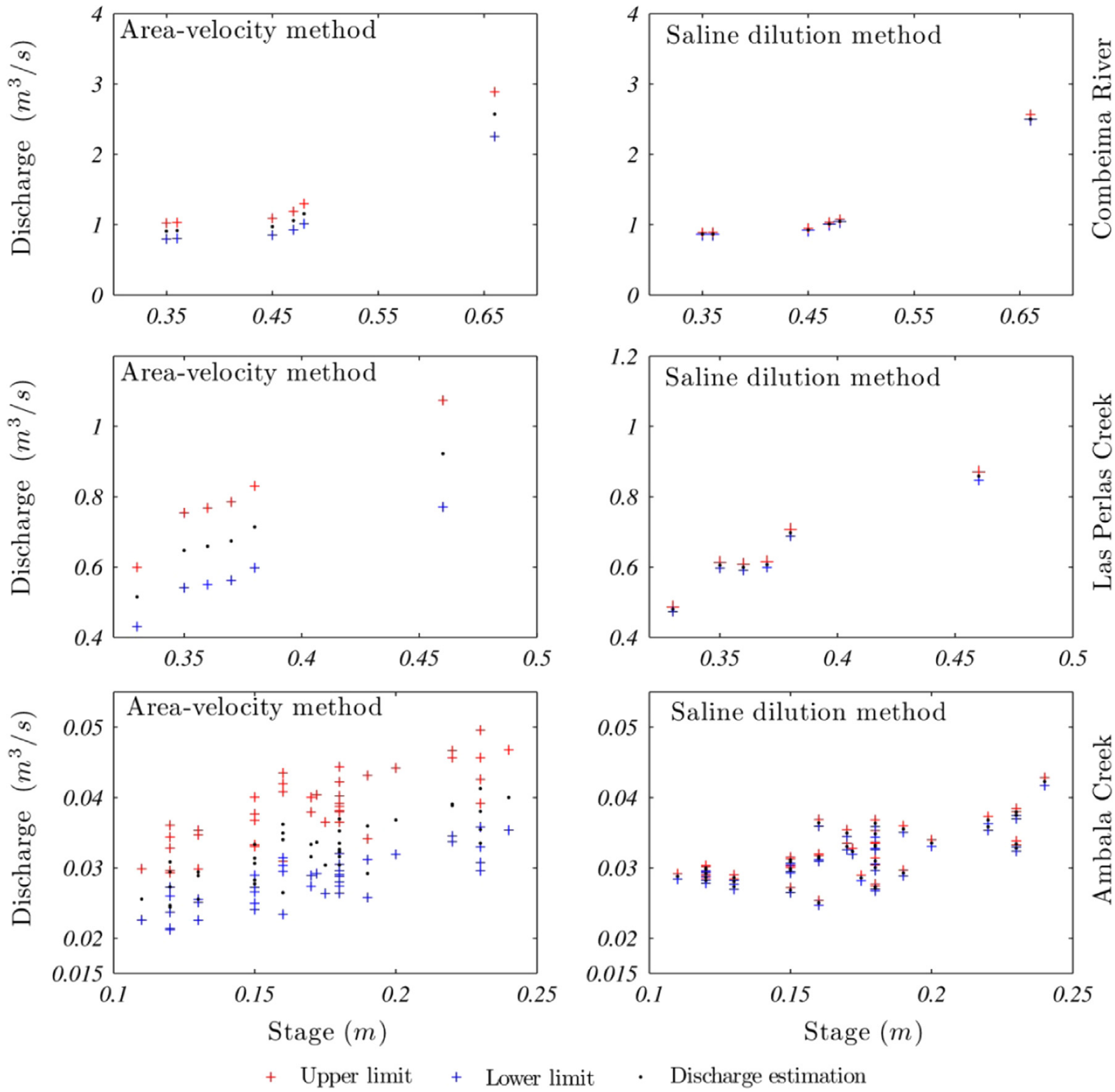

Fig. 6. Discharge estimations and uncertainty confidence intervals at a 95% significance level. Left: Area-velocity method. Right: Saline Tracer Method.

Electrical conductivity in water will depart from initial conditions until reaching a peak to later reach initial conditions. By plotting the change in electrical conductivity versus time, and determining the area below the curve the discharge can be determined. Eq. (6) can be used for that purpose [9]:

$$Q = \frac{V * C1}{\int q - (t * Co)} \tag{6}$$

where V is the volume of the saline dilution, $C1$ is the salt concentration of the saline dilution, t is the duration of the measurement in seconds, Co is the initial concentration of the stream and $\int q$ is expressed as:

$$\int q \approx \sum \Delta t * \frac{Cn + C_{n+1}}{2} \tag{7}$$

where Δt is the time lapse between measurements, Cn is the concentration n of the point measurement and $C_{n+1}$is the concentration obtained in the following measurement.

It is also important estimating the length of the mixing zone to verify that the saline dilution is completely dissolved in the control volume. To this end, the distance between the point of application of the saline dilution and the point of discharge estimation must be determined, as expressed in Eq. (8):

$$Lm = K\frac{vB^2}{Ez} \tag{8}$$

where K is a constant that depends on the dilution concentration, location and number of tracer applications [17], v is the mean velocity (m/s), B is the stream width (m) and Ez is the lateral mix coefficient [19]. In high-grade streams, the length of the mixing zone can be lower due to the grade and the turbulence caused by the stream morphology and rocky streambed. In this case the place where the tracer was applied, it was located 50 m upstream above the control sections indicated in Table 1.

2.6. Slug method

This is a method used to measure the variation of conductivity resulting from a known volume of saline dilution used as a tracer [10]. The discharge can be computed using Eq. (9):

$$Q = Cs * \frac{Vs}{\int_0^T (Cc - Cb)dt} \tag{9}$$

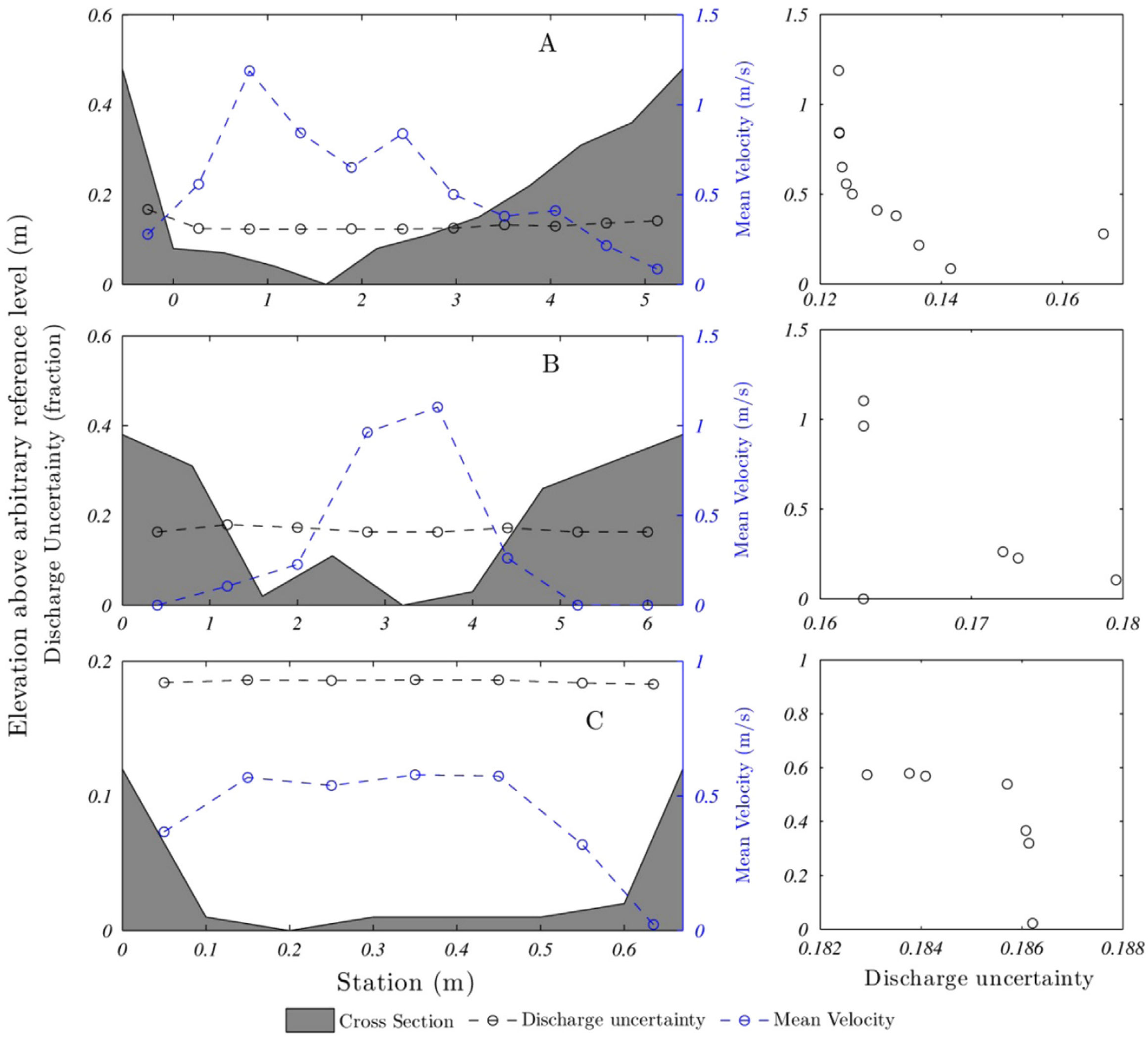

Fig. 7. Discharge uncertainty and velocity distribution on cross section. (A) Combeima watershed (B) Las Perlas Creek (C) Ambalá Creek.

where Q is the discharge, Vs is the volume of tracer slug, Cc is the initial electrical conductivity of the stream, Cs is the electrical conductivity of the saline dilution and Cb is the electrical conductivity in the downstream point where the measurement is taken [3].

In order for this method to produce reliable results, it is necessary to verify that the length of mixing is complied with. The measuring time starts when the saline dilution is first applied and ends when the conductivity readings stabilize after the tracer has gone by, reaching initial conditions [3].

2.7. Uncertainty of the Saline Tracer Method

The uncertainty of this method is associated with the accuracy of the equipment U_i and the measurement of the volume of the container with the saline dilution U_v, which can be expressed with Eq. (10):

$$U_q = U_i + U_v \tag{10}$$

In this case, since the uncertainty depends only on the systemic errors, the occurrence of random errors is less probable because it is no longer required measuring directly a variable related to the stream morphology or the velocity in the cross-section. In consequence, the uncertainty associated to discharge estimations using tracer is constant.

In order to increase the uncertainty during discharge estimation with tracers, an abrupt change in the natural concentration of the stream would need to take place during the observation since salt is a conservative substance [20]. This may happen on high waters because of the high volumes of sediments transported [3].

3. Results and discussion

3.1. Discharge estimations with saline dilution and Area Velocity Methods

Graphs with the behavior of the saline tracer during the discharge estimation are presented for each studied stream in Fig. 3. The natural concentrations were 480, 437 and 101 µs/cm for the Combeima River, Las Perlas and Ambalá creeks, respectively, while the peak concentrations were 559, 507 and 848 µs/cm for the example shown in Fig. 3. Peak values were directly proportional to the amount of salt used.

Discharge observations cover the range between 0.2 m^3/s at Ambalá Creek to 3 m^3/s at Combeima River (Fig. 4). The relationships between stage and discharge are presented in Fig. 4. In contrast to the area–velocity method, the tracer method shows lower discharge estimations.

Discharges obtained by the saline dilution and area-velocity methods in the same control section are presented in Fig. 5. To verify equality of conditions, both types of observations were performed simultaneously.

Following Fig. 5, Q_{mol} is the discharge determined by the area–velocity method and Q_{Trac} is the discharge calculated by the saline dilution slug method. In the particular case of Combeima River $Q_{mol}=1.317^{*}Q_{Trac}$, while for Las Perlas Creek $Q_{mol}= 0.861^{*}Q_{Trac}$, and in Ambalá Creek $Q_{mol}=1.535^{*}Q_{Trac}$. In average, the discharge relation is $Q_{mol}= 1.238^{*}Q_{Trac}$, i.e., for Combeima River and Las Perlas Creek the area-velocity method overestimated the discharge determined by the tracer method. This is opposed to the findings of Zellweger et al. [20] where the value of the discharge estimated with current meter was 18.75% less than that estimated with saline tracer.

3.2. Discharge uncertainty estimation

According to international standards [13], uncertainty values were defined with respect to systemic and random errors occurring under the particular conditions of the discharge estimation location and the equipment used. According to Fig. 6 the uncertainty of the tracer method was constant and had a value of ±1.35% for the three studied streams. The uncertainty related to the discharge estimation by the area-velocity method was variable. The predominant percentage of uncertainty regarding discharge estimation with current meter is associated to the number of vertical subsections for each observation. In Combeima River, the uncertainty related to the discharge took values between 12.3% and 16.68%. It covered the range of 16.29% to 17.96% in Las Perlas Creek, for the case of Ambalá Creek; discharge uncertainty was in the range of 18.29% to 18.62%.

3.3. Uncertainty and velocity distribution in the cross-sections

Fig. 7 defines the typical relationship between velocity, discharge uncertainty and cross section geometry. Cross-section is defined by the gray shading; the black line shows the uncertainty variation in each vertical subsection along the cross-section. These series are aligned with the left *Y*-axis; the blue lines represent the behavior of the measured velocities using the current meter in each vertical subsection and are aligned with the right *Y*-axis.

For the case of Combeima River, the uncertainty of discharge estimations with the area–velocity method is greater at lower velocities, which are related to low depths (Fig. 7A). A lower uncertainty was determined in the center of the cross-section in Las Perlas Creek, which is typically the deepest point of the cross-section (Fig. 7B). By comparing Fig. 7a, b and c, it was found that the uncertainty of discharge estimations with the area-velocity method decreases as the mean velocity increases. By contrast, we could not find a relationship between uncertainty and flow depth.

4. Conclusions

The uncertainty of the discharge estimations by the area–velocity method decreases as the mean velocity rise in the cross-section. However, this method has lower reliability for low and high velocities compared to the tracer method, since the latter involves systemic errors only and the uncertainty remains constant.

The uncertainty estimated for the Combeima River and Las Perlas and Ambalá creeks with the area–velocity method reflects the uncertainty associated with the number of vertical subsections used for discharge estimation with current meter, as discussed by Herschy [21].

In the studied streams, the area–velocity method had an uncertainty of 14.35% greater than that calculated for the discharge estimations using the saline tracer, which differs from the results reported by Zellweger et al. [20].

It was found that the uncertainty of discharge estimations was greater for low-velocity streams. However, according to our observations we did not find any linkage between flow depth and uncertainty.

Acknowledgments

The authors would like to thank the GMAE research group of Universidad de Ibagué, the Hydrology lab of Universidad del Tolima, and the Doctoral grants program of Colciencias 567 of 2012.

Appendix

See Tables A1 and A2

Table A1
Discharge data estimated by area–velocity and Saline Tracer Methods.

Date (dd/mm/yy)	Catchment	Stage (m)	Area–velocity method					Saline tracer method		
			Area (m^2)	Velocity (m/s)	Discharge (m^3/s)	*U*	*L*	Discharge (m^3/s)	*U*	*L*
15/11/13	Combeima	0.4700	1.6622	0.6357	1.0566	1.1873	0.9259	1.0211	1.0349	1.0073
16/11/13	Combeima	0.6600	3.2306	0.7957	2.5705	2.8873	2.2537	2.5337	2.5679	2.4995
17/12/13	Combeima	0.4500	1.5574	0.6229	0.9702	1.0903	0.8501	0.9349	0.9475	0.9223
23/01/13	Combeima	0.3600	1.5304	0.5989	0.9166	1.0302	0.8030	0.8776	0.8895	0.8658
03/02/14	Combeima	0.4800	1.7439	0.6625	1.1553	1.2980	1.0125	1.0593	1.0736	1.0450
22/02/14	Combeima	0.3500	1.4782	0.6143	0.9081	1.0205	0.7956	0.8759	0.8877	0.8640
15/11/13	Las Perlas	0.3700	1.5560	0.4329	0.6735	0.7853	0.5618	0.6067	0.6149	0.5985
16/11/13	Las Perlas	0.3500	1.3603	0.4758	0.6472	0.7536	0.5408	0.6046	0.6128	0.5965
17/12/13	Las Perlas	0.3600	1.4903	0.4419	0.6585	0.7675	0.5496	0.5988	0.6069	0.5907
23/01/13	Las Perlas	0.4600	1.9604	0.4704	0.9221	1.0738	0.7704	0.8583	0.8699	0.8467
03/02/14	Las Perlas	0.3800	1.1723	0.6091	0.7141	0.8306	0.5976	0.6969	0.7063	0.6875
22/02/14	Las Perlas	0.3300	1.0518	0.4894	0.5147	0.5992	0.4302	0.4794	0.4859	0.4729
29/01/14	Ambalá	0.1800	0.0894	0.3945	0.0352	0.0422	0.0305	0.0300	0.0304	0.0296
29/01/14	Ambalá	0.1800	0.0770	0.4104	0.0316	0.0379	0.0274	0.0330	0.0335	0.0326
31/01/14	Ambalá	0.1700	0.0722	0.4615	0.0333	0.0400	0.0289	0.0349	0.0354	0.0345
31/01/14	Ambalá	0.1800	0.0770	0.4795	0.0369	0.0443	0.0320	0.0363	0.0368	0.0358
12/02/14	Ambalá	0.1300	0.0530	0.5450	0.0289	0.0347	0.0251	0.0280	0.0284	0.0276
12/02/14	Ambalá	0.1200	0.0482	0.5114	0.0246	0.0296	0.0214	0.0299	0.0303	0.0295
14/02/14	Ambalá	0.1720	0.0810	0.4152	0.0336	0.0404	0.0292	0.0323	0.0328	0.0319
14/02/14	Ambalá	0.1700	0.0810	0.3898	0.0316	0.0379	0.0274	0.0330	0.0335	0.0326
14/02/14	Ambalá	0.1900	0.0890	0.4036	0.0359	0.0431	0.0312	0.0355	0.0360	0.0350
17/02/14	Ambalá	0.1200	0.0560	0.4875	0.0273	0.0328	0.0237	0.0282	0.0285	0.0278
17/02/14	Ambalá	0.1500	0.0710	0.4415	0.0313	0.0376	0.0272	0.0299	0.0303	0.0294
17/02/14	Ambalá	0.1300	0.0600	0.4902	0.0294	0.0353	0.0255	0.0286	0.0290	0.0282
18/02/14	Ambalá	0.1500	0.0700	0.4761	0.0333	0.0400	0.0289	0.0296	0.0300	0.0292
17/02/14	Ambalá	0.1600	0.0760	0.4761	0.0362	0.0435	0.0314	0.0315	0.0320	0.0311
17/02/14	Ambalá	0.2300	0.1100	0.3455	0.0380	0.0456	0.0330	0.0379	0.0384	0.0374
18/02/14	Ambalá	0.1500	0.0710	0.4313	0.0306	0.0368	0.0266	0.0268	0.0272	0.0265
18/02/14	Ambalá	0.1800	0.0833	0.3872	0.0323	0.0387	0.0280	0.0348	0.0353	0.0343
18/02/14	Ambalá	0.1800	0.0833	0.3649	0.0304	0.0365	0.0264	0.0332	0.0336	0.0327
18/02/14	Ambalá	0.1500	0.0688	0.4029	0.0277	0.0333	0.0240	0.0311	0.0315	0.0307
18/02/14	Ambalá	0.2200	0.1007	0.3858	0.0389	0.0467	0.0337	0.0358	0.0363	0.0353
18/02/14	Ambalá	0.2000	0.0920	0.3999	0.0368	0.0442	0.0319	0.0335	0.0340	0.0331
18/02/14	Ambalá	0.1200	0.0552	0.4421	0.0244	0.0293	0.0212	0.0298	0.0302	0.0294
18/02/14	Ambalá	0.1600	0.0726	0.4811	0.0349	0.0419	0.0303	0.0364	0.0369	0.0359
18/02/14	Ambalá	0.1750	0.0799	0.3804	0.0304	0.0365	0.0264	0.0286	0.0289	0.0282
18/02/14	Ambalá	0.1600	0.0728	0.4670	0.0340	0.0408	0.0295	0.0313	0.0317	0.0309
18/02/14	Ambalá	0.2300	0.1066	0.3874	0.0413	0.0496	0.0358	0.0375	0.0380	0.0370
18/02/14	Ambalá	0.2200	0.1210	0.3228	0.0391	0.0457	0.0345	0.0368	0.0373	0.0363
18/02/14	Ambalá	0.1100	0.0585	0.4365	0.0255	0.0299	0.0226	0.0288	0.0292	0.0284
18/02/14	Ambalá	0.1800	0.0996	0.3274	0.0326	0.0381	0.0288	0.0273	0.0277	0.0270
18/02/14	Ambalá	0.1600	0.0879	0.3010	0.0265	0.0309	0.0234	0.0250	0.0253	0.0247
18/02/14	Ambalá	0.2400	0.1347	0.2969	0.0400	0.0468	0.0353	0.0423	0.0428	0.0417
18/02/14	Ambalá	0.1800	0.0986	0.3395	0.0335	0.0391	0.0296	0.0271	0.0274	0.0267
18/02/14	Ambalá	0.1300	0.0704	0.3626	0.0255	0.0298	0.0225	0.0273	0.0277	0.0269
18/02/14	Ambalá	0.2300	0.1289	0.2598	0.0335	0.0391	0.0296	0.0328	0.0332	0.0323
18/02/14	Ambalá	0.1200	0.0645	0.4559	0.0294	0.0344	0.0260	0.0286	0.0290	0.0282
18/02/14	Ambalá	0.1200	0.0645	0.4779	0.0308	0.0360	0.0272	0.0292	0.0296	0.0288
19/02/14	Ambalá	0.1500	0.0821	0.3442	0.0282	0.0330	0.0249	0.0309	0.0313	0.0304
19/02/14	Ambalá	0.1900	0.1055	0.2767	0.0292	0.0341	0.0258	0.0292	0.0296	0.0289
19/02/14	Ambalá	0.2300	0.1066	0.3327	0.0354	0.0426	0.0307	0.0334	0.0338	0.0329
19/02/14	Ambalá	0.1800	0.0860	0.3894	0.0335	0.0402	0.0291	0.0310	0.0314	0.0305

Table A2
Equipment and flow measurement.

Gauging Station	Equipment	Current meter measuring	Conductivity meter measuring
Combeima River	Current meter 		
Las Perlas Creek	Con 		
Ambalá Creek	Con 		

References

[1] W. Boiten, Hydrometry. A comprehensive introduction to the measurement of flow in open channels, 3rd ed., UNESCO, IHE, 2008, p. 280.
[2] G. Braca, Stage–discharge relationships in open channels: practices and problems, Università deg li Studi di Trento, Dipartimento di Ingenieria Civile e Ambientale, Trento, Italy (2008), p. 24, FORALPS Technical Report, 11.
[3] K. Elder, R. Kattelmann, R. Ferguson. Refinements in dilution gauging for mountain streams. In Hydrology in Mountainous Regions. I - Hydrological Measurements; the Water Cycle. International Association for Hydrological Science (Proceedings of two Lausanne symposia, August 1990). IAHS Publication No. 193, (1990) pp. 247–254.
[4] N.D. Gordon, et al., Stream Hydrology: An Introduction for Ecologists, 2nd ed., Wiley, Chichester, United Kingdom (2004), p. 448.
[5] J. Helmbrecht et al., Estudio de viabilidad y redacción de un pliego de bases para la contratación de un servicio de mantenimiento, uso y calibración de instrumentos de medida de caudales, Proyecto redactado para la Agència Catalana de l'Aigua (ACA), como base para el Manual de Aforos de la Unidad de Hidrología Barcelona, 2004.
[6] J. Helmbrecht, J. Lopez, J.J. Villegas, Cálculo de incertidumbres en la medida de caudales en ríos y canales: herramientas y aplicaciones prácticas innovadoras. 〈〈http://www.ingenieriadelagua.com/2004/JIA/Jia2011/pdf/p588.pdf〉〉.
[7] R. Herschy, Hydrometry: Principles and Practices, 2nd ed., Wiley, Chichester, United Kingdom (1998), p. 384.
[8] R. Herschy, The uncertainty in a current meter measurement, Flow. Meas. Instrum. 13 (5–6) (2002) 281–284.
[9] D. Hongve, A revised procedure for discharge measurement by means of the salt dilution method, Hydrol. Process. 1 (3) (1987) 267–270.
[10] R. Hudson, J. Fraser, Introduction to salt dilution gauging for streamflow measurement Part IV: the mass balance (or Dry Injection) method, Watershed Manag. Bull. 9 (1) (2005) 6–12.
[11] ISO-98-3, Uncertainty of measurement. Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), International Standards Organization, Geneva, 2008, ISO 98–3:2008.
[12] ISO–748, Liquid Flow Measurement in Open Channels: Velocity-Area Methods., International Standards Organization, Geneva, 1979, ISO–748:1979.
[13] ISO–748, Liquid Flow Measurement in Open Channels: Velocity-Area Methods, ISO-748:2001, 2001.
[14] J. Le Coz, B. Camenen, X. Peyrard, G. Dramais, Uncertainty in open-channel discharges measured with the velocity–area method, Flow. Meas. Instrum. 26 (2012) 18–29.
[15] R. Moore, Introduction to Salt Dilution Gauging for Streamflow Measurement: Part 1, Streamline Watershed Manag. Bull. 7 (4) (2004) 20–23.
[16] World Meteorological Organization, Guide to Hydrological Practices. Volume I: Hydrology-From Measurement to Hydrological Information, 6th ed., 2008, WMO-No 168, 296 pp.
[17] F. Kilpatrick, E. Cobb, Measurement of discharge using tracers, Tech. Water-Resour. Investig. USGS (1985) 1–52.
[18] P. Wood, A. Dykes, The use of salt dilution gauging techniques: ecological considerations and insights, Water Res. 36 (12) (2002) 3054–3062.
[19] N. Yotsukura, E.D. Cobb, Transverse diffusion of solutes in natural streams , U.S. Geological Survey Professional Paper, 582-C, 1972.
[20] G.W. Zellweger, R.J. Avanzino, K.E. Bencala, Comparison of tracer-dilution and current-meter discharge methods in a small gravel-bed stream, Little Lost Man Creek, California. U.S. Geol. Surv. Tech. Rep. WRIR (1989) 89-4150.
[21] R.W. Herschy, The accuracy of current meter measurements, Proc. Inst. Civ. Engrs., Part 2 65 (1978) 431–437.