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HYDROLOGY

EFFECT OF WEIR´S THEORETICAL DISCHARGE COEFFICIENT ON DISCHARGE MEASUREMENTS IN SMALL ANDEAN STREAMS

EFECTO DEL COEFICIENTE TEÓRICO DE DESCARGA DE VERTEDEROS SOBRE LA MEDICIÓN DE CAUDALES EN PEQUEÑOS RÍOS ANDINOS

Mario Guallpa*[1], Rolando Célleri[2], and Patricio Crespo[2]

[1]*Ingeniero de Recursos Hídricos, Empresa Pública Municipal de Telcomunicaciones, Agua Potable, Alcantarillado y Saneamiento de Cuenca ETAPA EP, Ecuador.*
[2]*Profesor, Departamento de Recursos Hídricos y Ciencias Ambientales, Facultad de Ingeniería, Universidad de Cuenca, Ecuador.*

*Corresponding author: mario.x.guallpa@gmail.com

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Abstract

Andean ecosystems provide important hydrological services for downstream communities. Due to this importance, several hydrological studies have been carried out in recent years, with emphasis on hydrological processes identification and land use change impacts. In several studies, but also for the operation of small-scale irrigation and drinking water projects, small streams have been equipped with compound, sharp-crested weirs for discharge estimation. To transform the water level (stage) into a discharge (water rate), weir equations use theoretical discharge coefficients, which do not necessarily apply under the actual field conditions, mainly site fluviomorphology and weir construction aspects, introducing uncertainty in their measurements. Therefore, this study analyzes the effect of using theoretical coefficients instead of adjusted coefficients in field. The study was conducted on 9 micro-catchments ($0{,}2 - 7{,}53 km^2$) located in the Zhurucay Ecohydrological Observatory in the paramo of southern Ecuador. To calibrate the coefficients, discharge curves were generated by mechanical and salt-dilution gauging methods. Results revealed that the discharge coefficients differed from their theoretical value by up to 15% for triangular (V-notch) weir section (DCvn) and by up to 41% for rectangular weir section (DCr). The DCvn affects 4 times more in low and medium discharges estimation than DCvn in high discharges. On the other hand, salt-dilution method is more precise for medium and high discharges, but at very low discharges, it overestimates discharge up to 10%. Overall, results suggest that it is essential to calibrate the discharge coefficients in the field to avoid errors in hydrological studies.

Keywords: Hydrology, Tropical Andes, Hydrological monitoring, Gauging methods, Ecuador.

Resumen

Los Ecosistemas Andinos proveen importantes servicios hidrológicos para comunidades aguas abajo de los ríos. Debido a esta importancia, se han realizado varios estudios hidrológicos en los últimos años, con énfasis en la identificación de procesos hidrológicos e impactos de cambio de uso de la tierra. En estas investigaciones y para la operación de pequeños proyectos de riego y agua potable, los ríos de montaña se han equipado con vertederos compuestos de pared delgada para estimar los caudales. Para transformar el nivel de agua en caudal, las ecuaciones de los vertederos emplean coeficientes de descarga teóricos, los cuales no necesariamente se ajustan a las condiciones reales de campo, principalmente a la fluviomorfología del sitio y aspectos constructivos del vertedero, complicando sus mediciones. Por ello, este estudio analiza el efecto de utilizar coeficientes teóricos en lugar de coeficientes ajustados en campo. El estudio se realizó en 9 microcuencas ($0{,}2 - 7{,}53 km^2$) ubicadas en el Observatorio Ecohidrológico de Zhurucay, en el páramo del sur del Ecuador. Para calibrar los coeficientes, se generaron curvas de descarga mediante mediciones de dilución de sal y mecánicos. Los resultados revelaron que los coeficientes de descarga difieren de su valor teórico hasta en un 15% para vertederos de sección triangular (DCvn) y hasta un 25% para sección rectangular (DCr). El DCvn afecta 4 veces más en la estimación de caudales bajos y medios que el DCr en caudales altos. Por su parte, el aforo por dilución de sal es más preciso para caudales medios y altos, pero en caudales bajos, este sobrestima un 10%. En general, los resultados sugieren que es esencial ajustar los coeficientes en campo para evitar errores en diferentes estudios hidrológicos.

Palabras clave: Hidrología, Andes Tropicales, Monitoreo Hidrológico, Aforos, Ecuador.

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Orcid IDs:

Mario Guallpa: http://orcid.org/0000-0001-6651-2672
Rolando Célleri: http://orcid.org/0000-0002-7683-3768
Patricio Crespo: http://orcid.org/0000-0001-5126-0687

1 Introduction

More than 50% of the world population obtains water from mountains. The Andes, which cover a continuous mountain chain in Venezuela, Colombia, Ecuador, Peru, Chile, Bolivia and Argentina, are of more than 2 500000 km^2 and are home to more than 85 million inhabitants (around 45% of total country population). In addition, at least another 20 million people living in the Pacific coastal cities of South America also depend on water originated in the Andes (Hofstede et al., 2003; CONDESAN, 2012). Páramo, puna, jalca and montane cloud forest ecosystems are the water towers of the Andes (Ochoa-Tocachi et al., 2016a), and their natural hydrological regulation is considered key for the operation of unregulated (i.e. without human-made reservoirs) drinking water and irrigation systems in high Andean areas (De Bièvre et al., 2003; Hamel et al., 2018).

Several hydrological studies have been carried out in recent years in Andean páramo catchments, ranging from understanding hydrological processes and runoff generation (Mosquera et al., 2015; Correa et al., 2017, 2019; Mosquera et al., 2018; Lazo et al., 2019) to the impacts of agriculture (Buytaert et al., 2005, 2006; Crespo et al., 2010; Ochoa-Tocachi et al., 2016a) and afforestation with exotic species (Buytaert et al., 2007; Crespo et al., 2012; Bonnesoeur et al., 2019, 2018; Marín et al., 2018). Similar studies have been conducted in Andean forests (Tobón, 2008; Roa-García et al., 2011; Crespo et al., 2012). These studies rely on hydrological data gathered in experimental and representative catchments. Such is the importance of hydrological monitoring that has given rise to the Regional Initiative for the Hydrological Monitoring of Andean Ecosystems-iMHEA (Célleri et al., 2010; Ochoa-Tocachi et al., 2018). iMHEA monitors rainfall and discharge in more than 25 micro-catchments (between 0,2 and 10 km^2) distributed throughout the Tropical Andes.

In most of these small research catchments, V-notch weirs (triangular section) are used to measure open channel discharge (Célleri et al., 2010; Crespo et al., 2010; Guallpa and Célleri, 2013; Mosquera et al., 2015; Ochoa-Tocachi et al., 2016b) as they allow converting stage (or head) to discharge with high precision and accuracy through the weir equation. However, it is very difficult to find ideal field conditions for weir construction and for installation of water level sensors (Guallpa and Célleri, 2013). These departures from ideal conditions increase the uncertainty in measurements, because the discharge coefficient of the weir equation is affected. According to several authors (Westerberg et al., 2011; Guallpa and Célleri, 2013), these uncertainties should be critically evaluated before estimating water resources, but in practice are rarely done.

Theoretical discharge coefficients have been determined in laboratory through tests under controlled conditions (Bergmann, 1963). However, when weirs are constructed in small mountain rivers and ravines, field conditions are different from laboratory. Two conditions that are difficult to meet in the field are: 1) water level must be measured at an upstream minimum distance of four times the maximum head over the weir crest; and 2) incoming water flow speeds must be close to zero. The first condition is not fulfilled because, in most cases, the sensor is installed next to the weir crest, so the measurements are affected by the drawdown over the weir; this position is chosen since this is the least likely place where sediments carried in rainy seasons can cause damage to the submerged electronic sensor.

On the other hand, the riverbed steep slope (Mosquera et al., 2015) and peak flow rates do not allow keeping low flow speeds over the weirs. For these reasons, the weir's discharge coefficient will be different from the theoretical values. Nonetheless, no studies have been found so far that evaluate the impact of using theoretical discharge coefficients instead of those determined in the field. According to Birgand et al. (2013); Coxon et al. (2015), there is a literature gap about the potential uncertainty associated with discharge measurements under non-ideal conditions. In this context, the objective of this study is to identify the effect of using theoretical weir coefficients on discharge calculation under non-ideal weir-construction conditions in Andean headwater catchments.

2 Materials

2.1 Study Area

The study was conducted in the Zhurucay Ecohydrological Observatory (Figure 1), which is located in the paramo ecosystem in southern Ecuador. Zhurucay is a tributary of the Jubones River that flows into the Pacific Ocean (Mosquera et al., 2015; Correa et al., 2019). Zhurucay has a drainage area of 7,53km^2 and an altitudinal range between 3400 and 3900 $ma.s.l$. The average annual rainfall is 1345 mm; rainfall is well distributed during the year and it is characterized by frequent and low intensity events (Padrón et al., 2015). The annual evapotranspiration (ETa) is 622 mm (Ochoa-Sánchez et al., 2019). Vegetation is mainly composed of tussock grasses (72 % of the basin) and cushion plants (24 %); forest species such as Polylepis and Pines cover the rest of the catchment (Correa et al., 2017; Carrillo-Rojas et al., 2019).

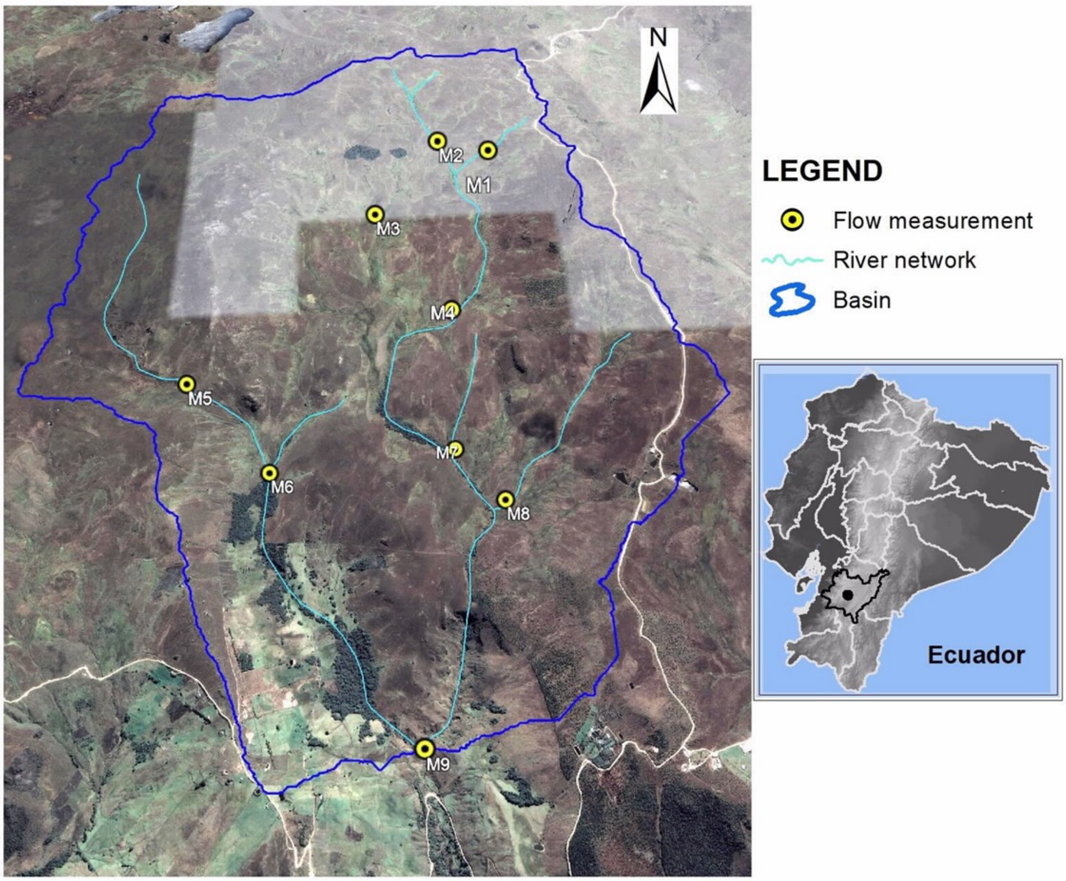

Figure 1. Study site: Zhurucay Ecohydrological Observatory. M9: rectangular weir. M1 to M8: V-notch weirs.

2.2 Weirs

Discharge monitoring in Zhurucay follows a nested approach, using 9 weirs located up or downstream stream the confluences. Those weirs are either compound V-notch sharp-crested weirs (consisting of one v-notch part (triangular section) and a rectangular part, and denoted as M1 to M8) or a sharp-crested rectangular weir (M9). There is free discharge downstream the weirs (i.e., there is air under the sheet of discharge over the weir or the nappe), which is a requirement for using the weir equation (Figure 2). Each weir has a water level sensor with an accuracy of 1 mm, and records data with a 5-min frequency. Compound V-notch weirs were placed in the smaller streams (0,2 to 3,28km^2) as they allow measuring very low discharges accurately (Célleri et al., 2012). Weir construction and specifications can be found in Bergmann (1963); United States Bureau of Reclamation (2001).

Figure 2. Examples of a rectangular weir (left) and a compound (V-notch-rectangular) weir (right) in the study area.

There are specific weir equations for V-notch and rectangular weirs. For V-notch weirs, when the discharge occurs within the triangular section, we used the Kindsvater equation (Equation 1) given by United States Bureau of Reclamation (2001). For suppressed, sharp-crested rectangular weirs, Kindsvater and Carter (1959) developed equation (Equation 2). The same authors developed an equation to estimate the discharge that passes over a compound weir, consisting of one V-notch part (with a 90-degree notch angle) and a rectangular part (Equation 3).

$$Q = 1{,}37 * h^{5/2} \quad (1)$$

$$Q = 1{,}77 * L * h^{3/2} \quad (2)$$

$$Q = 1{,}37 * (h^{5/2} - (h-H)^{5/2}) + 1{,}77 * B(h-H)^{3/2} \quad (3)$$

For equations 1 to 3: Q is discharge (m^3/s), h is the water head above the bottom of the notch (m), measured at a point at a horizontal distance of 4H upstream the weir, H is the v-notch height (m), B is the combined width (m) of the weir´s rectangular parts, L is the width (m) of the rectangular weir; and 1.37 and 1.77 are the theoretical discharge coefficients for the v-notch (DCvn) and the rectangular section (DCr), respectively. The H of all Zhurucay weirs is 30 cm. For this study, low discharges were considered up to 5,5 l/s ($h < 11$ cm), 5.5 and 67,5 l/s ($11 \leq h < 30$ cm) for medium discharges, and values higher than 67.5 l/s ($h \geq 30$ cm) for high discharges.

3 Methods

Discharge coefficients of equations 1 to 3 were questioned and recalculated. First, water level (stage) and discharge were measured in the field, in several field campaigns, making sure the complete range of flow rate conditions (low to very high) was registered (Section 3.1). Measurements for medium and high flow rates (8 to 10 discharge measurements) were done in February-May period (rainy period), and for low flow rates (5 to 7 measurements) in August and September (dry period). Then, we calculated the effective discharge coefficients and analyzed the impact of using theoretical ones for discharge estimation (Section 3.2).

3.1 Methods for discharge measurements

Three discharge-gauging methods were used to estimate the head-discharge curves: volumetric (volume-time), velocity-area (Current meter) and dilution method. In this section, we provide the details of each method. The dilution method is described in more detail since it is the least common.

3.1.1 Volumetric Method

A 20 liters bucket was used to collect water flowing over the v-notch weirs. The time to fill the bucket was measured by stopwatch. The discharge was estimated as the division of the bucket volume to the time needed to fill the bucket (Hydromatch, 2014). This method was used to measure discharges with water level above the weir bottom of up to 15.5 cm. Several measurements were taken in succession as to have an indication of the accuracy of results.

3.1.2 Velocity-Area Method (Current meter)

The discharge was determined from measuring the stream cross-section area and the average velocity of flow. This method is detailed in the Hydrological Practices Guide of the World Meteorological Organization (WMO, 1994). These measurements were made upstream or downstream of the weir (distance of 5 m approximately), where the water flow conditions were stable. Flow velocity was measured using a current meter propeller revolving about a horizontal axis. Each revolution of the propeller generates an electrical impulse that is recorded by a datalogger. The speed of revolution is proportional to the flow velocity (WMO, 1994). Before undertaking field measurements, the equipment was calibrated in the laboratory according to the factory manuals. This method was used to measure medium to high discharges, when the water head above the weir was higher than 15 cm. The method was not used for low discharges because the low water levels meant the propeller was not submerged totally.

3.1.3 Chemical method (Salt Dilution)

This method relies on the ability of the stream to uniformly dilute the tracer in the water (Rantz, 1982). Mountain rivers and streams have slopes greater than 35% on average (Mosquera et al., 2015) and turbulent flow. These features allow for the application of the salt dilution method in the study area. Furthermore, according to Kite (1993), this technique should be applied when discharge is lower than 15 m^3/s. In the study area, the maximum measured discharge is $6m^3/s$ at the outlet (M9). Therefore, the method was applied to gauge low, medium and high discharge.

The specific method used was the instantaneous injection (Rantz, 1982). The detailed procedure for the field gauging is described in Frederick and Cobb (1985); Kite (1993); Bronge and Openshaw (1996). This can be summarized in four steps: 1) diluting a known salt quantity in a bucket of water, 2) injecting the solution upstream of the gauging section at a point where the flow is turbulent, 3) measuring the initial Electric Conductivity (EC) at the gauging section and then for every time step (the time step for the present study was 1 second), 4) taking continuous measurements until EC reaches the initial value ($\pm 2\mu S/cm$). When initial–maximum relations of electric conductivities are between 2.5 to 3, discharge measurements are very accurate (Bronge and Openshaw, 1996; Comina et al., 2013).

To calculate discharge, the time-EC curve has to be constructed. The area beneath the curve corresponds to the rise in EC because of the injected salt. The salt equivalent that crosses the section in each time step is then obtained by means of the conversion factor (K). For our case, $K = 2{,}0832$ ($l/mg * \mu S/cm$). The area beneath the curve is determined using equation 4, and the gauging discharge using equation 5. Where A is the area beneath the gauging curve ($\mu S/cm * s$); EC(t) is electric conductivity in the time t ($\mu S/cm$); ECbg is the river's initial electric conductivity ($\mu S/cm$); M is the amount of salt that is injected (mg); K is the conversion factor; and Q is the estimated discharge (l/s).

$$A = \int \left(EC(t) - EC_{bg}(t)\right) dt \approx \sum \left(EC(t) - EC_{bg}(t)\right) \Delta t \tag{4}$$

$$Q = \frac{M}{A/K} \tag{5}$$

In order to make sure that the saline solution that is injected to the river is properly mixed, it is necessary to consider an adequate distance between the injection point and the gauging section. Although there are several equations to calculate this so called mixing length (Kite, 1993; Comina et al., 2013, 2014), it is better to determine this length on the field for every site (Tazioli, 2011). As a rule of thumb, this length should be between 20 and 70 meters, depending on the discharge and the conditions of the flow in the gauging section (Sappa et al., 2015). Besides, the distance between the injection point and the gauging section must be straight and without ponding for the salt not to be separated from the main flow (Hudson and Fraser, 2002). Because every stream of the 9 micro-catchments has different fluviomorphological properties, different salt amount-discharge relations were used for the flow gauging. Table 1 shows a guide for flow gauging in the páramo ecosystem with the salt dilution method, based on initial and maximum EC ratio (μ_{max}/μ_0) which have to be between 2.5 to 3 for an adequate flow gauging (Comina et al., 2013).

Table 1. Relationship among the salt amount, mixing length and discharge for flow gauging using the salt dilution method in the studied basin.

Salt amount (M)	Mixing length	Discharge (Q)	M/Q	$\frac{\mu_{max}}{\mu_0}$
gr	m	l/s	$\frac{kg}{m^3}$	-
10	13	2.19	4.56	3.17
10	13	3.17	3.15	2.98
14	13	5.31	2.63	3.26
16	15	8.51	1.88	2.68
35	18	14.34	2.44	2.73
36	15	18.89	1.9	3.27
65	18	42.16	1.54	2.94
85	20	51.17	1.66	2.78
148	20	81.75	1.81	3.1
177	25	138.46	1.27	2.29
360	25	384.22	0.93	2.74
420	30	621.65	0.67	2.6
2500	50	1420	1.76	2.8

μ_{max}: max conductivity.
μ_0: initial conductivity.

The determined length for the different streams is between 13 m and 50m. Except from the low flow rate conditions, the lengths were in the 20-70 m range, as suggested by (Sappa et al., 2015). Even though the values shown in Table 1 can be used as a reference to gauge flow rates in basins of similar conditions, it has to be taken into account that the amount of salt to dilute and the mixing length depend on the velocity and turbulence of the flow, on the initial EC, and on the slope and ponding conditions of the water in the stream.

For the total number of flow rate gauging essays that were performed, the average relation was 2.01 kg of salt per m^3, with a minimum of 0,67kg/m^3 and a maximum of 4,56kg/m^3. These relations are in agreement with Valdes (2007), who recommended values in the 2-5 kg/m^3 range. On the other hand, (Hudson and Fraser, 2002) shown that the salt quantity is not critical for the application of the salt dilution method. They concluded that if the amount of salt is increased, the area beneath the EC curve would proportionally increase and have a minimum impact on discharge estimations. Nonetheless, they suggest using concentrations of $2kg/m^3$.

3.2 Discharge coefficient calibration

To calculate the discharge curve for each weir, the best gauging method for different field conditions was determined. For low discharge, the volumetric method was considered as the reference because of the high precision that it has for these conditions. For medium and high discharge, the salt dilution method was considered as the reference because it is very accurate in mountain rivers (Kite, 1993) and its precision is higher than 95% under full mixing conditions (Moore, 2004). To make sure that the results of the present study are robust and to calculate the relative differences among the three described methods, the discharge was gauged using all of them simultaneously.

Once the discharge curves are calculated, the Discharge Coefficients (DC) for each weir can be determined. The DCs were calculated by means of the least squares adjustment method (World Bank y Government of the Netherlands funded, 1999), using the stage-discharge relation for each weir and keeping the exponents of the equations constant (Equations 1 to 3). To obtain the best-adjusted discharge curve to gauging points, the Percent Absolute Bias (PAB) (Equation 6) was used as the statistical index to evaluate the difference between the observations (gauging) and the calibrated discharge curve. Where X is the adjusted data; Y is the observed data; and $\langle X,Y\rangle$ is one-half of the average of the $X+Y$ sum. The criteria to categorize the results was adopted from Tokay et al. (2010), shown in Table 2.

$$PAB = \frac{(1/n)\sum_{i=1}^{n} \|X_i - Y_i\|}{\langle X,Y\rangle} \tag{6}$$

Table 2. Criteria for the Percent Absolute Bias index (PAB).

PAB	Adjustment
< 5	Excellent
$5-10$	Very good
$10-15$	Good
$15-20$	Reasonable
> 20	Poor

4 Results and Discussion

4.1 Comparison among flow rate gauging methods

For low discharge conditions, the salt dilution method slightly overestimates the values when compared to the volumetric method $(0{,}14 l/s)$ (Figure 3 and Table 3 show the average differences among the three gauging methods for 9 micro-catchment). This overestimation might be due to the fact that for low discharge conditions the saline solution does not fully mix in the stream, which is the main condition for an efficient gauging, thus causing this error. As the discharge values rise, turbulence also increases and the difference between the salt dilution and the volumetric methods diminishes to a point in which the volumetric method results in higher values for medium discharge conditions. This is because the precision of the volumetric method decreases for higher discharge, i.e. the container is filled with water much faster and the recording time is shorter (< 2 seconds), which impedes time to be measured accurately and generate measurement errors.

Table 3. Differences among the three flow rate gauging methods.

		Flow rate gauging methods					
	Stage	**Volumetric**		**Velocity-Area**		**Salt Dilution**	
	cm	**l/s**	**Difference* (%)**	**l/s**	**Difference* (%)**	**l/s**	**Difference* (%)**
Low discharge	5	0.73				0.9	23.28
	5.2	0.8				0.9	12.5
	5.4	0.86				0.95	10.46
	6.8	1.52				1.7	11.84
	7.5	1.96				2	2.04
	7.9	2.16				2.05	-5.09
	9.5	4.34				4.5	3.68
	10	5.2				4.73	-9.03
	10.5	5.62				5.31	-5.51
Medium discharge	11	6.81	-0.88			6.87	
	11.5	7.37	5.44			6.99	
	12.5	9.64	8.43	15.62	75.77	8.89	
	13.1	10.8	10.2	17.09	74.45	9.8	
	14.5	13	7.43	18.27	51.06	12.1	
	15.5	15.9	6	22.76	51.79	15	
	17.2			24.93	38.5	18	
	18			26.55	32.1	20.1	
	24.8			54.64	26.5	43.2	
	25.6			57.4	21.1	47.4	
	29.8			88.63	15.4	76.81	

*For low discharges, the difference is with respect to volumetric method while for medium and high discharges is with respect to salt dilution method.

The velocity-area method overestimates the discharge (40% compared to the salt dilution method on average (Figure 3 and Table 3)). This might be due to the fact that the gauged streams do not meet the conditions recommended by the World Meteorological Organization (WMO, 1994), in particular that the flow lines must be parallel along the stream section and that the minimum stage above the weir must be 15 cm. These results are similar to the ones in Gees (1990); Tazioli (2011), who found differences up to 38% and 50% respectively for low and medium discharge conditions. On the other hand, Sappa et al. (2015) concluded that the salt dilution and the velocity-area methods are similar, with small differences between 1% and 8%. However, the differences with our research are that in the aforementioned study, channels with laminar flow were used for the current meter gauging. Based on these results, the discharge curve for the different weirs was constructed considering data from the volumetric method for low discharge conditions ($Q < 5{,}5$ l/s) and from the salt dilution method for medium ($5{,}5 \leq Q < 67{,}5$ l/s) and high discharges ($Q \geq 67{,}5$ l/s) conditions.

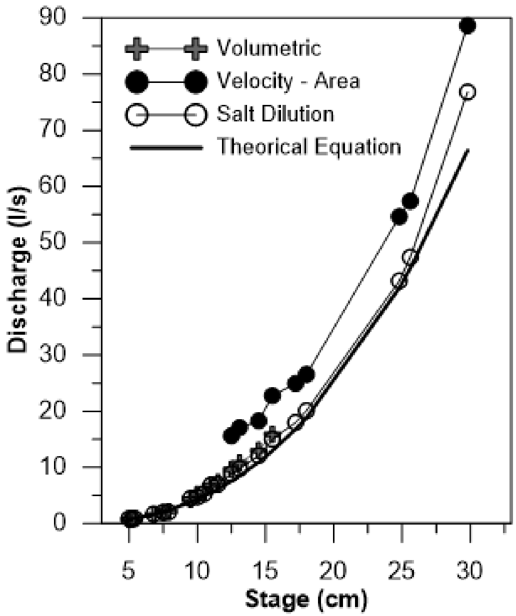

Figure 3. Stage-discharge relation using the three gauging methods, average of 9 weirs.

4.2 Discharge coefficients calibration

Table 4 shows calibrated discharge coefficients for the 9 weirs; five DCr were not calibrated because there were insufficient flow rate gauging data on high discharge in these weirs. The adjustment error for the discharge values obtained in the flow rate gauging are low when compared to the ones calculated using the calibrated discharge curve ($PAB \leq 5\%$ in the Table 4). One the other hand, DCvn vary between 1.19 and 1.56 for the triangular section (theoretical $DCvn = 1{,}37$), and between 1.53 and 3.00 for the rectangular section (theoretical $DCr = 1{,}77$). These differences represent a relative error up to 15% for V-notch weir section (DCvn) and by up to 41.0% for rectangular weir section (DCr) compared with theoretical values (Table 4). The differences between theoretical and calibrated coefficients are because of the specific features of each stream and weir, such as the structure building, the riverbed slope and the cross section.

A more precise hydrograph was obtained by using the calibrated discharge curves. This allows for the determination of the error on water yield of each micro-catchment when using the theoretical equations with the uncalibrated coefficients. Runoff coefficient ($RC =$ input precipitation/outlet runoff) represents the water yield of a catchment. The relative error on the RC is between 2.11% and 15.51% with both negative and positive bias found among this group of weirs, 6.56% on average for all weirs (Table 4). As is observed, when the weirs are not calibrated, the water balance calculation of the micro-catchments is affected.

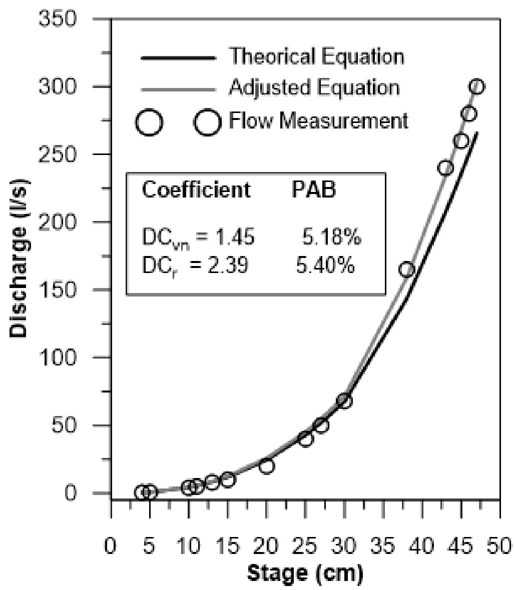

Figure 4. Calibration of discharge curve for compounded weir M4.

A sensitive analysis of discharge coefficients in the hydrograph was carried out (Figure 4). First, the accumulated annual discharge was determined by changing only the adjusted DCvn in the equation 3; then, the same estimation was done by using only the calibrated DCr ($DCvn =$ theoretical coefficient). According to these analyses, for a hydrological year, DCvn affects 4 times more in low and medium discharges than DCr in high discharges. Discharge estimation is more sensitive to DCvn because most of the time (95% of the total records) discharge is lower than $65{,}5 l/s$ ($h < 30$ cm in this study); i.e. flow rate passes only over the triangular section of the weirs. Furthermore, the theoretical equation for the triangular section is valid only for discharge higher than 1.41 l/s ($h = 6{,}4$ cm) (United States Bureau of Reclamation, 2001), which is higher than the low discharge values observed for the study area (0,70 l/s; $h = 5$ cm), especially for dry conditions.

Table 4. Calibrated discharge coefficients for the weir equations and their effect on the Runoff Coefficients (RC) of each micro-basin.

Weir	Discharge Coefficients						Initial	Corrected RC	Relative Error RC
	DCvn			DCr			mm/mm	mm/mm	%
	Value	PAB	Relative Error DCvn	Value	PAB	Relative Error DCr			
M1	1.235	3.9	10.90 %				0.625	0.564	10.82
M2	1.19	3.8	15.10 %				0.648	0.564	14.89
M3	1.557	1.95	-12.00 %				0.564	0.64	-11.88
M4	1.45	5.18	-5.50 %	2.39	5.4	-25.90 %	0.623	0.666	-6.46
M5	1.56	3	-12.20 %				0.56	0.63	-11.11
M6	1.521	8	-9.90 %				0.446	0.491	-9.16
M7	1.3	6.9	5.40 %	1.825	2.8	-3.00 %	0.873	0.855	2.11
M8	1.417	4.7	-3.30 %	3	4.3	-41.00 %	0.731	0.776	-5.8
M9				1.533	5.2	15.50 %	0.782	0.677	15.51

DCvn = Discharge coefficient for Triangle section (V-notch). *DCr* = Discharge coefficient for rectangular section. *RC* = Runoff coefficient.

5 Conclusions

The present study was focused on determining the discharge coefficients for weirs installed in the field and its importance for discharge calculation. In regard of the different flow rate gauging methods, it can be concluded that the velocity-area method is not applicable in all conditions because of the numerous assumptions it poses that are not generally met for mountain rivers; this caused overestimation of the discharge of 40 % on average. The salt dilution method is the best for medium and high discharge conditions, but for low discharge, underestimates 10 % on average when compared to the volumetric method, which is more precise for these conditions. The use of this method is particularly convenient because it is low-cost, easy to apply; it has low impact and high precision.

On the other hand, even if the geometry was the same for the compounded weirs, the calibrated coefficients varied between 1.190 and 1.557 for DCvn and between 1.53 and 3.00 for DCr, due to different specific site characteristics. When the theoretical discharge coefficients are used, the error on the micro-catchments water yield varies between 2.11 % and 15.51 % for the different weirs in a hydrological year. These errors affect directly the closure of the hydrological balance of the micro-catchments. Therefore, we conclude that every weir needs to have a site calibration of the discharge coefficient as a requirement to obtain reliable discharge estimations.

The methodology and the results of the present study will be useful for different water monitoring projects in Andean ecosystems. The values of discharge can be evaluated and corrected in order to minimize the error in hydrological studies and water resources development projects.

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