Validation Of Salt Dilution Method For Discharge Measurements In The Upper Valley Of Aniene River (Central Italy)

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Abstract: - Stream discharge can be measured using several methods, which can be influenced by the natural streaming characteristics of the river. The conventional approach to measuring stream flow is the current meter method, based on determining the mean discharge using the velocity and the cross sectional area. This method allows quick stream flow measurements, but in mountain streams, during turbulent flow conditions, or in case of flow depths, smaller than the recommended performance limits for conventional current meters, can give unreliable measurements. An alternative method of stream flow measurement is the salt dilution method that involves injecting an artificially tracer (usually NaCl) and determining its dilution, following complete mixing into the flow, by means of integration of the electrical conductivity as a function of time. This technique is available for use in mountain streams where the other procedures are more problematic. This paper deals with the preliminary results referred to the validation of the salt dilution method in the Upper Valley of Aniene River (Central Italy), in the aim if defining a reliable methodology for the evaluation of discharge in mountain streams, where turbulent flows make difficult apply the conventional current meter method. In the following they are presented the preliminary results of stream discharge measurements, coming from three different campaigns driven from September to October 2014, executed in one of the sections of Aniene River. The comparison of these elaborations, carried on by the application of both methods, is useful to define the reliability and accuracy of discharge measurements carried out by salt dilution method.

Key-Words: - discharge measurement, salt dilution method, mountain streams, current meter method, slug injection, Aniene River

1 Introduction

Karst aquifers play a key role in human life and economic activity and constitute more than 30 % of the EU land mass [1]. The fast dynamic of karst aquifers discharge is, as a consequence of strong interconnection between groundwater, surface water and precipitation, due to a network of highly permeable flow features, embedded in a less permeable fractured rock matrix [2]. In these complex hydrogeological scenarios, stream discharge can be influenced by changes in meteorological conditions, tributary streams or from groundwater seeping into the river. Variations in stream flow discharge can bee used for characterizing karst systems and investigating the processes that control interactions between groundwater and surface water [3]. Water resources assessment is an important tool to evaluate groundwater dynamics in relation to human impacts and drinking water consumption [4]. Thus, the determination of the amount of stream flow discharge is a direct measure of the amount of water available for drinking, industrial, and agricultural purposes. Stream discharge is also correlated with the habitat biodiversity and the assimilation of nutrients and sediment in runoff, reflecting the integrity of the riparian ecosystem [5]. This paper presents preliminary results of discharge measurements carried out in a gauging section along the Aniene River by the application of traditional current meter and salt dilution method, in framework of the Environmental Monitoring Plan related to the catchment project of the Pertuso spring, in the Upper Valley of Aniene River (Central Italy), which is going to be exploited to supply an important water network in the South part of Roma district [6].

Discharge measurements have been carried out performing a slug injection of a NaCl solution and recording electrical conductivity in a downstream section, while at the same time, current meter measurements have been taken in a section placed between the injection point and the electrical conductivity measurement section.

The aim of this work is the validation of the salt dilution method as alternative methodology in mountain stream, where the unsteady flow conditions can make difficult and expensive the application of the conventional velocity area method.

2 Problem Formulation

The measurement of stream flow rate is usually required for river management purposes including water resources planning and protection of flood prevention.

Stream flow measurement technology has evolved rapidly over recent decades. According to the U.S. Geological Survey (USGS) procedure, river discharge can be usually calculated by the velocity area method, as the product of average stream flow velocity at a cross section, perpendicular to the main stream flow, and the cross sectional area. In this method, the river is divided into segments and the discharge through each segment is calculated by multiplying the average velocity in each segment by the segment area. A current meter is usually used to measure the stream velocity at each selected segment. The sum of the products of area velocity for each segment gives the total stream discharge [7].

The conventional velocity area method has some limitations in mountains stream where the irregular cross section and the strong turbulence decrease the accuracy with which water depth and flow velocity can be measured. In addition, flow depths and velocities during low flow conditions may be too small for reliable measurements [8]. This method is also both expensive and difficult especially during floods or unsteady flow conditions due to the instability of measuring instrument. The unsteady flow may be caused by turbulent conditions, irregular bed stream geometry and the growth of weeds (Fig. 1). Thus, the current meter method requires a definitive relationship between velocity measurement and area of the cross section, which is difficult to establish in mountain river, where the hydraulic pattern changes seasonally. This method is generally used because is the most practical and quick for stream flow measurements, except where the river is very shallow or in turbulent condition. Thus, under such conditions, the alternative method of salt dilution may be more suitable.

Figure 1 - An example of unsteady flow conditions (Aniene River)

In the salt dilution method, a tracer solution is injected into the river to be diluted by the stream discharge. Downstream of the injection point, when vertical and lateral dispersion throughout the flow is complete, the discharge may be calculated by the measurement of the electrical conductivity as a function of time. Common table salt (sodium chloride, NaCl) is generally used for salt dilution measurements because it is inexpensive, easily available and non-toxic for the concentrations and exposure times typically associated with discharge measurements.

The salt dilution method is generally used for discharge measurements in mountain streams where swallow depths, turbulent conditions and the irregular, bad geometry of the stream can make difficult to establish the hydraulic profile, and even difficult to measure stream flow velocity with the traditional current meter [9].

A limit of this methodology is the amount of tracer to be added to increase the electrical conductivity in the stream flow, which is related to the stream background level of the conductivity. Moreover, only a runoff less than $4 m^3 s^{-1}$ can be made easily, because the amount of salt to be dissolved is difficult to handle (about 20 kg of salt for $4 m^3 s^{-1}$ runoff) [10].

2.1 The test site

The study area is located along the SW boundary of the Simbruini Mountains, characterized by the confluence of the Fiumata Valley and the Granara Valley from which starts the Valley of Aniene River [11]. In this area it outcrops an important carbonate karst aquifer, mainly made of highly permeable Cretaceous carbonate rocks, deeply fractured and mostly soluble (Fig. 2).

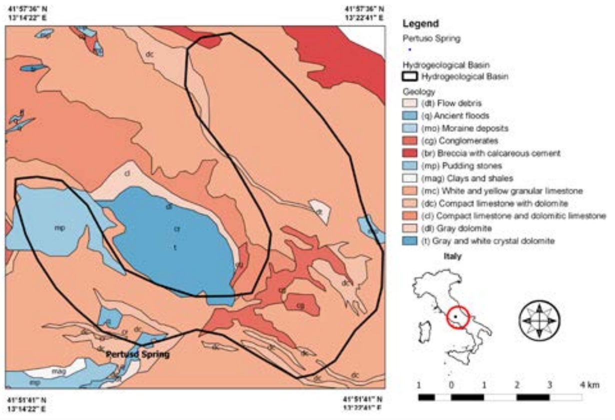

Figure 2 - Simplified geological map of the study area

The discharge measurements were carried out in the Upper Valley of Aniene River, between the town of Filettino and Trevi nel Lazio (FR), in Latium Region, Central Italy (Fig. 3). The Aniene River crosses the Natural Park of Simbruini Mountains, the largest protected area of Latium Region, which belongs to Nature 2000 network as Special Protection Areas (SPAs). The Park is characterized by karst landscape where take origin mountains springs that discharge into the Aniene River, like the Pertuso spring which supplies drinking water to the city of Rome and currently is feeding the Comunacqua hydroelectric power plant, owned by ENEL group.

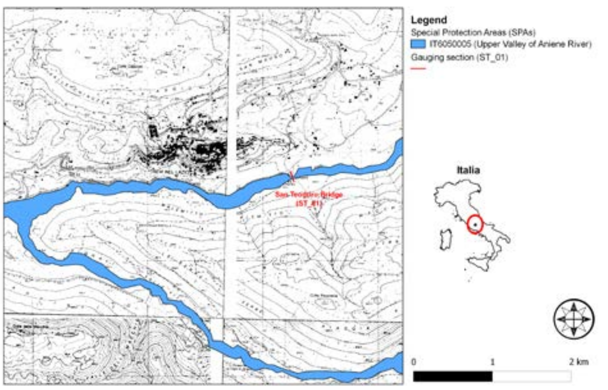

Figure 3 - Study area and location of gauging section

In the framework of this work, the discharge data have been collected referred to three campaigns driven from September to October 2014, using the current meter method and the salt dilution method.
San Teodoro Bridge (Fig. 4) has been chosen as gauging section (ST_01), allowing easy installing and management of the current meter, but also satisfying the salt dilution method requirements.

Figure 4 - San Teodoro Bridge gauging section (ST_01)

San Teodoro Bridge gauging station is relatively straight to ensure streamlines parallel to each other and reduce errors in velocity measurements. The bed stream relatively uniform and free of heavy aquatic growth allows keeping the current meter perpendicular to the flow while measuring velocity, to ensure a stable relation between stage and discharge. ST_01 gauging station is also suited for measuring stream flow by salt dilution method. As a matter of fact, in the section there are no backwater areas and local inflows between the injection and measurement points, where the salt can be delayed and separated from the main flow. The bridge makes easy the slug injection of the tracer solution and allows rapid dissolution and complete mixing into the flow.

At ST_01 gauging station the Aniene River surface width ranges from 4.5 to 5 meters and its depth from 0.2 to 1 meter, according to the limits imposed by the type of current meter used.

2.2 The current meter method

The current meter method involves measuring the area and the velocities of a stream at a cross section which is perpendicular to the main flow of the river. Usually, river discharge (Q) is calculated as the product of the cross section area (A) of flow by the average stream flow velocity (V) in that cross section:

$$Q = V \cdot A \tag{1}$$

Thus, the river cross section is divided into numerous vertical sub-sections (n), in each one the area is obtained by measuring the width (l_i) and depth (h_i) of the sub-section and the stream flow velocity is determined using a current meter. The total discharge is then computed by summing the discharge of each sub-section [12]:

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$$Q = \sum_{i=1}^{n} l_i \cdot h_i \cdot \overline{v_i} \quad (2)$$

The preliminary step in stream flow measurements is the determination of water widths by stringing a measuring tape from bank to bank at right angles to the direction of flow. In mountain stream, where the hydraulic pattern changes monthly, more than a single measurement is needed to characterize accurately the hydraulic profile of the cross section. For this reason it has been necessary determine the hydraulic profiles of the ST_01 for each discharge measurements campaigns driven in September and October 2014 (Figg. 5 and 6).

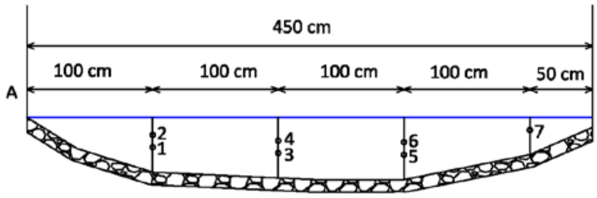

Figure 5 - Stream cross section illustrating sub-sections to determine discharge by current meter method (September 2014)

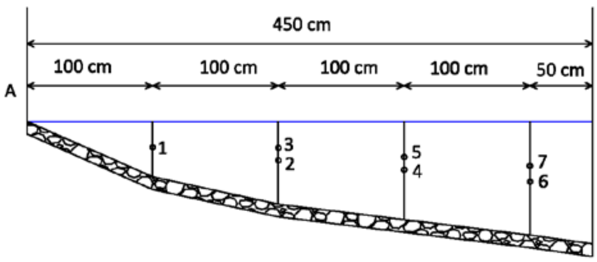

Figure 6 - Stream cross section illustrating sub-section to determine discharge by current meter method (October 2014)

This measuring tape is used to define the hydraulic profile of the cross section and the location of each velocity measurements. Determining the cross sectional area of a stream involves measuring water depths at a series of points across the stream and multiplying by the width of the stream within each segment represented by the depth measurement.

With the aim to obtain a mean velocity, ST_01 section has been divided into 4 vertical parts, almost equally spaced by 1.00 m. Along each one of these investigated verticals, up to 2 measuring points have been defined at different depths (0.2 and 0.3 m from bed stream).

The main equipment needed to measure the stream flow velocity in each verticals is a SEBA horizontal axis current meter F1, having a propeller diameter of 80 mm which, combined with SEBA Z6 pulse counter, allows to measure velocity between 0,025 m/s and 10 m/s. The SEBA current meter has been used as rod equipment with tail plane for best positioning to the flow direction.

The operating principle is based on the proportionality between the flow velocity and the resulting angular velocity of the rotor. For each measurement point, flow velocity is determined counting the number of spins of the meter rotor during a fixed interval of time. The current meter responds instantly to any changes in water velocity but in unsteady flow conditions is difficult obtain accurate measurements due to the difficult of keeping the current meter attached to the measuring line. Thus, in order to assess any fluctuations due to the turbulence condition and, also, to avoid accidental measurement errors, velocity has been measured for at least 60 seconds, according to EN ISO 748:2007 requirements [13].

This current meter method gives the local water velocity in each vertical following the application of a calibration equation between stream velocity (cm/sec) and the number of spins (sec^{-1}) (3).

$$v = 0.82 + 33.32 \cdot n \quad (3)$$

Stream discharge measurements obtained by the velocity area method are summarized in Tab. 1.

Date	Gauge Height (m)	Discharge Q (m^3/s)
10/09/2014	0.60	1.38
29/09/2014	0.50	0.98
17/10/2014	0.70	1.77

Table 1 - Mean discharge values obtained by current meter method

Table 1 shows the discharge values coming out from the three measurements campaigns, referred to the maximum height value, measured in the stream in each campaign. By the chance the average value among the three ones, calculated, is Q = 1.38 m^3/s, which is the same measured in the September 2014 campaign.

2.3 The salt dilution method

There are two variations on dilution gauging, depending on whether the tracer is injected into the stream at a constant rate or as an instantaneous slug. The salt dilution method by slug injection was chosen as the most practical method in the study area, because of the difficulty of handling the large quantities of salt solution required by the constant rate injection.

The basic principle of salt dilution method is to add instantaneously a known quantity of a NaCl solution into the stream and observe the variations in electrical conductivity at a point where it is fully mixed with the flow.

ST_01 gauging station is an ideal injection site because has the basic characteristics for accurate streamflow measurements by salt dilution method. In fact, the turbulent condition allows completely dissolution and fully mixing with the flow at the point where electrical conductivity is measured. San Teodoro Bridge has been used to dump the salt directly into the injection point: the turbulence created below the bridge allows the dissolution of the salt and the mixing into the stream.

According to IS0 9555-1:1994(E) requirements [14], the salt dilution method involves the injection of a volume of a NaCl solution at a cross section in which the discharge remains constant for the duration of the gauging. At a second cross section placed downstream the injection point, at a distance sufficient for the injected solution to be uniformly diluted, the stream electrical conductivity is determined over a period of time sufficiently long to ensure that the NaCl solution has passed through the second cross section [15].

It has been used a saturated NaCl-solution made by dissolving about 2 kg of salt in 10 liters of stream water, depending on the temperature and the background conductivity of the stream. A PC650 probe (Eutech Instruments) was used to collect the electrical conductivity measured data. The instrument is auto-ranging between 0 and 500 mS/cm, with an accuracy of ± 0.05%.

The dissolution of NaCl in water is proportional to water temperature and inversely proportional to the existing concentration of salt. After injection, the salt mixes into the stream by longitudinal dispersion, a process in which dissolved salt in the plume moves along its concentration gradient until a uniform concentration exists [16]. The instantaneously injection of NaCl solution into the stream produces downstream a wave of electrical conductivity increasing, as shown in Fig. 6.

The stream discharge, Q (m^3/s) is calculated by the following formula [17], based on the principle of the conservation of mass:

$$Q = C_s \cdot \frac{V_s}{\int_{t_0}^{t_0+t_p} \left[C(t) - C_b\right] \cdot dt} \tag{4}$$

where: V_s (m^3) is the volume of injected solution, C_s (μS/cm) is the electrical conductivity of the injected solution, C_b (μS/cm) is the stream baseline electrical conductivity, $C(t)$ (μS/cm) is the stream electrical conductivity at time t, t_0 (s) is the elapsed time, taking as origin the instant at which the injection started and t_p (s) is the time of arrival of the first molecule of tracer at the cross section.

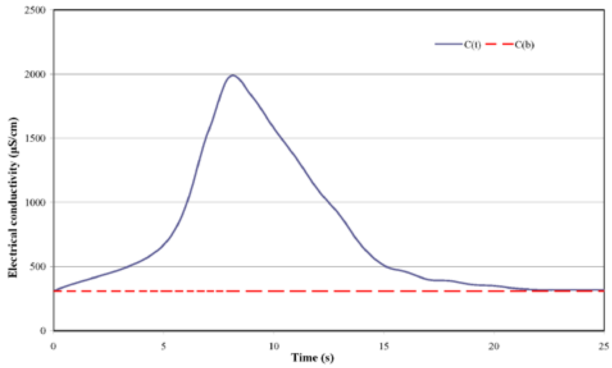

Figure 6 - An example of a salt dilution measurement done at ST_01

Table 2 lists discharge measurements obtain from the application of the salt dilution method carried out from September to October 2014.

Date	Gauge Height (m)	Discharge Q (m^3/s)
10/09/2014	0.60	1.30
29/09/2014	0.50	0.99
17/10/2014	0.70	1.71

Table 2 - Mean discharge values obtained by salt dilution method

The discharge values, measured by the salt dilution method, are definitely comparable with ones obtained by the traditional current meter method and in the following Table 3.

Date	Q (m^3/s)^1	Q (m^3/s)^2	Δ%
10/09/2014	1.38	1.30	8
29/09/2014	0.98	0.99	1
17/10/2014	1.77	1.71	6

Table 3 - Mean discharge values obtained by current meter method (1) and salt dilution method (2)

3 Problem Solution

Results of the two methods for determining stream flow discharge at San Teodoro Bridge gauging station (ST_01) were compared. Current meter method is usually the standard by which other stream flow measurement methods are compared.

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Thus, in Tab. 4, they are presented the results, coming from the application of the two methods, and the percentage differences, between each campaign result, expressed as:

Date	Gauge Height (m)	Q $(m^3/s)^1$	Q $(m^3/s)^2$	Δ %
10/09/2014	0.60	1.38	1.30	8
29/09/2014	0.50	0.98	0.99	1
17/10/2014	0.70	1.77	1.71	6

Table 4 - Mean discharge values obtained by the application of both methods

Preliminary results seem to give good indications for the validation of salt dilution method for discharge measurements. For example, at San Teodoro Bridge, both methods provide discharge measurements very close the to the other so that both methods could be performed for comparative purposes (Fig. 7).

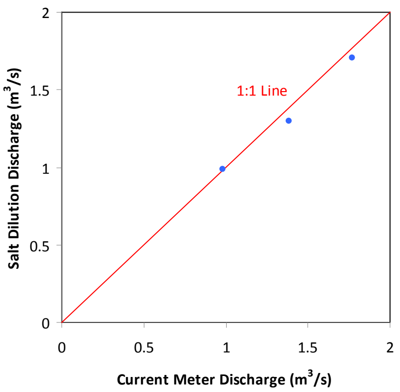

Figure 7 - Comparison of current-meter and tracer-dilution discharge measurements at ST_01

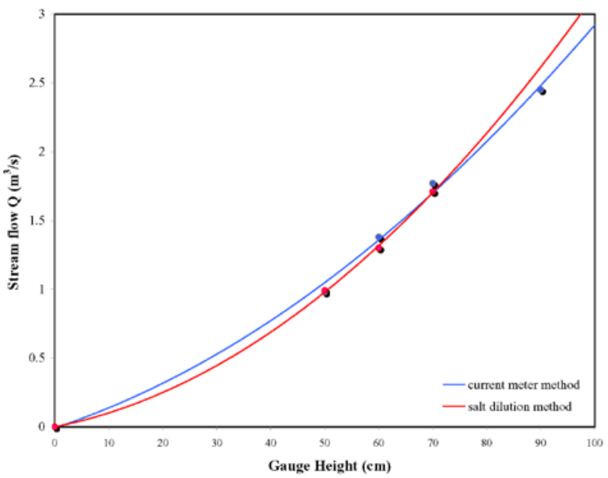

Figure 8 - Comparison of stream flow discharge as a function of time for current meter and salt dilution method

The rating curves for ST_01 gauging station show the changes in the stream flow depending on gauge height from September to October 2014. Rating curve based on current meter and salt dilution measurements, fitted by an exponential function, are very similar, with comparable discharge values coming from the application of both methods (Fig. 8).

The measurements collected by salt dilution method fell close to the rating curve based on current meter method, with a percentage differences of less 8%.

4 Conclusion

The purpose of this paper was to describe the preliminary results of a study to determine the feasibility and accuracy of discharge measurements using the salt dilution method in mountain river.

Data were collected from September to October 2014 at San Teodoro Bridge (ST_01), in the Upper Valley of Aniene River, by the application of conventional current meter and salt dilution method. The salt dilution stream flow has been compared to discharge measurements determined by current meter method. Based on these measurements, two different rating curves were developed to determine streamflow discharge.

The salt dilution method compares favorably in accuracy with current metering as a method of measuring streamflow in mountain river, and appears to be more accurate where the turbulence flow might interfere with current meter measuring. Furthermore, the salt dilution method is easier to apply and more economical in terms of equipment cost. Current meter method is well suited where flow conditions are close to laminar, whereas the salt dilution method are better fitting to river with unsteady flow conditions and the irregular stream bad geometry. However, in the traditional current meter method, excess sediment and seasonal growths of weeds can change the hydraulic profile of the cross section, requiring new rating curves at any measurements campaign.

Both methods seem to be complementary: in fact, while current metering requires laminar flow and is unsuited under turbulent conditions, the reverse is true of salt dilution gauging.

Even if the comparison with discharge measurements carried on by the application of both methods shows comparable values, several factors can affect the accuracy the discharge measurements

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obtained by salt dilution method. The loss of tracer between the injection point and the downstream cross section makes not applicable the equation for the conservation of mass and consequently the computation of stream discharge. Other factors that may have caused inaccuracies between current meter and salt dilution stream flow measurements are the tracer probe accuracy limits and the incomplete mixing throughout the stream cross section before the downstream gauging section is reached.

This fact let us pointing out the real importance of the determination of the degree to which an added tracer is diluted by the flowing water. The success of the slug injection methods requires the complete mixing of the added tracer diluted by the flowing water in as short a distance as possible.

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