Experimental methods for river discharge measurements: comparison among tracers and current meter

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Abstract Discharge measurements in natural watercourses are performed in order to determine the value of the surface outflow of a basin, its temporal variability, and the outflow characteristics. The methods conventionally used for these measurements utilize an immersed current meter in different points of a river section, which acquires the mean flow velocity. Using this measurement, the discharge can be calculated. Some experimental problems arise, however, when there is a very high discharge. An important method, valid in such cases, is the artificial tracing method. In particular, the use of chemical tracers for small watercourses is very convenient because they are low cost, easily handled, low impact and provide satisfactory results. In the past, radioactive tracers such as tritium have been used in large rivers, while fluorescent tracers have been commonly exploited in the USA and now elsewhere. However, if the water is turbid, the suspended sediments may easily absorb some tracers. In this paper, the preliminary results of a comparison between current meter and artificial tracer measurements are reported. In particular, field tests in a small tributary have been performed, in order to investigate the behaviour of different tracers.

Key words tracer; current meter; river discharge; stage–discharge relationship; suspended sediment; stream

Méthodes expérimentales pour mesurer le débit des cours d'eau: comparaison entre les traceurs artificiels et le courantomètre

Résumé Les mesures de débit en cours d'eau naturels sont effectuées afin de déterminer la valeur de l'écoulement de surface à l'exutoire d'un bassin, sa variabilité temporelle, et les caractéristiques de cet écoulement. Les méthodes classiquement utilisées pour ces mesures utilisent un courantomètre immergé en différents points de la section d'une rivière, qui mesure la vitesse d'écoulement moyenne. En utilisant cette mesure, le débit peut être calculé. Certains problèmes expérimentaux surgissent cependant en présence d'un débit très élevé. Une méthode importante, valable dans de tels cas, est la méthode de traçage artificiel. En particulier, l'utilisation de traceurs chimiques pour de petits cours d'eau est très pratique car ils sont peu coûteux, faciles à manipuler, à faible impact et fournissent des résultats satisfaisants. Dans le passé, des traceurs radioactifs comme le tritium ont été utilisés dans les grands fleuves, tandis que des traceurs fluorescents ont été couramment employés aux Etats-Unis et maintenant ailleurs. Cependant, si l'eau est turbide, les sédiments en suspension peuvent facilement absorber certains traceurs. Dans cet article, les résultats préliminaires d'une comparaison entre des mesures par courantomètre et par traceur artificiel sont présentés. En particulier, des tests de terrain sur un petit affluent ont été réalisés, afin d'étudier le comportement de traceurs différents.

Mots clefs traceur; courantomètre; débit fluvial; relation hauteur–débit; sédiments en suspension; cours d'eau

1 INTRODUCTION

Discharge measurements in natural watercourses are performed in order to determine the value of the surface outflow of a basin, its temporal variability, and the outflow characteristics. Hydrometric stations are usually equipped with a staff gauge, which records values continuously over defined time periods. Unfortunately, there are not as many hydrometric stations as would be ideal, though there are enough for

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sufficient data collection. A stage–discharge relationship allows the water level data to be converted into river discharge information. Such relationships can be explained using analytical formulas, but it is better to obtain experimental data and calibrate it using direct measurements of the river discharge. In this case, it is crucial to use appropriate tools to measure the watercourse discharge with good precision, accuracy and repeatability.

The methods conventionally used for these measurements utilize a current meter immersed in different points of a river cross-section, to acquire the mean flow velocity of the section. Based on this measurement, the discharge can be calculated using different computational methods. Such measures are reliable and simple to perform in many situations. Some experimental problems arise, however, when there is a very high discharge. This normally occurs during flood events, especially when different materials (such as tree trunks and bushes, etc.) are transported in the water (Becchi and Tazioli 1987). Another problem arises when the water depth is insufficient for immersion of the equipment, or when the flow velocity is lower than the minimum required by the setting (Guizerix and Florkowski 1983). Further, turbulence hampers the use of the current meters. In these conditions, it is preferable to use other methods to measure discharge. An important alternative is the artificial tracing method (Florkowski *et al*. 1969, Guizerix and Florkowski 1983, Airey *et al*. 1984, Florkowski 1991, Hulla *et al*. 1999, Christiansen 2009).

The artificial tracing technique is still not widely used. For instance, authorities responsible for basin management are often not aware of this technique and thus ignore its potential, even when traditional techniques are not easily applied. One of the first applications of artificial tracing was the use of radioactive substances (^{3}H, ^{82}Br, ^{131}I) or simple chemicals such as sodium chloride (Florkowski 1991). The use of chemical tracers for small watercourses is particularly convenient because they are low cost, easily handled, low impact and provide satisfactory results. However, the use of such methodology in wide rivers is also reported in the literature (Florkowski *et al*. 1969, Guizerix and Florkowski 1983, Spreafico and Grabs 1993, Caplow *et al*. 2004). In fact, in the past, radioactive tracers such as tritium have been used in large rivers, while fluorescent tracers have been commonly exploited in the USA.

Nevertheless, the use of these tracers introduces some problems. For instance, if the water is very turbid, the suspended sediments may easily absorb some tracers (Flury and Wai 2003). In other cases, even if the tracers are suited for the hydrometric and turbidometric features of the watercourse, they cannot be used regularly because of normative restrictions regarding radiological protection (this is the case for tritium). Therefore, the search for an ideal tracer is still in progress. We believe that the choice is not unambiguous, but that it depends on many factors. One of the main factors is the conditions at the specific site.

In this work, experimental data comparing measurements performed contemporaneously with different tracers and current meters under different watercourse conditions are presented for medium-sized rivers as well as small tributaries. The chosen basins (the rivers Esino, Musone and Aspio, and the Triponzio Stream) are located in the Marche Region of Central Italy. Numerous experiments have also been performed to verify the amounts of the tracers absorbed by sediments during flood events. Finally, particular care has been used in setting the outflow scale for different sections where stations have been installed to continuously measure the hydrometric levels.

2 METHODOLOGY

2.1 Use of current meters

In principle, a current meter is used to measure the water velocity at various vertical locations within a transverse section of a watercourse and the area to which each measurement refers is determined The flow velocity is multiplied by each corresponding area, and the sum of these products gives the average watercourse discharge in the selected section.

The ISO (International Standardization Organization) standard ISO-748:2007(E) (ISO 2007) establishes the specifications regarding the correct measurement of the mean velocity for the different vertical locations, the calculation of the discharge using different graphical or arithmetic methods, and the choice of the smallest number of vertical locations. In each case, a certain flexibility is necessary to adjust these specifications to the different conditions that are met at each site over time.

In general, current meter measurements are characterized by their ease of use, high precision (especially if the watercourse is not too deep, or in flood) and repeatability. Drawbacks include particular conditions present in the river bed, or the presence of turbulence and high flow speeds, which usually occur under flood conditions. Under these conditions, it is impossible to perform measurements with an appropriate number of vertical data points to guarantee acceptable precision. In many cases, the error associated with this technique is greater than 50%, and the method often underestimates the discharge through the section.

It has also been shown (Whalley *et al*. 2001) that at very low speeds, the performance of current meters may vary greatly, often with significant deviations. In these cases, increasing the number of measured vertical points or the number of points along the same vertical line can often improve the measurements. In every case, a larger number of vertical points results in better resolution and, therefore, more accurate calculations for the watercourse. In our comparison between conventional methods and the tracing technique, we performed current meter measurements at high resolution, i.e. considering a large number of vertical locations and points.

For the years 2000–2008, a series of measurements was performed using current meters in the basins of the Esino and Musone rivers (Fig. 1), which corresponded to stations equipped for continuously measuring the hydrometric level. Over the period 2006–2009, different measurements were performed in the Aspio River basin (Fig. 1), and some of these were coupled with artificial tracing measurements. Corresponding to every measurement, a survey of the transverse section of the river bed was performed; such measurements were also made after significant flooding events. The discharge measured with current meters ranges from a minimum of 0.01 $m^3 \cdot s^{-1}$ to a maximum of 10 $m^3 \cdot s^{-1}$.

2.2 Artificial tracers

To determine water discharge using tracers in the water, the integration method was applied (Guizerix and Florkowski 1983). This method requires the instantaneous release of a known tracer concentration in a section of the watercourse, and the subsequent determination of the tracer concentration in a downstream measurement section. The choice of the most suitable tracer depends on numerous factors, including: the chemical characteristics of the water, the type of suspended sediment, the distance between the release section and the measuring section, the hydrological characteristic of the watercourse, the type of flow to be measured and the sensitivity of the tracer measurement equipment.

The amount of tracer to be introduced into the river is based on the estimated discharge and the detection limit of the equipment. The tracer, which has a concentration C_0, is introduced in the watercourse with discharge Q.

The budget is then written as:

$$C_0 = \int_S \int_0^\infty \mathrm{d}Q \cdot c\mathrm{d}t \tag{1}$$

where the notation S represents the surface integral of dQ; after a distance L, which is called the good mixing length, the expression $\int c\mathrm{d}t$ becomes constant in each flow section:

$$C_0 = Q \cdot \int_0^\infty c\mathrm{d}t \tag{2}$$

During a given time range, T, which is equal to the time needed for the tracer to be transported downstream, an average value for the sample, $\bar{c}$, is found by sampling the tracer concentration present in the measurement station at regular time intervals.

Then:

$$\int_0^\infty c\mathrm{d}t = \bar{c} \cdot T \tag{3}$$

Finally, the discharge is calculated as:

$$Q = \frac{c_0}{c} \cdot \frac{V}{T} \tag{4}$$

where c is the concentration of the sample in volume V.

It is important that the specific conditions are verified, including the following: the tracer cannot be absorbed by the medium, the solution must be well mixed and the flow regime is assumed to be permanent. The method can be applied even in moderate unsteady conditions—assuming an approximate solution of the continuity equation (Gilman 1977)—if, during the tracer dilution test, the change in flow is negligible.

It is important to emphasize how significant the good mixing length is. The good mixing length is the distance, measured along the general path of flow, between the injection cross-section and the downstream cross-section at which the specified degree of mixing is obtained (ISO 1994). To estimate the

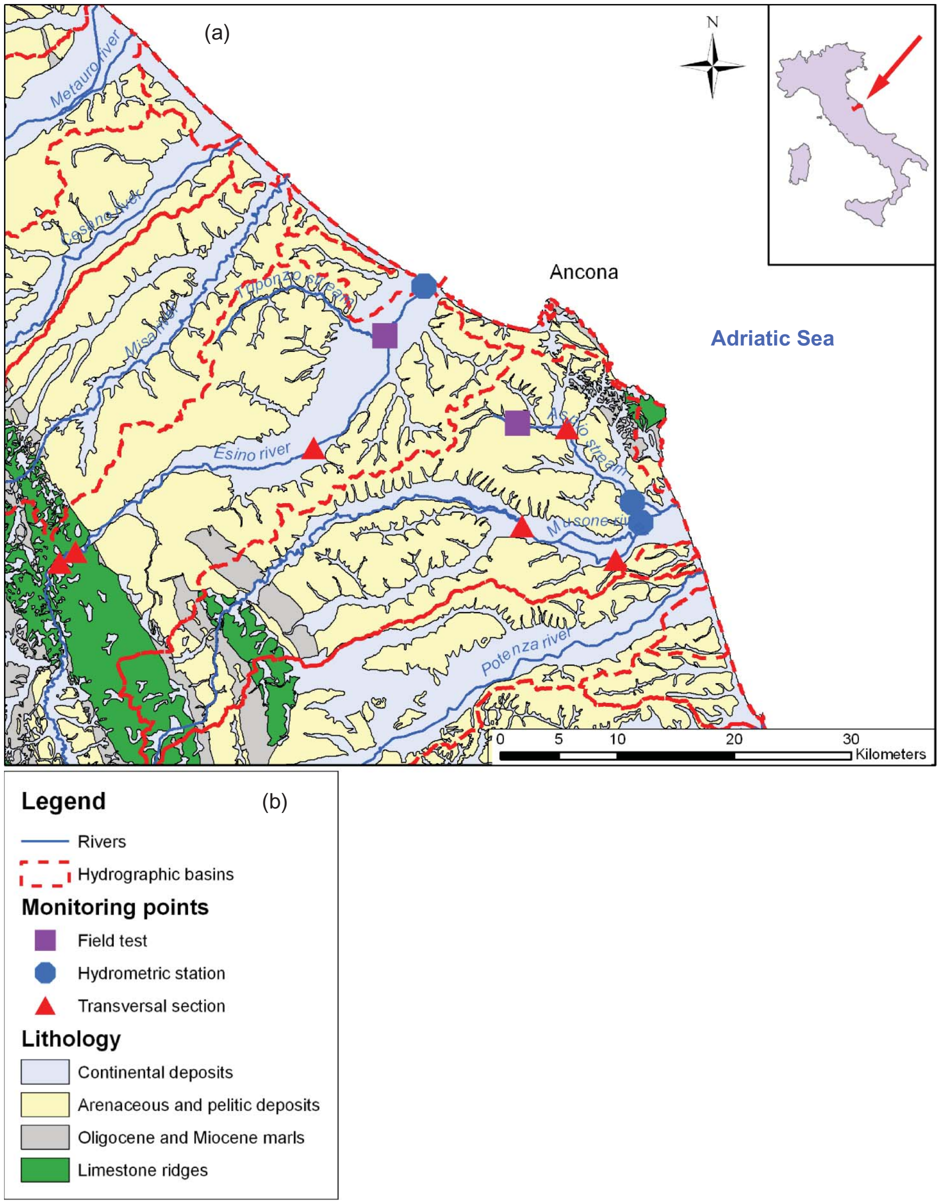

Fig. 1 (a) Basins of the rivers Esino, Musone and Aspio. Geology and location of the measurement stations and of the sections where different methodologies are being compared for discharge determination. (b) Legend to map in (a): ■: field test; ●: section where measurements of discharge have been made; ▲: hydrometric stations and sections where discharge is measured.

amount of tracer to be introduced into the water, it is assumed that mixing does occur and that the average tracer concentration is 10 times higher than the detection limit of the tracer itself. Although different formulae are available in the literature that give computational criteria for establishing the good mixing length (Guizerix and Florkowski 1983), it is better to derive it experimentally. Such formulae are useful as a first approximation, but they often cannot be applied because of unknowable parameters. In the watercourse section where the measurements are taken, the tracer concentration can be determined according to the type of tracer used, either directly in the field or in the laboratory by analysing samples collected *in situ* at defined intervals.

The present work describes results obtained by using chemical (NaCl, NaI, NH_4Cl) and fluorescent (fluorescein and Rhodamine WT) dye tracers to measure the watercourse discharge. In general, it was observed that the choice of tracer type is linked to several factors. Sodium chloride is the most frequently used chemical tracer and provides the best results (Drost 1989, Kumar and Nachiappan 2000). Furthermore, it has a low environmental impact.

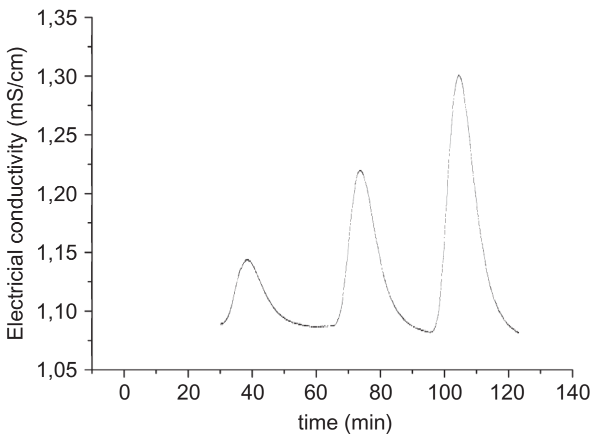

Fig. 2 Tracing curves relative to a multiple tracing performed for a section in the Aspio River. The curves refer to releases of NaCl at different times, with increasing quantity. The resulting discharge was equal to 0.080 ± 0.001 $m^3 \cdot s^{-1}$.

The only drawback to using NaCl is that the tracer is slightly absorbed by the clay minerals found in suspended sediments. Sodium iodide exhibits better absorption characteristics. Of the fluorescent tracers, Rhodamine WT has been much praised, especially in terms of chemical stability (Vasudevan *et al*. 2001, Dierberg and DeBusk 2005).

In order to illustrate the use of a chemical tracer, Fig. 2 shows the restitution curve for multiple tracings with NaCl in a section of the Aspio River. In this experiment, three consecutive tests were performed (using different tracer quantities at different times), and results were obtained with a satisfactory standard deviation.

2.2.1 Tracer absorption by suspended sediments To investigate the behaviour of tracers being absorbed by suspended sediments in a watercourse, experiments were performed in the laboratory to reproduce turbidity and tracer conditions from the field.

By means of dedicated equipment, it was possible to simulate a flood event lasting several hours at the same water temperature as is present in the rivers. During the flood, increasing concentrations of sediment collected directly from the watercourse section were mixed into the water. One fluorescent tracer (Rhodamine WT) and two chemical tracers (NaCl, NaI) were compared to study different tracer behaviours. The results indicate that the chemical tracers were not absorbed by sediments to any great extent. For example, even at high concentrations, the NaI tracer exhibits nearly zero absorption by the studied sediments (Fig. 3).

In contrast, increasing concentrations of Rhodamine WT were absorbed by the sediments (mostly silty and clayey sediments) as the concentration of suspended solid increased (as also reported by Sabatini and Austin 1991). Values from a few field tests are also reported in Fig. 3; these results agree with the laboratory tests. A further investigation of granulometric features and mineralogical properties and types of fluvial sediments, based on laboratory experiments and X-ray analysis, is under way to determine what elements are present, and in what amounts and distribution.

The construction of a curve to interpolate between the experimental points (i.e. a best-fit curve) has inherent errors that inevitably impact on the calculations for the watercourse. Such a relationship for considering the effects of tracer absorption on the watercourse discharge calculation is therefore only used to underline the phenomenon, but it is inadvisable to use such a curve for practical purposes in discharge determination. The error can be significantly reduced by setting the fluorometer in the laboratory to reproduce the same conditions as the test site, and by using a sample of turbid water withdrawn before the beginning of the test as a blank. These practices minimize the effects induced by the absorption of tracers by sediments.

2.3 Comparison of current meter and tracer methods

In all of the studied sites, different sets of measurements were performed concurrently with current meters and artificial tracers. On two occasions (on the Aspio River and on the Triponzio Stream), the results from multiple dilutions of different tracers (electrolytic and fluorescent dye) were used for comparison with current meters.

The measurements performed with NaCl generally compare well with the measurements made with the current meter method, at least within the limited range of discharges where the comparison has been done (Fig. 4). For areas with very low discharge, the discrepancy among the measurements increases. At small flows, the current meter measurements are less reliable because of the shallow water depth and the low flow speed. For increasing levels of flow discharge, the measurements with the tracers slightly underestimate the flow relative to the measurements using current meters. For even higher discharges, a

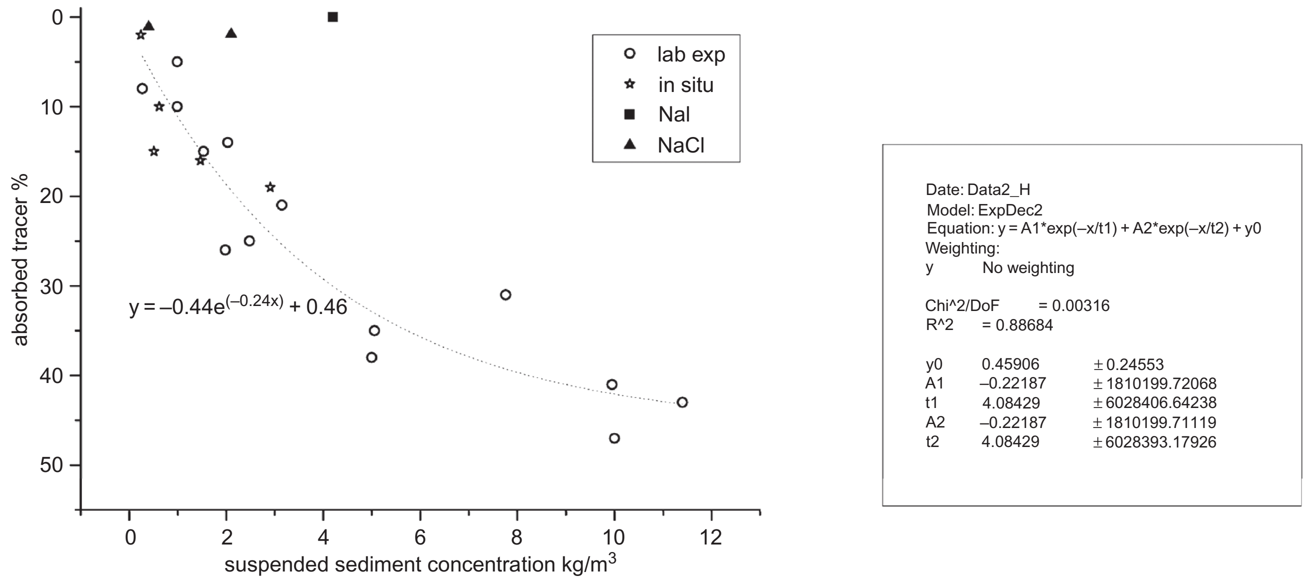

Fig. 3 Absorption tests for tracers absorbing into sediments. Circles refer to the tests performed in the laboratory with Rhodamine WT; stars represent the results of tests performed in the field. Some tests have also been performed with NaCl (▲) and NaI (■).

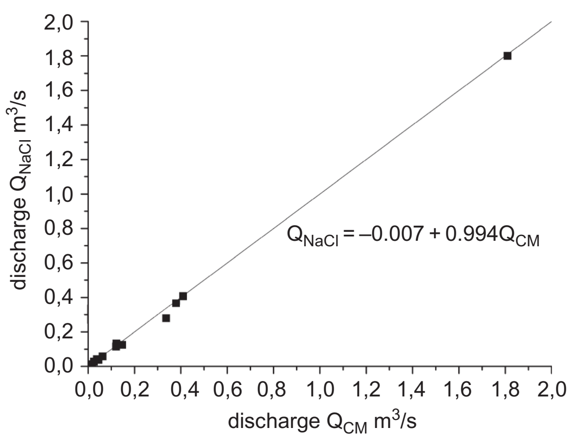

Fig. 4 A comparison of discharge measurements performed in different sections on the Aspio River and on the Musone River. Results were obtained using sodium chloride as a tracer (Q_{NaCl}), and with a current meter (Q_{CM}).

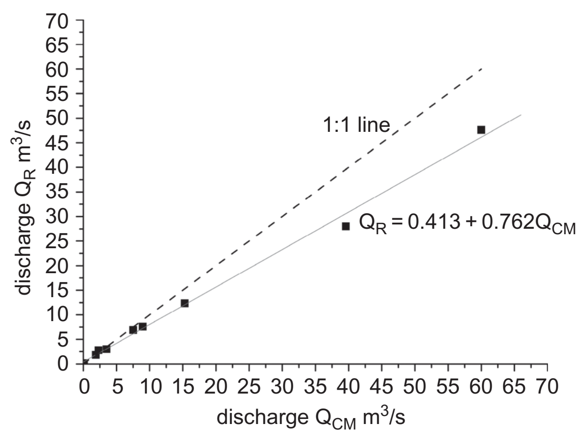

Fig. 5 A comparison showing measurements obtained using Rhodamine WT as tracer (Q_R) and current meters (Q_{CM}). The values refer to measurements of discharge performed in sections of the Esino River.

comparison between current meters and Rhodamine WT was performed because of Rhodamine WT's good performance, and of the small amounts necessary for a good measurement.

Figure 5 shows that, for increasing discharge, current meters underestimate the flow measurement, with a sizeable discrepancy of nearly 30%. The reason for this behaviour is not unequivocal. Measurements made at very high discharge rates were performed under difficult conditions, with only a few vertical data points available. Furthermore, the measurements were performed when the river level was higher than bankfull and so there was flow in the floodplain (i.e. a non-homogeneous process), which introduces several errors due to both different flow velocities and the restricted number of vertical points available for measurement.

Given these considerations, it is necessary to decide on the type of measurement technique to use for the watercourse with reference to the conditions of the course and the type of flow. In many cases—if the morphological conditions around the river allow the section where the tracer injection occurs to be moved further upstream—the use of dye tracers in flood conditions is preferable. A simplified approach for choosing the most suitable method of measurement in small- to medium-size rivers and streams (regarded as a first approximation to aid in this decision) is as follows:

- the current meter is not suitable for extremely low and high flow rates;
- electrolyte tracers (such as NaCl) are essential in cases of minimum flow (i.e. very low height of the water), and can be used even in medium-flow conditions, but they are not suitable for high flows;
- dye tracers (such as fluorescein and Rhodamine WT) can be used in medium- and high-flow conditions.

3 FIELD TEST OF THE TRIPONZIO STREAM

To investigate the behaviour of the different tracers used in these measurements, and to verify the comparability of the various methods (and the application of hydraulic formulas, such as the Chezy expression), a field test was prepared in a channelized section of a small watercourse, the channel being made of concrete materials (Fig. 6). The length of the studied section is 190 m (the distance between the release section and the measurement section downstream). The concrete channel section is trapezoidal, with a width of 0.85 m at the base and 1.15 m at the top; the mean depth of the water in the section was 0.17 m during the first field experiments (September 2007) and 0.29 m during the second test (October 2007).

3.1 Preliminary measurements

The first series of measurements was performed through float-mounted equipment opportunely selected for the test conditions. The float has the advantage of following the flow surface velocity. After five successive measurements were performed over 10 min, the average surface velocity was determined to be 0.34 m/s. The discharge calculated from these measurements was 0.052 $m^3 \cdot s^{-1}$.

Downstream, a small jump is present in the concrete channel, which allows for a direct measurement of the flow discharge using a volumetric method, a tank of known volume and a chronometer. A sequence of 10 repeated measurements was performed at different times, with a mean value of 0.0128 $m^3 \cdot s^{-1}$ and a standard error of 0.0002 $m^3 \cdot s^{-1}$. Therefore, the results calculated using the float overestimated the discharge amount compared to those obtained using the volumetric method. Further, the volumetric method is undoubtedly more exact.

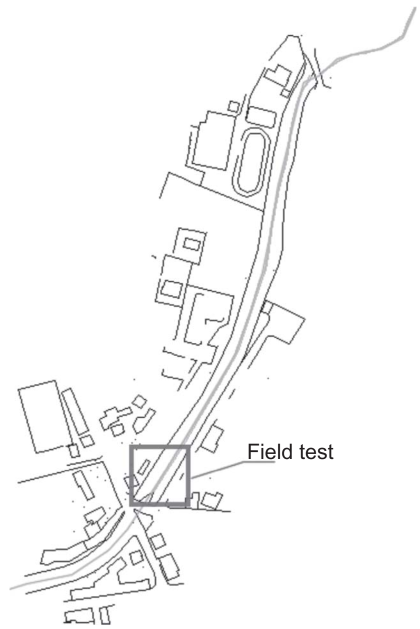

Fig. 6 Location of the field test on the Triponzio Stream.

3.2 Measurements using current meters

The measurements using current meters were repeated three times in different time periods during the day: the first period was at the beginning of the test day and the last at the end of the operations. A net of points with a resolution of 0.1 m was selected, with current meters placed at 0.07 m above the bottom of the channel, beginning at 0.3 m from the right bank of the channel and continuing to 0.9 m from the right bank. Some errors in the computational terms of discharge are expected; some zones of the flow were discarded because they had low flow speeds and therefore constitute a non-negligible flow type compared to the active surface.

The discharge was calculated in the "main section" following the methods outlined above. The section was divided into a number of homogeneous areas, which were inclusive along the vertical strips in which velocity was measured. With this method, a flow discharge of 0.0193 $m^3 \cdot s^{-1}$ was determined. The standard error (less than 30%) is a result of the discharge value being an average of three different measurements, and the removal of the portion of the section where the flow was too slow. The degree of error confirms that channels of shallow depth and limited flow are not reliably measured using current meters, which have a high error in these situations. Confirming this, a second set of measurements was made in deeper water, and a discharge of 0.0941 $m^3 \cdot s^{-1}$ was determined with a smaller error.

3.3 Measurements with artificial tracers

Prior to working with the artificial tracers, the distance required for good mixing was determined experimentally. This determination was performed by considering certain sections at different distances from the release point and then measuring the concentration at many points in each of them. The short length of the field test allowed good mixing to occur at points not very distant from the release point.

3.3.1 Electrolytic tracers This measurement involves the release of an electrolytic solution and the subsequent measurement of the electrical conductivity in a downflow section. The setting curve of electrical conductivity–concentration was determined in the laboratory, which allowed the values of conductivity measured at the site to be expressed in terms of saline concentration. Such a curve is determined by diluting increasing amounts of salt into water that has been withdrawn from the stream.

In order to determine the appropriate salt to perform measurements of water discharge, different chemical compounds were tested in the laboratory, including: sodium chloride (NaCl), sodium iodide (NaI), ammonium chloride (NH_4Cl), calcium chloride ($CaCl_2$) and potassium hydroxide (KOH). Each compound has a different behaviour with respect to the medium in which the tests were performed. In particular, some salts can have interference problems with other dissolved salts in the water and thus be in competition with them. Also, ionic exchange or absorption by the sediments in suspension or on the bottom of the channel can take place. Moreover, some tracers have environmental compatibility problems. In any case, following several tests, the two salts with the greatest reliability were NaCl and NaI. The absorption and precipitation phenomena were not observed for these two salts. Therefore, NaCl was used in these measurements.

The tracing tests were performed by instantaneously introducing—albeit at different moments—increasing amounts of tracer into the water. The first tracing used a small quantity of salt (0.05 kg), the second introduced around 0.2 kg of salt, and the third tracing introduced 1 kg of salt. Before release, the salt was dissolved in water and well mixed. The results show that in the first case the amount of salt was too low to be identified correctly by the conductivity meter. The other tracing tests produced nearly identical discharge results, with a difference in the measurements of less than 0.0005 $m^3 \cdot s^{-1}$. The flow discharge calculated with this method is equal to 0.0118 $m^3 \cdot s^{-1} \pm 2.65\%$.

3.3.2 Measurements with fluorescent tracers This method uses the emission of small quantities of tracers and the collection of samples in the measurement section at different times. The samples are subsequently analysed in the laboratory, and their individual fluorescence is measured in terms of the intensity of relative fluorescence (UF%). In this way, the curve of fluorescence *vs* time can be determined. The integral of this curve provides the flow discharge.

3.3.2.1 Fluorescein Sodic fluorescein, or uranine ($C_{20}H_{10}Na_2O_5$), is commonly used for measurements of discharge for surface water or for groundwater. This chemical has an acceptable environmental impact and it is easily detectable using a fluorometer (Field *et al*. 1995, Behrens *et al*. 2001, Hart *et al*. 2003, Buzàdy *et al*. 2006, Rowinski and Chrzanowski 2010). The maximum emission is 513 nm, and it has a very low tendency for absorption and a detection limit of 0.002 μg/L. Problems associated with this tracer include the presence of colouring substances in the water with similar fluorimetric radiation, and extreme sensitivity to the temperature and acidity of the water. The use of this chemical is further complicated by background luminescence, which can make interpretation of the results difficult.

The test was performed by introducing 1 ml of (previously diluted) tracer solution into the water in the channel. The flow discharge obtained using this method provides superior results to those obtained using NaCl (0.0133 $m^3 \cdot s^{-1} \pm 2.97\%$).

3.3.2.2 Rhodamine WT Rhodamine ($C_{29}H_{29}N_2O_5Na_2Cl$; Sabatini and Austin 1991, Panini *et al*. 1999, Close *et al*. 2002, Dierberg and DeBusk 2005, Tazioli and Tazioli 2005) has the advantages of being easily detectable by its strong fluorescence, having a large diffusivity, being chemically stable and having a non-aggressive character towards aquatic ecosystems.

It has a maximum radiation of 583 nm, a detection limit of 0.006 μg/L, and a moderate tendency to be absorbed into sediments.

The test was performed by introducing 0.7 ml of diluted tracer solution into the water of the channel. The resulting discharge was very similar to that obtained using fluorescein: 0.0134 $m^3 \cdot s^{-1} \pm 2.49\%$.

Comparing the results obtained using the different methods, it is evident that the average discharge is equal to 0.0138 $m^3 \cdot s^{-1}$, with a 5% standard error in the first series of tests. For these tests, the error becomes much lower (around 2%) if we do not consider the values obtained using the current meters. A second series of measurements (using salt, fluorescent tracers, current meters and the volumetric method) was performed some days later with a more elevated water level. A mean discharge equal to 0.094 $m^3 \cdot s^{-1}$ with a standard error of less than 2% was calculated for all of the methods considered. Therefore, for higher discharges, the results obtained with the different methods are absolutely comparable, and this is also true for the error.

3.4 Calculation of flow discharge with the Chezy formula

To understand the error produced by applying hydraulic formulae to small channels (such as the Triponzio Stream), the Chezy formula was applied to the channel under examination (from the field test on the Triponzio Stream).

The various coefficients and parameters of the formula were chosen by looking at the site characteristics and the channel features.

It can be concluded that for small channels (such as this one), this formula overestimates the value of discharge, and the overestimation is as great as one order of magnitude. Given this information, this is not a reliable method for calculating the flow discharge in low-flow conditions. The values obtained from the Chezy formula varied from 0.087 to 0.205 $m^3 \cdot s^{-1}$, using the Strickler coefficient or the Manning coefficient, respectively, for calculating the dimensional Chezy coefficient (C) in the following formula:

$$V_o = C \cdot \sqrt{g \cdot R \cdot i} \quad (5)$$

where R is the hydraulic radius of the channel, g is the gravitational acceleration and i is the slope of the channel.

4 ACCURACY OF THE DISCHARGE MEASUREMENTS: CONSIDERATION OF THE "RATING CURVE"

For most cases, the conventional measurement of flow discharge using current meters can provide satisfactory results. Sometimes, it seems that the discussion of the "goodness" of a particular method compared to another should be considered as a theoretical discussion, or that the examination should be limited to a range of discharge (very low or very high) that occurs only rarely in most parts of natural watercourses.

This is not the case, however. Often, the discharge measurements (using current meters or artificial tracers) are performed with the purpose of determining a rating curve (i.e. a stage–discharge relationship) to calibrate a water-level meter installed in the watercourse, or to check the accuracy and validity of an existing rating curve. For these purposes, the precision with which the measurements are performed is fundamental to a satisfactory result, because a small error in the curve's determination can result in a meaningful error in the evaluation of flow discharge.

The general form of the equation that links the discharge to the water level (the basis for the construction of the rating curve) is $Q = a \cdot H^b$, where a and b are experimentally determined coefficients that are connected to the features of thalwegs and flow. Normally, if a good number of measurements per site are available, it is better to determine this relationship experimentally. Interpolation between the given points is done using the method of the least squares. In this case, by extrapolating over the range of values where direct measurements are not available, it is possible to produce a curve that allows the flow discharge to be obtained from hydrometric heights measured at the site at other times.

In sections with irregular shape (as is the case in most parts of natural watercourses), the application of mathematical formulae leads to notable errors, and it becomes necessary to design different rating curves for the different zones of the section (e.g. for minimum flow in the river bed, or river flow in the floodplain). However. doing this does not eliminate uncertainties, because they depend on the character of the non-uniform flow. For these reasons, the formulae have to be validated using experimental measurements. In some cases, this constitutes the only acceptable method for setting up a rating curve.

It is known, that the relationship between stage and discharge has to be checked frequently, because of the possible variability of the section that it refers to. It must also be emphasized that, for relationships obtained during floods, errors can be found in the extrapolation to the lowest discharges. In the Aspio River, a stage–discharge relationship determined using the measurements of some exceptional flood events resulted in (for low hydrometric levels) minimum flows between 0.2 and 0.5 $m^3 \cdot s^{-1}$. In reality, the different measurements made on site (and in the same period) with current meters and tracers furnished discharge values of 0.03 to 0.15 $m^3 \cdot s^{-1}$, without strong variations in the topographic sections. Therefore, such curves must be suitably re-adjusted, since, otherwise, they create a risk of overestimating the available minimum volumes of water. This could lead to large errors, for instance, in the case of design of hydroelectric power plants or storage for drinkable water. The curvature of the “rating curve” can also be very different if it is simply extrapolated using field data without any measure of discharge during exceptional flood events. Figure 7 shows that extrapolation of rating curves for points beyond those measured can sometimes lead to errors of more than 50%. Curve 1 was drawn by measuring some moderate flood events, and Curve 2 refers to measurements taken entirely during periods of minimum flow and moderate flow. Including measures of exceptional floods, together with measures of the lowest discharges, tends to correct the rating curve to give reliable values in different ranges of measurements (Curve 3 in Fig. 7).

Given this, it is preferable to determine the rating curve using (at least) a pair of measurements performed with artificial tracers in the more critical ranges of measurement (i.e. minimum-flow events or flood events).

5 CONCLUSIONS

This study highlights the importance of choosing an appropriate method for obtaining discharge measurements in rivers, streams or other natural watercourses.

The most important factor to obtain is an accurate rating curve that is able to translate river stage values (continuously measured in river stations) into discharge, for every flow condition. Confidence in the rating curve is vital, as it is used to obtain discharge values for designing buildings and other structures in the basin. So it is essential that the measured data are reliable and have a low uncertainty.

In the present work, alternative methods for flow measurement in small- to medium-sized rivers were

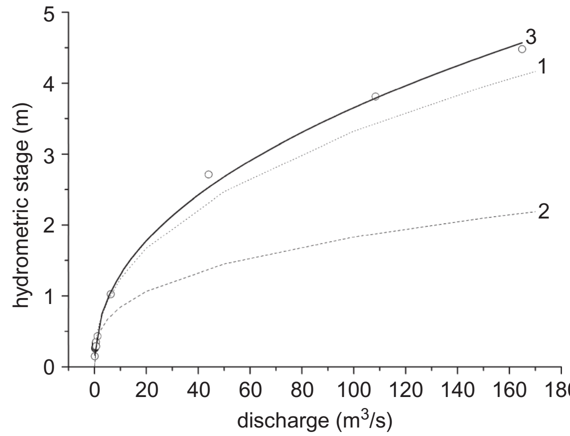

Fig. 7 Example of stage–discharge relationships valid for the years 2007, 2008 and 2009 in the Aspio River (Curve 1: based only on results of measurements obtained for moderate flow conditions; Curve 2: extrapolation of discharge measurements obtained during periods of minimum flow; Curve 3: rating curve valid for the examined section, derived using different measurements performed during a period of minimum and moderate flow, and some measurements related to large floods).

presented. These methods are strongly recommended for small watercourses during any conditions, but, sometimes, they can be useful also in medium-sized rivers when flow conditions make it impossible to use traditional methods.

In general, the use of current meters is simple and expedient, and the meters provide overall acceptable values in normal discharge ranges. However, for minimum flow and for some flood events, it is also appropriate to perform some measurements with artificial tracers.

Such measurements, in fact, provide accurate rating curves and a precise control for the validity of routine measurements made with current meters, especially in small- to medium-sized rivers.

However, it is necessary to be aware of the problem of tracer absorption in suspended sediments that are transported by river flow, especially during floods. For this reason, new measurements and field and laboratory tests (extended to other watercourses in central Italy) are being conducted to address this problem.

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