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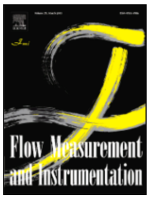

Short communication

Estimating discharge in drainage channels through measurements of surface velocity alone: A case study

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ABSTRACT

In the scientific literature it is possible to find at least two methods for estimating discharge in an open channel which represent a valid alternative to the Velocity-Area method; both offer a considerable advantage in that they are simple to apply and require knowledge solely of the channel bathymetry and maximum surface velocity. The first method is based on the entropy concept introduced into hydraulics by Chiu in the 1990s, whilst the second is focused on the reconstruction of dimensionless isovels in the channel cross-section.

Both the methods have been extensively described in previous works and validated for medium/large-sized cross-sections where surface measurements are taken by current-meter or Acoustic Doppler Current Profiler (ADCP) sensor. In this technical paper, they are instead applied to a water drainage channel in a reclamation territory characterized by a very low velocity which required a particular measuring technique, called "total station". This technique demonstrated to be reliable in situations where the velocity is very low and cannot be measured with other "no-contact" techniques, such as those based on the Doppler method, which are normally used when the use of current meters is not possible.

1. Introduction

The standard method for estimating discharge in an open channel is the Velocity-Area method [22], which requires velocity measurements in numerous points throughout the flow area, the geometry of the cross-section concerned being known. Though this method is considered to be particularly reliable, it can be laborious and time-consuming, involving a considerable commitment of equipment and personnel. It may also be difficult in practice, both because it entails measuring velocities in the lower portion of the flow area, and because of the danger operators are exposed during exceptional flood events. As it is obvious that the time and costs involved in measuring discharge increase proportionately with the number of velocity measurements that need to be made, numerous researchers have sought to define methods for estimating discharge on the basis of an extremely reduced number of velocity observations.

One approach in this respect is the entropy method [3], which is based on a linear relationship between the mean velocity $\bar{U}$ and maximum velocity $u_{\max}$ of a channel cross-section [23,4,5]; this relationship is a function of a dimensionless parameter M, so that $\overline{U} = f\left(u_{\max}, M\right)$. From an operational standpoint, however, it is first necessary to estimate the parameter M in order to convert the maximum observed velocity $u_{\max}$ into the cross-sectional mean velocity $\bar{U}$ [18,19,8]. A recently proposed procedure [11] makes it possible to estimate the parameter M based on the measurement of surface maximum velocity alone. At the same time, it allows to derive $u_{\max}$ indirectly from the latter, thus enabling a rapid calculation of M and of $\bar{U}$ and hence discharge.

The same authors have recently developed another method [12] which can be used to reconstruct the pattern of dimensionless isovel contours associated with a particular roughness configuration; this method enables discharge calculation relying on any velocity measurement taken in the flow area, including, in particular, the maximum surface velocity.

Both of the above-mentioned methods have the undoubted advantage of enabling discharge to be estimated based on the measurement of maximum surface velocity alone and have been validated for medium/large-sized cross-sections [11,12]. This paper aims to compare and assess the reliability of these methods when applied to a cross-section of a drainage channel in a reclamation territory characterized by smaller dimensions and a surface velocity which is so low that it re-

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quires a special measurement technique. More precisely, the "total station" technique is here used; measuring velocity with current meters was not possible, since there is no cableway at the cross-section, the channel cannot be waded through, as the bottom is extremely muddy and of a considerable depth, plus the use of a boat would have altered the flow conditions, given the very slow flow regime. Moreover, the use of instruments based on radar-Doppler technology was not possible, because they can only be used in a decidedly higher range of velocities than is to be found in the channel concerned.

Below we outline the principal notions of the two methods considered and then, after describing the cross-section in question, describe the technique adopted to measure the surface velocity; subsequently we present and discuss the results obtained and, finally, present our conclusions.

2. Estimating discharge

2.1. Estimating discharge with the entropy method

In order to estimate discharge through the linear relationship $\overline{U} = f\left(u_{\max}, M\right)$ at the basis of the entropy method, it is necessary to have a preliminary estimate of Farina et al. [11], who may be referred to for greater details, developed a method for determining this parameter based on the cross-section geometry and the measurement of maximum surface velocity $u_{D,}$ where D indicates the depth on the vertical where the maximum surface velocity occurs. The general idea for the estimation of M is that the cross-sectional mean velocity $\bar{U}$ can be approximately determined using two different procedures, briefly described below and illustrated in Fig. 1. Since both are function of the entropy parameter M (alone), the latter is initially set at a tentative value.

Procedure 1:

This entails first calculating the cross-sectional maximum velocity $u_{\max}$ knowing u_D, the depth D at the point corresponding to u_D and the ratio between h (depth at the point in which the maximum velocity $u_{\max}$ occurs relative to the free surface) and D. The mean velocity $\bar{U}$, hereinafter indicated as $\bar{U}_1$, is estimated by means of the aforesaid linear relationship depending on M (Fig. 1, path on the left).

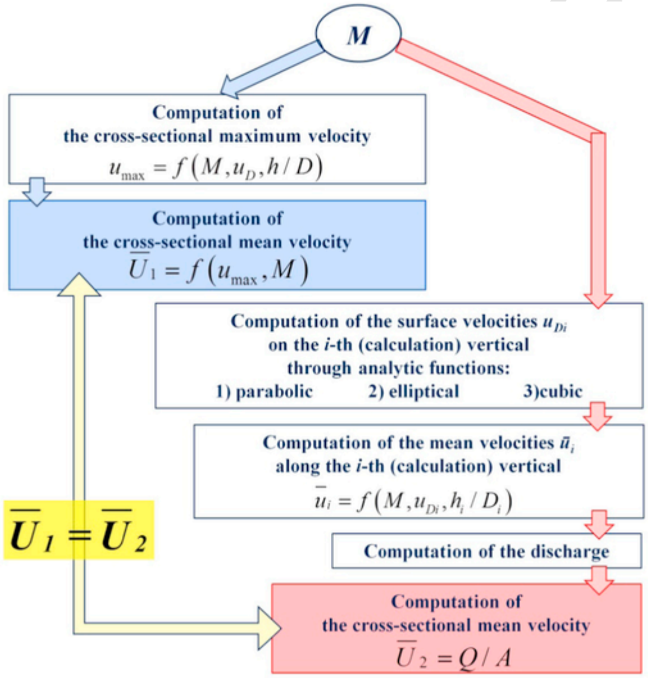

Fig. 1. Flow diagram at the basis of the method Farina et al. [11]. The ratio $h_i/D_i\ \forall i$ can be considered equal to zero in very wide rectangular cross-section [7].

Procedure 2:

As surface velocity measurements are not available for different verticals, but only the maximum value u_D is known, their distribution is approximated by relying on particular analytic functions (parabolic, elliptical and cubic) which are based on the only available measurement. The surface velocities u_{Di} calculated for *hypothetical* verticals are converted, on the basis of the hypothesized value of M, into mean velocities $\overline{u_i}$ along these (calculation) verticals. The mean velocities $\overline{u_i}$ enable discharge to be estimated using the Mean-Section Method [22]. Finally, the cross-sectional mean velocity $\bar{U}_2$ is estimated as the ratio between discharge and flow area (Fig. 1, path on the right).

In this context it is evident that the optimal value of M is the one where the two aforesaid velocity cross-sectional mean velocities coincide ($\bar{U}_1 \cong \bar{U}_2$).

In summary, it is important to note that each assumed distribution of surface velocities influences the estimate of M, hence of $\bar{U} = f\left(u_{\max}, M\right)$ and, the flow area being known, of discharge Q.

2.2. Estimating discharge with isovels

Farina et al. [12] developed an alternative method in addition to the one previously described, similarly based on a single point velocity measurement, specifically, the maximum surface velocity. This approach draws its inspiration from the Biot Savart law [14] – to which Maghrebi et al. (2005) also refer in their own work – which can be used to calculate the intensity of a magnetic field generated at a point in space by an infinitely long wire carrying a stationary and steady current. Farina et al. [12] applied this law in the field of the hydraulics to quantify the effect on velocity, at a generic point in a channel cross-section, as produced by a generic portion/segment among those into which the wetted perimeter is divided. This effect depends on the roughness in that segment, expressed as Manning's roughness coefficient, and on the distance separating it from the point considered. The approach described enables the pattern of "isoeffect" contours, duly nondimensionalized, to be represented based on the geometry of the bathymetric profile and the distribution of roughness characterizing the channel bed.

Moreover Farina et al. [12] showed that the roughness, when assumed uniform along the cross-section, seems to have only a very moderate impact on the isovel pattern. This finding suggests that, when the Manning coefficient is uniform along the cross-section, the reconstruction of the dimensionless isovel pattern can be assumed independent from the roughness value itself and thus no assumptions are necessary on its value.

These contours can moreover be read as dimensionless isovels (normalized to the cross-sectional mean velocity) [12]: precisely for this reason it is sufficient to measure the velocity at any point in order to be able to estimate, based on the ratio between that measurement and the dimensionless velocity at that point, the cross-sectional mean velocity and hence the discharge, where the flow area is known.

For an assigned isovel pattern, corresponding to a pre-established distribution of roughness, Farina et al. [12] conducted an analysis to assess sensitivity to the position of the velocity measurement used to estimate discharge. This analysis revealed that the points in the central/upper part of the flow area generally enable a more accurate estimation than those nearest the bottom and banks. In particular, it is worth observing that measuring the maximum surface velocity alone enables a reliable estimate of discharge to be obtained in large natural channels, with a relative error of approximately 10% [12].

3. Case study

The subject of the experimentation was a drainage channel called Fossa Masi (Ferrara- Italy), which belongs to the network managed by the reclamation Agency called “Consorzio di Bonifica Pianura di Ferrara”. The channel is used for various purposes depending on the season. In the winter season (October-March) it is practically empty and used as necessary to drain excess rainwater, whereas during the irrigation period (April-September) it is partly filled, since water is introduced for irrigation. The water levels are maintained through suitably placed sluice gates. In the event of rainfall, the latter are adjusted as necessary to enable more rapid emptying of the channel.

In the literature it has been observed that the cross-sectional maximum velocity generally occurs in the upper portion of the flow area [18,19,4,6,8]. Furthermore, in straight stretches with wide, almost rectangular or trapezoidal cross-sections, it is reasonable to assume that the maximum *surface* velocity manifests itself in the central part of the flow area and this is where field measurements were performed.

Given that the surface velocity, the essential factor for estimating discharge, is extremely low in the channel in question, some preliminary considerations were necessary. First of all, the cross-section does not have a cableway for taking measurements with current meters; nor is wading an option, given the extremely muddy bottom, which would cause the technician to sink into the mud while attempting to cross. Using a boat was considered inadvisable, because its presence would have produced a significant alteration in the field of motion, thus influencing the velocity measurement. It was therefore deemed that a “no-contact” technique should be used to measure velocity. However, the techniques based on the principle of the Doppler effect had to be ruled out: despite being very simple and fast from an operational standpoint, they have a working range of 0.4 – 10 m/s [10,13,17,2,9], making them unsuited to the case in question, since the current remains below that range. Bolognesi et al. [1] thus tested other surveying techniques on the same channel, i.e. topographic techniques (total station), photogrammetric techniques (terrestrial close range photogrammetry) and techniques based on the use of a video camera installed on a UAV, determining the velocity of movement of specially designed floats lowered onto the surface of the water. All these latter measurements proved to be in good agreement and, therefore, these surveying techniques can be judged equally reliable.

In light of the above, for this study it was decided to use the velocity measurement obtained using a total station, since this instrument also made it possible to measure some geometric data and elevations that were indispensable to this study. In order to measure the surface velocity it was necessary to create two sections, A-A and B-B, parallel to each other and perpendicular to the axis of the channel. These sections delimited a stretch of a known length, equal to about 15 m, upstream of which floats would be released and the transit time measured (Fig. 2). For this purpose, 2 total stations were positioned by the 2 sections, their collimation axes parallel and perpendicular to the axis of the channel.

The floats were specially built in a laboratory as small polystyrene “boats” that would remain mostly above the surface of the water, clearly visible to the instruments during the velocity measurement; moreover, a plastic blade was inserted into the polystyrene body to act like a “keel”, so that the float would follow the flow of the current as closely as possible. The floats were lowered with fishing rods into the central part the channel, upstream of the stretch under observation, between the two sections A-A and B-B.

The distance between the instruments being known, a measurement was made of the time elapsing between the observed passage of the float from the first to the second total station. The velocity of the moving object along the central axis of the channel was calculated based on the space/time ratio; several velocity measurements were made and the corresponding mean value, $\boldsymbol{u_D} = \mathbf{0.167\ m/s}$, was used to estimate discharge.

Fig. 2. Location of the investigated cross section along the Fossa Masi channel.

Bathymetric survey data for the Fossa Masi cross section at the test site, essential for the application of the method for estimating discharge and for calculating the flow area, were provided by the provincial reclamation agency. Fig. 3 shows the geometry of the channel cross-section in question (in black) and the elevation of the free surface measured by the total station, equal to 10.83 m (in blue); the flow width L and flow area A corresponding to that elevation were 9.46 m and 7.72 m^2, respectively.

The stretch of the channel considered is upstream of a sluice gate located under a bridge (Fig. 2). At the time the measurements were taken, in summertime, the sluice gate was completely lowered, so that its bottom end was resting upon the concrete base at the bottom of the channel in proximity to the bridge: it thus acted like a weir (Fig. 4).

Based on the geometric data and elevations of the weir measured by means of the total station and schematically illustrated in Fig. 5, a determination was made of the discharge Q_{rif}. This discharge was taken as the reference value with which to compare the corresponding values provided by the two methods applied in this study. Bazin's formula for calculating flow over a rectangular contracted sharp-crested weir was applied to estimate discharge in the Fossa Masi channel in the cross-section at the site of the bridge:

$$Q_{rif} = C_Q bh\sqrt{2gh} = \mathbf{0}.888\ m^3/s \tag{1}$$

where

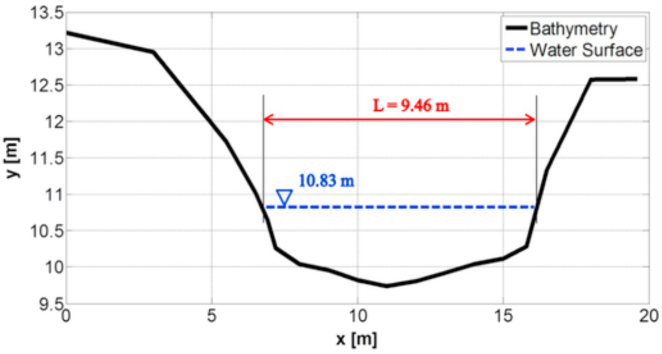

Fig. 3. Topographical survey of the analyzed channel. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

Fig. 4. The downstream weir along Fossa Masi channel.

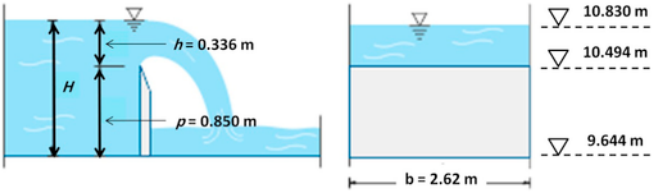

Fig. 5. Scheme of the rectangular contracted weir.

$$C_Q = \left[0.405 - 0.03\frac{L-b}{L} + \frac{0.0027}{h}\right]\left[1 + 0.55\left(\frac{b \cdot h}{L \cdot H}\right)^2\right] = 0.393 \tag{2}$$

and wherein b represents the crest width in m, L the channel width, equal to the flow width, h the height of the fluid above the crest in m, p the height of the crest/sluice gate in m, $H = h + p$ the total height of the fluid upstream of the crest in m, and C_Q the discharge coefficient.

4. Analysis and discussion of the results

The method of Farina et al. [11] was used to identify the optimal value of M, that is, the value where the cross-sectional mean velocities of Procedures 1 and 2, previously mentioned, coincided. It is worth remembering that in order to apply this method the ratio h_i/D_i (where h_i is the depth at the point in which the maximum velocity occurs on the i-th vertical and D_i is the water depth on that vertical) must be fixed. This ratio should be deduced on the basis of a series of observations, which were not available in this case study. In such a case, it could be expressed as a function of M according to the relationship provided by Chiu and Tung [6] (see also [11]); on the other hand, considering that in this specific case study the cross section is almost rectangular and very wide (with a ratio between flow width and depth about 10), it was assumed that the maximum velocity occurs on the surface [7] and thus the ratio h_i/D_i was set equal to 0 for any vertical i. The calculation was repeated for each geometric function used to derive the distribution of surface velocity; specifically, the following functions were used in this study: (a) parabolic function type 1: two parabolas are drawn, the vertex of both coinciding with the only point of velocity measurement and passing through the left and right banks; (b) parabolic function type 2: two parabolas are drawn, with their vertices on the banks and each passing through the only velocity measurement point; (c) elliptical function: two branches of an ellipse are drawn, both passing through the velocity measurement point and through the banks; (d) cubic function: two cubic parabolas are drawn, with their vertex on the banks and both passing through the only velocity measurement point.

For each case, a different value of M was obtained. Combined with the maximum measured surface velocity u_D, it enabled the cross-sectional mean velocity $\bar{U}$ and discharge Q to be estimated using the entropy method. On the basis of the results obtained, as shown in Table 1, it can be observed that the variation in M is relatively pronounced between 0.5 and 2.89, whereas the variation in $\bar{U}$, and hence in the discharge Q, is slightly more limited: the values of the latter fall in the range of 0.698–0.919 m^3/s. In particular application of the parabolic function type 1 or type 2 to derive the distribution of surface velocity leads to quite low discharge values, corresponding to a percentage error (underestimate) of about 20%. On the other hand elliptical and cubic function lead to a very good discharge estimations, corresponding to percentage errors of about 3% (overestimate) and 5% (underestimate) respectively. Better results in terms of discharge estimation obtained by using the elliptical and cubic functions are comprehensible by considering that these functions lead to a more constant and uniform surface velocity in the central region of the flow width than the parabolic functions (see also [11]), in agreement with the very wide rectangular nature of the cross-section considered.

The alternative method of Farina et al. [12] enabled us to represent the pattern of dimensionless isovels based on the known geometry of the bathymetric profile and the distribution of roughness characterizing the channel bed. In particular, a survey was conducted to examine the state of the river bed at the investigated cross-section and led us to assume a uniform distribution of roughness. Thus, on the basis of what previously written in the method presentation section (see also [12]), the Manning coefficient effect was neglected and the non-dimensionalized isovel pattern was reconstructed taking into account only the geometry of the bathymetric profile without any assumption on the Manning's coefficient value.

The isovel pattern obtained, normalized relative to the cross-sectional mean velocity, is shown in Fig. 6 and is consistent with the characteristic pattern of very wide rectangular cross-sections [7], in which the isovel contours remain parallel to the bottom and the maximum velocity occurs on the surface (at the Fossa Masi cross-section, in fact, the ratio between flow width and depth is about 10). The two-dimensional distribution of velocity obtained by dimensionalizing the pattern on the basis of the only available measurement u_D (maximum surface velocity) results in a discharge estimate of about 0.827 m^3/s. It is worth observing, therefore, that with this method as well, the measurement of maximum surface velocity alone enables a reliable estimate of discharge to be obtained, with a relative error (underestimate) of about 7%.

Furthermore, it is worth noting that the two methods have been found to perform better, for discharge estimation, than the one proposed by the Mysore Engineering Research Station (reported by [20]):

$$\text{Mod A}: \quad \overline{U} = 0.8529 \cdot u_D + 0.0085 \tag{3}$$

and that, quite similar, reported by Subramanya [21]:

Table 1
Values of M, $\bar{U}$, Q and relative error obtained using each of the 4 geometric functions considered.

	M	$\bar{U}$	Q	$\frac{\lvert Q-Q_{rif}\rvert}{Q_{rif}}$
		[m/s]	[m^3/s]	[%]
Parabolic T1	0.72	0.093	0.721	18.74
Parabolic T2	0.50	0.090	0.698	21.39
Cubic	1.89	0.108	0.836	5.76
Elliptical	2.89	0.119	0.919	3.51

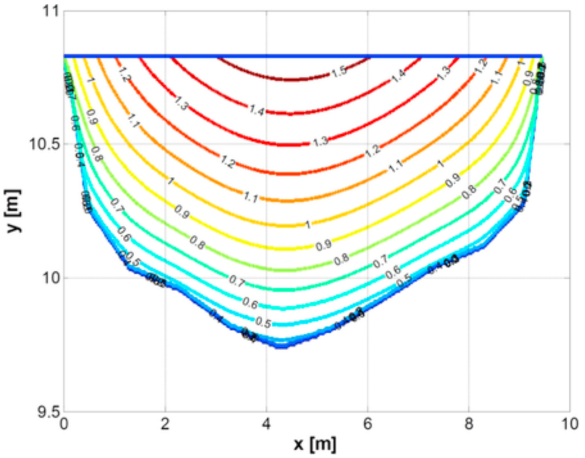

Fig. 6. Dimensionless isovel pattern produced by the method described in Farina et al. [12].

$$\text{Mod B}: \quad \overline{U} = (0.85 - 0.95) \cdot u_D \qquad (4)$$

In particular the derivation of the cross-sectional mean velocity directly from the maximum surface velocity by means of Eqs. (3) and (4) leads to percentage error in discharge estimation of about 31% (overestimate) and 23–38% (overestimate) respectively.

The results gained from all the considered methods are summarized and compared in Table 2.

Summarising, the use of the entropy and isovel methods allows for a reliable measurement of discharge in a drainage channel, typically in backwater conditions due to the many sluice gates located along the extent of the channel itself, without relying on current meters and/or surface velocity measurement systems based on technology that exploits the Doppler effect. It was sufficient to have at our disposal topographic survey data and two total stations for measuring the surface velocity along the axis of the channel. On the other hand, the use of traditional methods for estimating the mean cross-section as fraction of the surface velocity results, in this case, in a larger error in discharge evaluation thus suggesting that such an approach is less adequate than the proposed ones for drainage channels in reclamation areas.

5. Conclusions

Two methods were considered to estimate discharge in a cross-section of an open channel, both representing a valid alternative to the standard Velocity-Area technique, which is based on a cumbersome and costly preliminary velocity sampling step.

Although the two methods differ in their methodological approach, their application can be performed by using the same set of information/data, namely, the geometry of the cross-section considered and a single measurement of maximum surface velocity.

Table 2
Values of $\bar{U}$, Q and relative error obtained using the entropy method, the isovel method, Mod A and Mod B.

	$\bar{U}$	Q	$\frac{\lvert Q-Q_{rif}\rvert}{Q_{rif}}$
	[m/s]	[m^3/s]	[%]
Entropy method	0.090–0.119	0.698–0.919	3.51–21.39
Isovel method	0.107	0.827	6.87
Mod A	0.151	1.165	31.20
Mod B	0.142–0.159	1.096–1.225	23.39–37.90

The methods have been validated in past studies on the basis of numerous field velocity measurements made in different cross-sections of medium/large size. In this study, the validation was extended to a drainage channel of smaller size and with a considerably lower surface velocity, which made it necessary to rely on a suitable "no-contact" topographic technique involving the use of total station survey instruments and floats positioned in the central part of the channel.

It was thus shown that in water drainage channels, for which, due to their backwater condition, it is not possible to set a rating curve, a measurement of discharge can be obtained without relying on current meters or instruments based on Doppler technology. Indeed it sufficient to have topographic survey data and the measurement of surface velocity taken along the axis of the channel using a strictly topographic technique and suitable floats.

Finally, in the case here considered, the two methods perform better than other traditional methods which assume the mean cross-section velocity as a fraction of the surface velocity.

Uncited references

[15, 16].

Acknowledgments

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