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Entropy Theory Application for Flow Monitoring in Natural Channels

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Abstract: A quick and accurate determination of flow passing through a river section is fundamental for a large number of engineering applications, such as flood forecasting models and the real time water resources management. Velocity is one of the basic variables of open channel flow and its variation across a section is described by the velocity profile distribution. This aspect has also been investigated through a probabilistic approach based on the entropy concept, which also expresses the mean flow velocity as a linear function of the maximum velocity through a dimensionless entropy parameter M. Therefore, the entropic relationship between the mean flow velocity and the maximum velocity has been investigated here for nine gauged river sections. Five of them are located in Italy and the other four are in Algeria. Based on the flow velocity measurements sample of each site, the robustness of the linear entropic relationship has been proved. The entropic parameter, M, which characterizes the relationship, has been found uniform for seven river sites with a value in the range of 2.1 – 2.5. For two river sites the value has been lower and equal to -0.22 and 0.33, respectively. As this parameter is fundamental for addressing the flow velocity measurements at equipped river sites, the morphological characteristics of river reaches where the gauged sections are located have been investigated and identified in terms of Rosgen classification. The seven gauged sections with uniform M value have been found belonging to the same stream classification, i.e. type C, except one located in Algeria which is type D. The other two with different M values have been ascribed as different types. The analysis, although preliminary, allows foreseeing new developments in the application of the entropy approach addressed to quantify high flow discharges, especially in new gauged river sites where M is unknown.

Keywords: Entropy theory; flow velocity; maximum flow velocity, rivers; Rosgen classification; hydraulic parameters.

1. INTRODUCTION

The accurate assessment of discharge at river sites is fundamental to address the water resource management in terms of both quality and quantity. Unfortunately, the discharge estimation is often affected by the lack of velocity measurements, often restricted by the excessive cost involved, which does not permit to establish a reliable stage-discharge relationship. Besides, even if velocity measurements are available, they are restricted in most cases to low flows, thus enabling a good discharge assessment only for lower water levels. Therefore, many studies attempted to overcome this shortcoming by addressing the analysis in terms of velocity profiles distribution. Although there are a large number of studies, few studies have been addressed for estimating the spatial velocity distribution during high flood conditions, wherein it is not possible to sample the whole velocity field, particularly in the lower portion of the flow area. In this case, the sampling procedure of velocity measurements at a river cross section could be difficult and particularly dangerous for cableway operators. On the contrary, the value of maximum flow velocity could be more easily obtained since its position is located in the upper portion of the flow area where velocity measurements can be carried out also during high flow conditions (Moramarco et al., 2004). Therefore, a model able to assess the velocity profiles, also when velocity data are not available in any portion of the flow area should be welcome. For this purpose, many researchers have resorted to the use of the analysis tool based on the entropy theory (Shannon, 1948) and the pioneer among them is Chiu (1987, 1988, 1989). Based on this theory, it was found that the mean flow velocity can be also be estimated from the value of maximum velocity through a linear relationship identified by the entropic parameter M (Xia, 1997). Moreover, it was found that the M value is constant not only at each gauged site but also the same along the main channel reach, where these sites are located (Moramarco et al., 2004).

This insight might be very interesting for new equipped river sites where an accurate linear relationship can not be fitted. Therefore, sampling of the maximum flow velocity in the upper portion of the flow area of these new sites would be sufficient for estimating the mean flow velocity.

Based on the above insights, the main purpose of the paper is to more deeply investigate the entropic linear relationship and to attempt in justifying the M value also in terms of morphological stream characteristics, such as proposed by Rosgen (1994). To this aim, stream-gauges located in some natural channels with different hydraulic and geometric characteristics are analyzed. Velocity measurements data carried out in the investigated gauged sites during different periods were used for the analysis.

2. THE ENTROPIC LINEAR RELATIONSHIP

The mean velocity, $\bar{u}$, and the maximum velocity, u_{max}, sampled at river cross section can be expressed by Chiu's relationship (Chiu and Said, 1995):

$$\bar{u} = \Phi(M)\, u_{max} \tag{1}$$

where:

$$\Phi(M) = \left(\frac{e^M}{e^M - 1} - \frac{1}{M} \right) \tag{2}$$

and M is the entropy parameter. Eq. (1) shows that $\bar{u}$ and u_{max} together can determine $\Phi(M)$ and then the entropy parameter M. Plotting the pairs ($\bar{u}$, u_{max}) sampled at gauged stations, the best fit line can be estimated thus providing the values of $\Phi(M)$ and M for the gauged section. Xia (1997) by investigating some equipped sites along the Mississippi river found that the M value was quite similar for sections located along straight branches and equal to 2.1; whereas for sites along bends the M value was different and equal to 4.8. At similar findings Moramarco et al. (2002, 2003 and 2004) arrived by investigating some gauged sections located along natural channels of the Upper Tiber basin. They found M values not different from the ones furnished by Xia (1997) and, further, the M value didn't change at sections along the same river or stream. By way of example, Figure 1 shows the entropic linear relationships for three gauged sections (see Table 1) located along the Upper Tiber River, in Central Italy: Santa Lucia (933 km^2), Ponte Felcino (2040 km^2) and Ponte Nuovo (4135 km^2). As it can be seen the same value of $\Phi(M)$=0.667 can be assumed for the three sites, obtaining M=2.1. Therefore, it would seem that along the investigated Tiber River reach between Santa Lucia and Ponte Nuovo, the $\Phi(M)$ value can be surmised as constant. The inference was verified by Moramarco and Saltalippi (2002) at a gauged river section, named Pierantonio, located between Santa Lucia and Ponte Felcino sites. It was found that the best fit line with $\Phi(M)$ = 0.667 well reproduced the pairs of ($\bar{u}$, u_{max}) belonging to the sample of velocity measurements carried out at Pierantonio. This preliminary results establishes a possible linkage between the entropic parameter M and the hydraulic and geomorphological characteristics of the river.

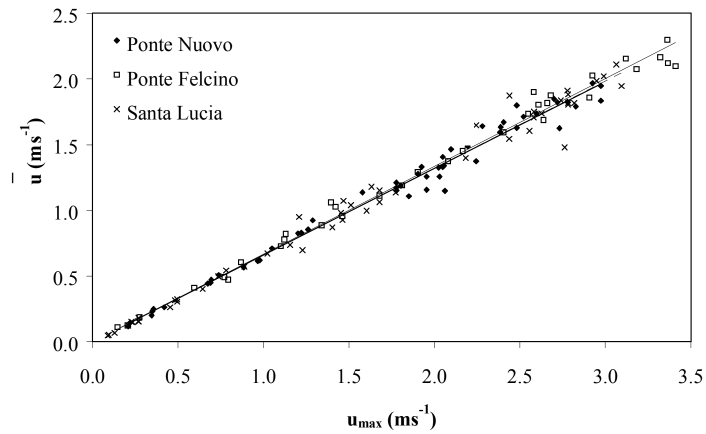

Figure 1. Relations between mean and maximum velocity in three gauged sections along the Tiber River. $\Phi(M) = 0.663$.

To test the entropic relationship accuracy at gauged sections different from those already investigated along the Tiber River, velocity data collected from six sites of different rivers were analyzed. Four of these gauged sites belong to rivers of North Algeria; the two remaining are located on the Basento River, in the South of Italy. The selected sections are equipped with remote ultrasonic water level gauge while the measurements of velocity were made by current meter from cableway or bridge cranes. By comparing the point velocities sampled along different verticals and applying the well-known velocity-area method, the maximum and mean velocities were estimated (Herschy, 1985). Topographical surveys of the equipped sections were also available in different years of the sampling. The values of $\Phi(M)$ and the entropy parameter M are shown in Table 2, for Tiber River sites.

Table 1. Flow characteristics, discharge, Q, and water depth, D, of the available velocity measurements, N, for the three gauged sections located along the Tiber River. The period of sampling is also shown.

Site	N	Q (m^3/s)	D (m)	Period
Santa Lucia	51	1-215	0,9-5,2	1986-2005
Ponte Felcino	34	2-412	0,8-6,2	1986-2005
Ponte Nuovo	54	3-537	1,1-6,7	1986-2005

Table 2. Value of the entropic parameter, M, and of the best fit slope, $\Phi(M)$, for the gauged sites along the Tiber River. The determination coefficient, R^2, is also shown.

Site	Φ(M)	M	R^2
Santa Lucia	0.662	2.08	0.98
Ponte Felcino	0.668	2.17	0.99
Ponte Nuovo	0.660	2.05	0.98

The four Algerian streams are located in the coastal Algiers hydrographic basin, which is characterized by a Mediterranean climate with mean annual precipitation of 800 mm. All these sites are subjected to high erosion processes during flood events because of the presence of sand sediments at the channel bed and banks. Table 3 shows the main flow characteristics of the investigated gauged sections.

Table 3. As in Table 1, but for the Algerian streams.

River	Site	N	Q (m^3/s)	D (m)	Period
Chiffa	Amont des Gorges	166	0,02-28	0,1-1,1	1990-2004
Sebaou	Baghlia	121	0,01-173	0,1-6,65	1990-2001
Mazafran	Fer à Cheval	317	0,01-350	0,1-7,8	1985-2005
Belah	Pont RN11	53	0,08-66,3	0,13-2,04	1993-2006

The $\Phi(M)$ value for each gauged station has been assessed based on the sampled pairs of ($\bar{u}$, u_{max}). Figure 2 shows the relationship between mean and maximum velocities for the Algerian gauged sections, assuming the real maximum velocity equal to the maximum value sampled at each site (Chiu, 1988).

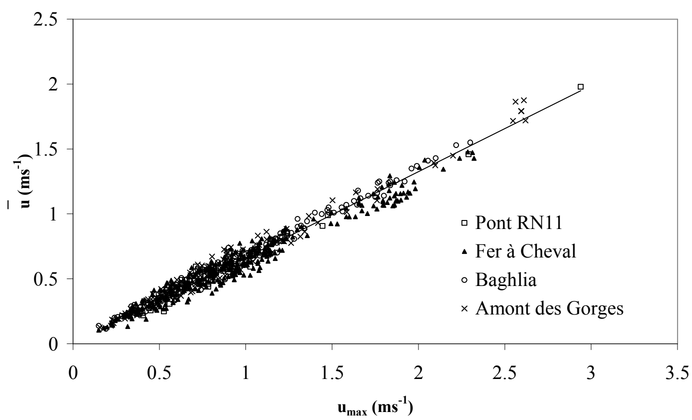

Figure 2. Relations between mean and maximum velocity in the gauged sections located in the Algiers basin. $\Phi(M)$ = 0.667.

For each investigated river site, the values of $\Phi(M)$ and of the entropy parameter M are shown in Table 4, along with the determination coefficient of the best fit line.

Table 4. As in Table 2, but for the Algerian sites.

River	Site	Φ(M)	M	R²
Chiffa	Amont des Gorges	0,689	2,49	0,98
Sebaou	Baghlia	0,681	2,37	0,99
Mazafran	Fer à Cheval	0,641	2,02	0,96
Belah	Pont RN11	0,663	2,10	0,97

A good linear relationship was found for a large range of discharges, water levels and sediment concentrations. Therefore, based on the estimated $\Phi(M)$ value, the assessment of $\bar{u}$ through the u_{max}, can be easily done without losing in accuracy. Considering that the maximum velocity is located at the deepest vertical near the water surface, the velocity measurements can be addressed at the purpose. We need to point out that also in this case the $\Phi(M)$ value can be considered uniform and quite similar to that estimated for the sites located in the Upper Tiber basin.

The analysis has been also extended for two more gauged sites on the Basento River, in Southern Italy. In this case, the sections are stable and no erosion processes have been taken place during the period of study. The first site, Campomaggiore, is located in the upper portion of the basin (840 km^2), characterized by a steep slope value and by the presence of boulders and cobbles in the cross section. The second one, Torre Accio, shows features typical of a valley reach (1380 km^2), with increasing sinuosity, extremely reduction of slope and the presence of fine sediments and silts. Both sites are characterized by the presence of shrubby vegetation and trees. Table 5 shows the main flow characteristics of the two river sites.

Table 5. As in Table 1, but for the Basento River sites, in Southern Italy.

Site	N	Q (m^3/s)	D (m)	Period
Campomaggiore	6	1-62	0,7–2,0	2002 - 2005
Torre Accio	7	1-180	0,5-3,3	2002 - 2005

As can be seen, the number of sample measurements in terms of Φ assessment, might be not properly representative for investigated sites. However, as some pairs of measured ($\bar{u}$, u_{max}) pertain to high flows, the analysis can be still valid, despite the limited sample size. The values of $\Phi(M)$ and of the entropy parameter M are shown in Table 6, for both Basento River sites.

Table 6. As in Table 2, but for the Basento River sites, in Southern Italy.

Site	Φ(M)	M	R²
Campomaggiore	0,48	-0,22	0,98
Torre Accio	0,53	0,33	0,94

In this case the entropic parameter was found different both among the two sites and from the one obtained for the Tiber River and the four Algerian rivers. Figure 3 shows the relationship between mean and maximum velocities for these gauged sections. Based on the $\Phi(M)$ values, it would seem that for both river sites the flow is slower than the one along the Tiber River and Algerian rivers.

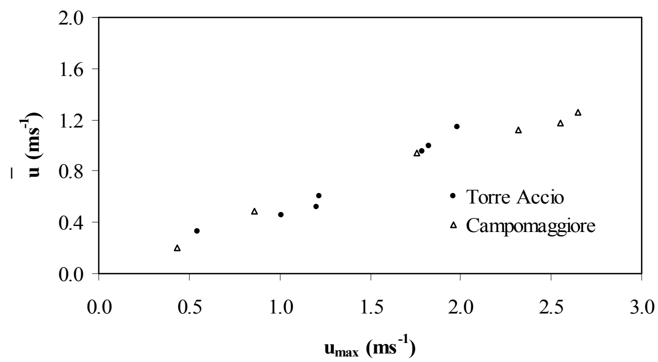

Figure 3. Relations between mean and maximum velocity in the gauged sections located along the Basento River (South Italy).

3. ENTROPIC PARAMETER AND RIVERS MORPHOLOGICAL CHARACTERISTICS

Considering the uniformity of Φ values at gauged sections, it has to be investigated if the Φ value can be explained in terms of stream types such as defined through the Rosgen classification (1994). Therefore, the morphological characteristics of rivers where the investigated gauge sections operate have been analyzed. In particular, the main stream types can be identified into seven major groups, i.e., A, B, C, D, E, F and G. Summarizing, rivers quite straight can be identified as type A; a river pattern with low sinuosity, B and G, and meandering type C and F. Complex patterns with high tortuosity and braided are defined as E and D, respectively. All these groups can be defined through the following morphological parameters (Rosgen, 1994): a) the entrenchment ratio; b) the W / D ratio, where W is the bankfull channel width and D is the bankfull mean depth; c) the sinuosity defined as the ratio of stream length to valley length and d) the slope evaluated in a reach of about 20 channel widths. In this case, the term “bankfull” is referred to water level corresponding to the discharge with a return period of 1.5 years. The entrenchment ratio is estimated as the ratio between the channel width, measured twice at the maximum bankfull depth and W, as previously defined. For more details the reader may refer to Rosgen’s work (1994). For each river site, the above mentioned morphological parameters have been assessed by using the available data from topographical surveys, cartographic maps as well as hydrological outcomes. Table 7 shows the above parameters for all investigated gauged sections with the corresponding stream type.

Table 7. Results of the Rosgen classification for the nine investigated sites.

Site	River	Entrenchment	W/D	Sinuosity	Slope %	Rosgen Class
Santa Lucia	Tiber	> 3.3	8	1.7	0.2	**C**
Ponte Felcino	Tiber	3	10	1.4	0.15	**C**
Ponte Nuovo	Tiber	> 11	12	1.8	0.14	**C**
Campomaggiore	Basento	1.2	8	1.5	1.62	**G**
Torre Accio	Basento	40	12	3.2	0.16	**E-C**
Amont des Gorges	Chiffa	2.4	29	1.4	0.5	**C**
Baghlia	Sebaou	2.3	51	1.5	0.2	**D**
Fer à Cheval	Mazafran	2.4	31	1.5	0.12	**C**
Pont RN11	Belah	1.2	24	1.3	1.3	**C-F**

It can be inferred that the gauged sections having the M values greater than 2 belong to stream type C, except the Sebaou River at Baghlia which is of type D, characterizing a braided shape (see Figure 4).

With regard to Pont RN11 on Belah River, the type can not be fairly defined because of lack of further information useful to accurately assess the entrenchment ratio. In this case, however, the river type might be referred to type C or F. On the contrary, for the two river branches located along the Basento River in South Italy, the upper reach has been identified as type G; whereas uncertainty occurs for the Basento at Torre Accio where the branch type can not be properly defined. Also in this case, further accurate information are required for assessing the entrenchment and W/D morphological parameters. However, the type E or C might represent the range more appropriate for the branch. Therefore, through this preliminary analysis, it would seem that a link between the entropy parameter and the morphological parameters might be found, at least in terms of overall insight. However, Figure 5 reveals that difference can be found between the morphology of the Tiber River at Ponte Nuovo (type C) from that of Sebaou River (type D) (shown in Figure 4) which has evident braiding characteristics.

Figure 4. Plan view of the Sebaou River branch at Baghlia (mean width 200 m).

Therefore, at this level of analysis, it is not possible to clearly explain the differences between these two river types, although they have the same Φ value. In this context and also based on the findings of Xia (1997), who estimated Φ values around 0.64 and 0.79 respectively along straight Mississippi River reaches and on bends, one would be prompted to reconsider the Rosgen classification, which could thus address the analysis on the relationship between the entropic parameter, M, and morphological characteristics of river branches.

Figure 5. Plan view of the Tiber River branch at Ponte Nuovo (mean width 60 m).

5. CONCLUSIONS

The entropic linear relationship has been investigated by using the velocity measurements data sampled at nine gauged river sites, operating in six rivers, of which two are in Italy: Tiber and Basento rivers, and four are in Algeria: Mazafran, Chiffa, Belah and Sebaou rivers. The value of the entropic parameter M was found quite similar ($M \cong 2.1$) for the Tiber River and the four Algerian rivers. A different value was obtained for the two sites located along the Basento River. Through a preliminary analysis on morphological characteristics of rivers and based on Rosgen classification, it would seem that gauged stations belonging to the same river type might have the same value of M. However, further data referring to other rivers are required to confirm this inference.

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