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Significance of hydraulic complexity parameters M_1 and M_2 based on the laboratory and field data

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ABSTRACT

Hydraulic complexity metrics referred to as M_1 and M_2 play an important role when it comes to the analysis of habitat metrics. In the present paper, the significance of these parameters is analysed by using laboratory data as well as field observations along the Tiber River in Italy. Based on the laboratory data, the estimated parameters allow us to characterise the high/low-velocity areas. Based on field observations, larger magnitudes of M_1 are linked to the zones with large changes in cross-sectional flow velocity. Larger magnitudes of M_2 are observed at the left bank of the channel for all flow conditions, suggesting locations with larger kinetic energy consumption for aquatic organisms. Overall, the findings of the present research would be of particular interest in quantifying biologically important flow patterns occurring at different spatial scales within different streams and flow conditions.

Key words: ecohydraulics, hydraulic complexity, river hydrodynamics, Tiber River

HIGHLIGHTS

- Investigating the hydraulic complexity parameters M_1 and M_2.
- Evaluating the hydraulic complexity parameters based on the laboratory data.
- Evaluating the hydraulic complexity parameters based on the field data of the Tiber River in Italy.

1. INTRODUCTION

In-stream habitat is defined as the physical habitat or 'living' space of in-stream biota that includes the channel's physical structure and the spatial and temporal dynamics of the flow regime (Maddock 1999). Local variables associated with topography and in-stream environments, such as bed slope, bed deformation, and near-bed velocity, affect habitat structure. The similarity among streams within river systems reflects the variations in hydrologic regimes at the regional level (Pedersen *et al.* 2004). In-stream habitat heterogeneity may be linked to both substrate and flow characteristics such as water depth or flow velocity. The spatial heterogeneity or variability of flow, associated with the hydraulic complexity within a stream, is extremely important for the aquatic habitat (Clark *et al.* 2008). Blettler *et al.* (2016) addressed the benthic macroinvertebrate distributions of the Bermejo River confluence in Argentina and the Paraguay River and showed that the macroinvertebrate diversity increased slightly downstream of the confluence. Gualtieri *et al.* (2017, 2020) investigated the hydraulic complexity parameters through the confluence of the Negro and Solimões rivers on the Amazon River in Brazil and their results highlighted that the strength of flow rotation was related to the presence of helical cells forming at the confluence itself.

The present work aims to uncover the significance of metrics M_1 and M_2 introduced by Crowder & Diplas (2002) for quantifying in-stream hydraulic complexity and describing the relationship between hydraulic complexity and fish habitat preferences. While the first parameter, M_1, represents the spatial change in a flow kinetic energy and is a measure of the amount of power expended in moving from one location to another the second parameter, M_2, is a measure of how much more energy an organism must expend if it moves from the lower velocity to the higher ones. Thus, the estimation of metrics M_1 and M_2 would give us the opportunity to evaluate the hydraulic conditions favouring the aquatic habitat without the detailed knowledge of flow turbulence characteristics. We refer the reader to Lacey *et al.* (2012) to find out more about the swimming mechanics and the behaviour of fish in turbulent flows.

To this end, laboratory and field data, collected in the Tiber River (Italy) for different flow conditions, are considered. The paper is organised as follows: first, the laboratory setup and field sites are introduced in Section 2, then the theoretical description of the hydraulic complexity parameters is addressed in Section 3. The results, based both on laboratory observations and field data measures, are presented in Section 4. The paper ends with the conclusion in Section 5.

2. EXPERIMENTAL AND FIELD CASE STUDY AND DATASET

2.1. Laboratory data

The laboratory experiments were carried out in a 7-m long and 0.40-m wide recirculating straight flume, constructed at the hydraulic laboratory of the University of Palermo (Italy). The data were collected during previous research works aiming at analysing the flow velocity field and the evolution of turbulent flow structures along the channel (Termini & Sammartano 2008; Termini 2015). Figure 1 shows the plane view of the laboratory flume.

The channel banks are of Plexiglas strips and the bed is rigid and of quartz sand (D_{50} = median sediment diameter = 0.65 mm). The velocity data were collected during an experimental run (i.e. the Smooth Banks (SB) run described in Termini & Sammartano (2008) and in Termini (2015) with flow discharge of 0.013 m^3/s and water depth $h = 5.15$ cm. During the run, the instantaneous streamwise velocity component was measured by using a 2D side-looking Acoustic Doppler Velocimeter (ADV) by SonTek Inc. For each cross-section, five verticals with a distance of 7 cm were selected, and along each vertical, 14 points with a vertical space of 3 mm were chosen.

2.2. Field data: upper Tiber River (central Italy)

The velocity dataset at Ponte Nuovo gauged site is used for the analysis. Ponte Nuovo is the outlet of the Upper Tiber basin and velocity data consist of velocity points whose number along the sampled verticals is sufficient (more than eight for some verticals) to shape the vertical velocity profile, even in the presence of secondary currents. A current-meter operated by a cableway system was used to record the streamwise flow velocity section (Tarpanelli *et al.* 2013). Specifically, a mechanical current-meter was used and the flow velocity was inferred from the rotation of a bucket-wheel with a diameter equal to 13 cm and a horizontal-axis impeller. The used current-meter was able to measure flow velocity in the range of 0.06–8 m/s (Moramarco *et al.* 2019). Three flow measurements carried out during different hydraulic conditions were considered for the analysis; they refer to low, medium, and high flow conditions and are summarised in Table 1. Each measurement consists of the number of verticals, either 6 or 8, and a number of velocity points, 56–79, which guarantee a good representation of the velocity profile.

3. SPATIAL METRICS FOR RIVER FLOW COMPLEXITY: THEORETICAL BACKGROUND

The velocity gradient is a fundamental component of a spatially varying flow pattern. Velocity gradients are present near banks, boulders, and other obstructions and are potentially useful measures for quantifying and distinguishing between flows having similar depth and velocity values, but surrounded by different spatially varying flow patterns. Two parameters

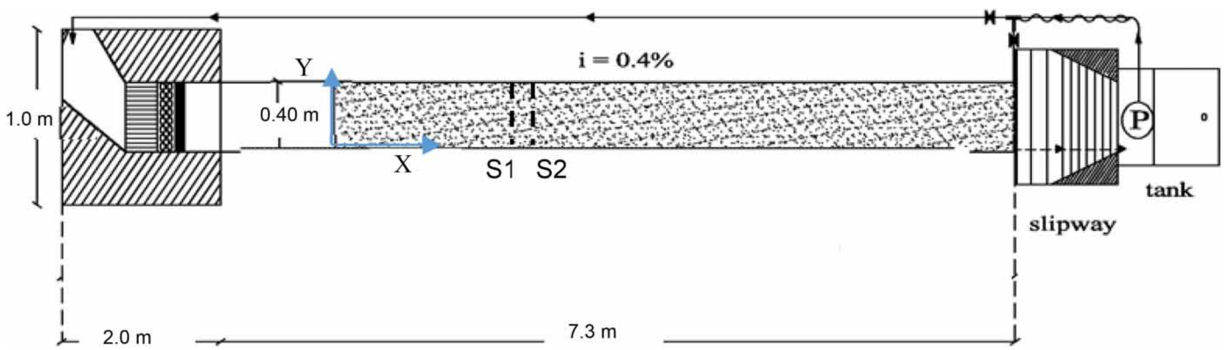

Figure 1 | Plane view of the laboratory channel.

Table 1 | Main characteristics of the flow velocity measurements at the Ponte Nuovo site (Upper Tiber River, central Italy)

Date (flow condition)	Number of verticals	Number of velocity points	Maximum water depth (m)	Discharge (m^3/s)
May 2003 (Low flow)	8	56	1.56	22
March 2000 (Medium flow)	8	79	4.01	274
November 1996 (High flow)	6	68	6.44	463

that incorporate local velocity gradients are evaluated as potential habitat metrics and they are inferred as follows (Crowder & Diplas 2000, 2002; Gualtieri *et al.* 2017):

$$M_1 = \frac{\partial}{\partial y}\frac{V^2}{2} = V\frac{\partial V}{\partial y} \cong V_{ave}\frac{V_2 - V_1}{\Delta_y} \tag{1}$$

$$M_2 = \frac{(\partial/\partial y)(V^2/2)}{(V^2/2)} \cong \frac{\left(\frac{1}{2}\right)(V_2^2 - V_1^2/\Delta_y)}{\left(\frac{V_{\min}^2}{2}\right)} = \frac{2V_{\text{ave}}((V_2 - V_1)/\Delta_y)}{V_{\min}^2} = \frac{2\,M_1}{V_{\min}^2} \tag{2}$$

where V is the velocity and V_1 and V_2 are magnitudes of streamwise velocity between the two consecutive velocity points 1 and 2, whose distance can be defined as Δ_y (for the present data $\Delta_y = 0.08$ and 1.0 m for the laboratory and field data, respectively) in the transverse direction; V_{ave} is the average of V_1 and V_2; $V_{\min}$ is the minimum value of V_1 and V_2. The first parameter M_1 represents the spatial change in a flow's specific kinetic energy (i.e. per unit mass and unit length (J/kgm)). The second parameter M_2 scales the spatial change in the kinetic energy of the flow at the point having the lower velocity magnitude. Thus, M_2 represents the normalised spatial change in a flow's specific kinetic energy. In other words, according to Crowder & Diplas (2000), the first parameter (M_1) is proportional to the drag force on an organism and it is a measure of the amount of power expended in moving from one location to another. Based on fluid dynamics, drag is the force acting against the relative movement of an object moving relative to a surrounding environment. This functionality is complicated and depends upon the shape of the object, its size, its velocity, and the fluid it is in. The second parameter (M_2) is a measure of how much more energy an organism must expend if it moves from a lower velocity to a higher velocity location. Figure 2 depicts the concept of hydraulic complexity parameters considering the aquatic organisms.

The primary reason for choosing the first parameter is that kinetic energy per unit mass ($V_2/2$) multiplied by a drag coefficient and a frontal area provides the drag force acting on a specific object or organism (Munson *et al.* 1990).

Hayes & Jowett (1994) and Fausch & White (1981) provided data that can be used to estimate the minimum and maximum possible values of $2V_{\text{ave}} \times |(V_2 - V_1)/\Delta y|/V_{\min}^2$ that existed at the fish locations observed in their studies. Specifically, both studies provided a range of focal point velocity values ($V_{\min}$), 'velocity shears', and 'velocity differences' that existed at fish locations.

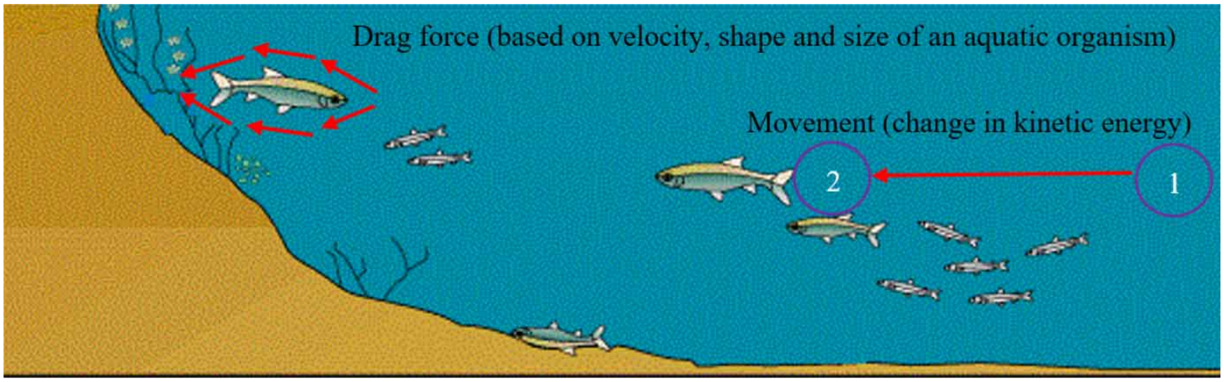

Figure 2 | Description of the hydraulic complexity parameters based on conceptual definitions.

The selected parameters M_1 and M_2 allow the evaluation of the velocity gradient and the variation in a flow's scaled specific kinetic energy, respectively, and this is important for distinguishing between flows characterised by similar values of water depth and velocity but different surrounding velocity gradients. Shields & Rigby (2005) based on field data from Crowder & Diplas (2000, 2002), reported an approximate range of observed magnitudes $0.0 < M_1 < 0.2$ J/kgm and $0.9 < M_2 < 1.3$ 1/m, respectively, for some specific flow conditions.

4. RESULTS AND DISCUSSION

4.1. Results based on the laboratory data

Figure 3 reports the distribution of flow velocity in the considered sections S1 and S2. This figure shows the regions of high/low-flow velocity: in section S1, the highest value of velocity occurs close to the free surface, at a distance $Y = 12.5$ cm from the right bank, and this region of high velocity tends to extend through the flow depth moving towards the bed; a similar behaviour can be observed in section S2 at a distance $Y = 12.5$ cm from each bank although close to the left bank (i.e. at $Y = 27.5$ cm) the high-velocity region extends more towards the bed. This behaviour is consistent with results obtained by Termini & Sammartano (2008) which highlighted the formation of alternating low/high-speed flow regions determining the evolution of alternating turbulent bursting events along the channel.

Figures 4 and 5 report the distributions of the parameters M_1 and M_2 estimated in sections S1 and S2 by using Equations (1) and (2). Figure 4 indicates that in section S1 high spatial velocity gradient, M_1, occurs in the right side of the cross-section and a lower peak value is found close to the free surface at a distance of around 16 cm from the left bank.

In section S2, the peak value of M_1 is found close to the bed on the right side of the cross-section and especially close to the free surface on the left side of the cross-section. In these locations, the organism must spend more energy to move.

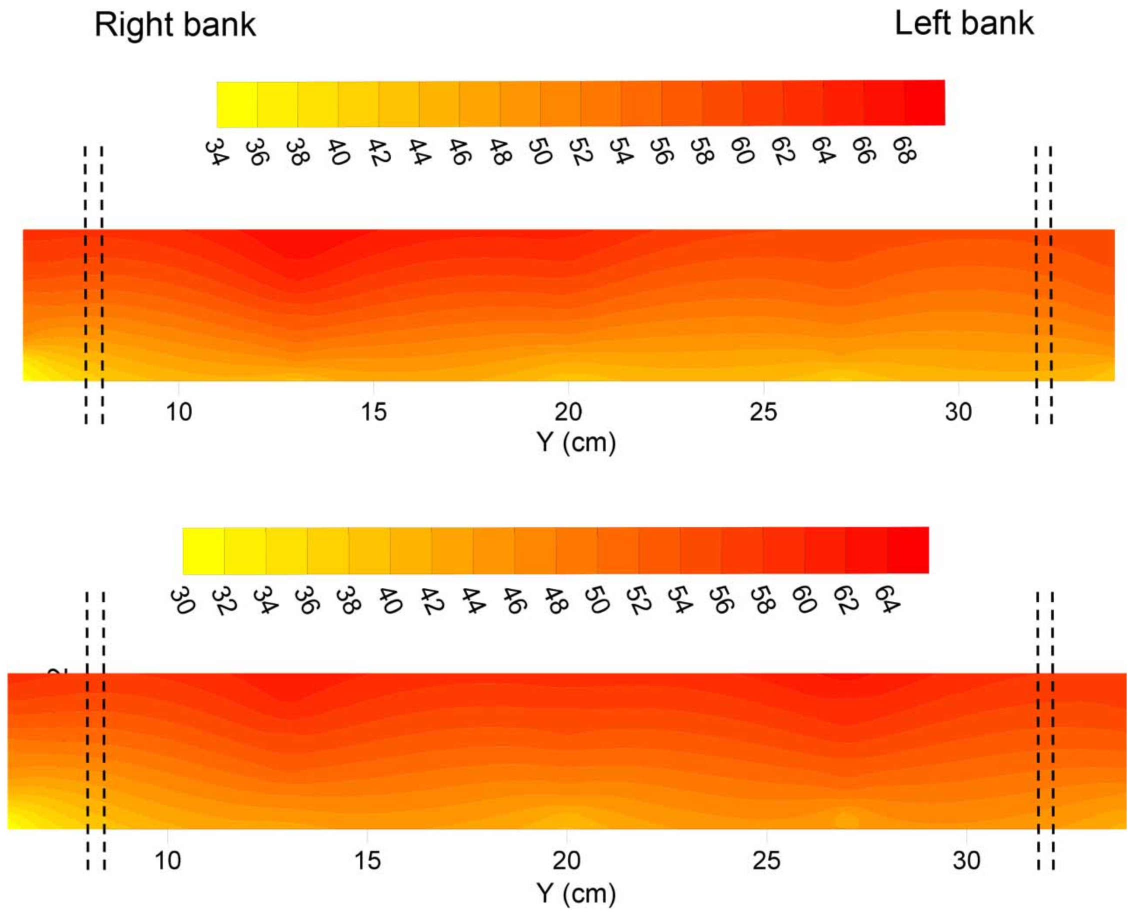

Figure 3 | Distribution of the flow velocity (cm/s) in analysed sections.

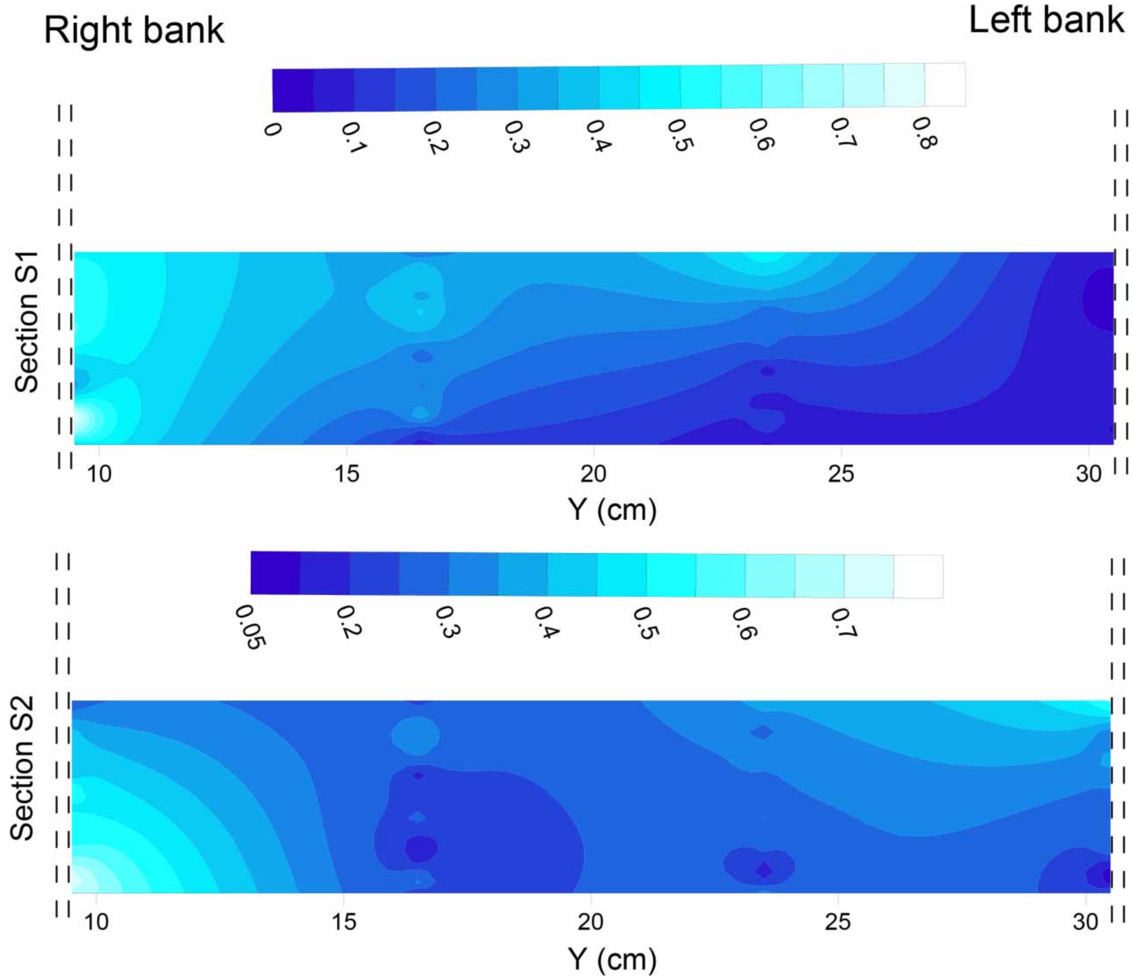

Figure 4 | Distribution of the parameter M_1 (J/kgm) in the analysed sections.

According to Equation (2), while the parameter M_1 could assume equal values with different combinations of $V_{1,}$ $V_{2,}$ and V_{ave}, the values of parameter M_2 may differ from those of M_1 depending on the value of $V_{min.}$ Figure 5 shows the distribution of M_2 in sections S1 and S2. As it can be seen, the higher values of M_2 are found on the right side of both sections, but on the left side of the section, S2 values of M_2 greater than those observed in section S1 are obtained.

Thus, Figures 4 and 5 indicate that M_1 and M_2 allow us to identify the accelerating/decelerating areas and the spatial distribution of the kinetic energy, which is defined by the alternating flow velocity pattern in the examined cross-sections. Therefore, they suggest conditions either favouring or not favouring the maintenance of the aquatic habitat.

4.2. Results based on field observations

Then, the significance of the selected parameters M_1 and M_2 is investigated by using also the data collected for the Ponte Nuovo section on the Tiber River. Figure 6 presents the cross-sectional distribution of the velocity for the Tiber River for high, moderate, and low flow conditions, carried out by the current-meter. The black dash-dot line highlights the bathymetry for each cross-section. As seen, for the Ponte Nuovo cross-section the larger magnitudes of velocity are observed at the centre for high and moderate flow conditions and at the left half for the low flow conditions. The discharge in general and the summer discharge, in particular, are of significant importance for maintaining high physical habitat quality (Pedersen *et al.* 2004).

Changing the flow conditions may affect the lives of organisms, for example, as velocity (or discharge) increases, macroinvertebrate diversity, and quality increase (Pedersen *et al.* 2004). The important point is that by increasing the discharge,

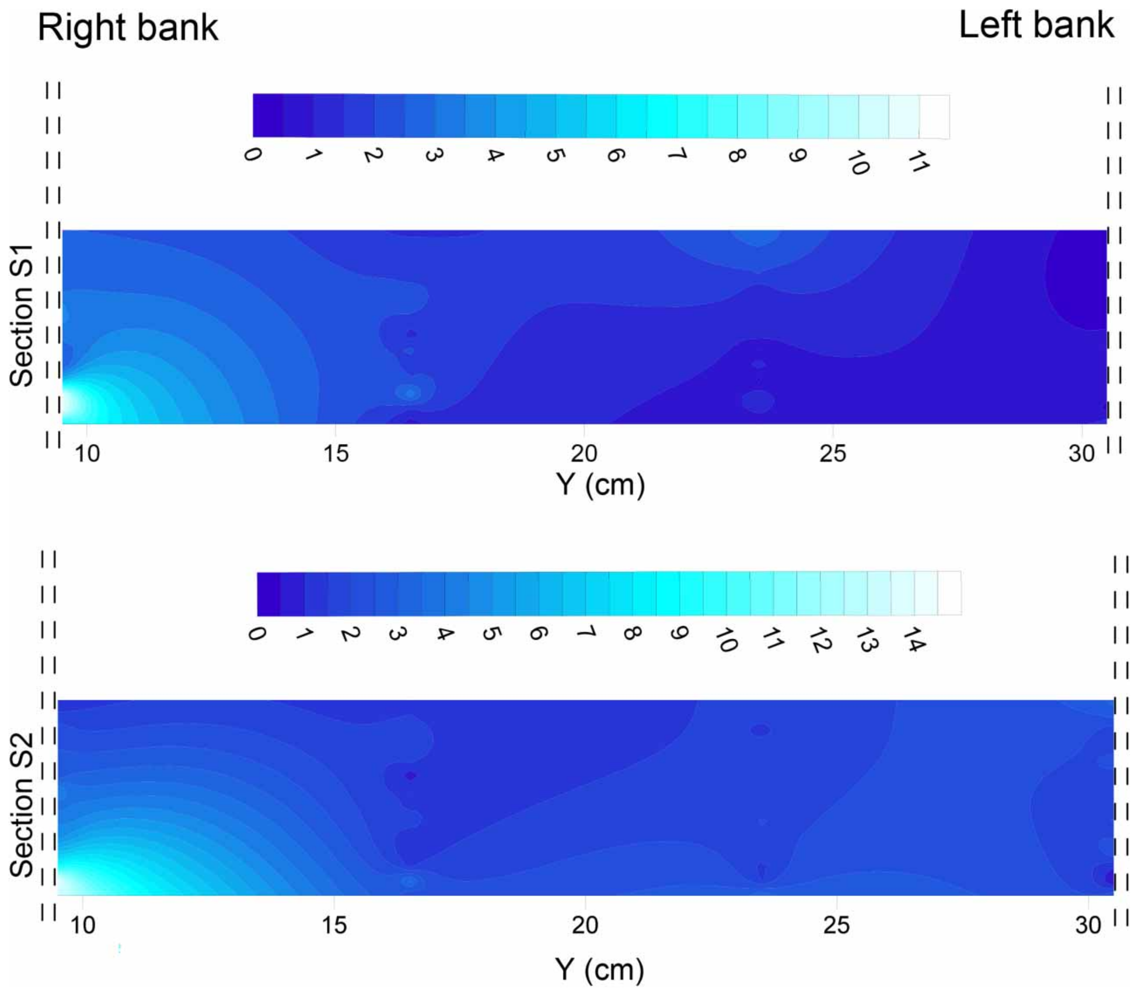

Figure 5 | Distribution of the parameter M_2 (1/m) in the analysed sections.

the velocity dip (the maximum velocity below the water surface) is formed which is more remarkable for the high-flow condition. It is believed that for the present cross-section, the dominant parameter for the formation of velocity dip is the aspect ratio (Moramarco *et al.* 2017; Kundu & Ghoshal 2019; Termini & Moramarco 2020; Bahmanpouri *et al.* 2022a, 2022b).

The knowledge of the velocity distribution allows the investigation of the two selected spatial metrics for river flow complexity. Figure 7 depicts the cross-sectional distribution of the parameter M_1 at Ponte Nuovo.

At the Ponte Nuovo site, the scale of parameter M_1 is 0.0–0.25 and 0.0–0.20 J/kgm for high and moderate flow conditions, respectively, while for low flow conditions, the scale is 0.0–0.02 J/kgm. The larger magnitudes of parameter M_1 are linked to the zones with a larger change in the velocity magnitude. That is, by changing the flow condition from low level to high level, larger magnitudes of drag force are applied to aquatic organisms. Gualtieri *et al.* (2017) reported an average magnitude of $0.01 < M_1$ (J/kgm) < 0.07 between Rio Negro and Rio Solimões in the Amazon River with $0.5 < \Delta_y$ (m) < 2.0. The kinetic energy in these flow structures can be used by swimming fish (Videler *et al.* 1999; Enders *et al.* 2003).

Figure 8 depicts the cross-sectional distribution of parameter M_2 for three different flow conditions. Based on parameter M_2, the kinetic energy at the point with the lower velocity magnitude represents the amount of energy an organism must expend if it moves from the lower velocity location to the higher velocity location. Larger magnitudes of M_2 are observed near the left bank, corresponding to lower velocity zones. A similar result was reported by Gualtieri *et al.* (2017) for the confluence of Rio Negro and Rio Solimões on the Amazon River and Shields & Rigby (2005) for the Tallahatchie River, Mississippi.

The minimum, average, and maximum magnitudes of M_2 are 0.01, 0.12, 1.13 (1/m) for high flow conditions, 0.01, 0.12, 0.7 (1/m) for moderate flow conditions, and 0.01, 0.09, 0.7 (1/m) for low flow conditions, respectively, at Ponte Nuovo section.

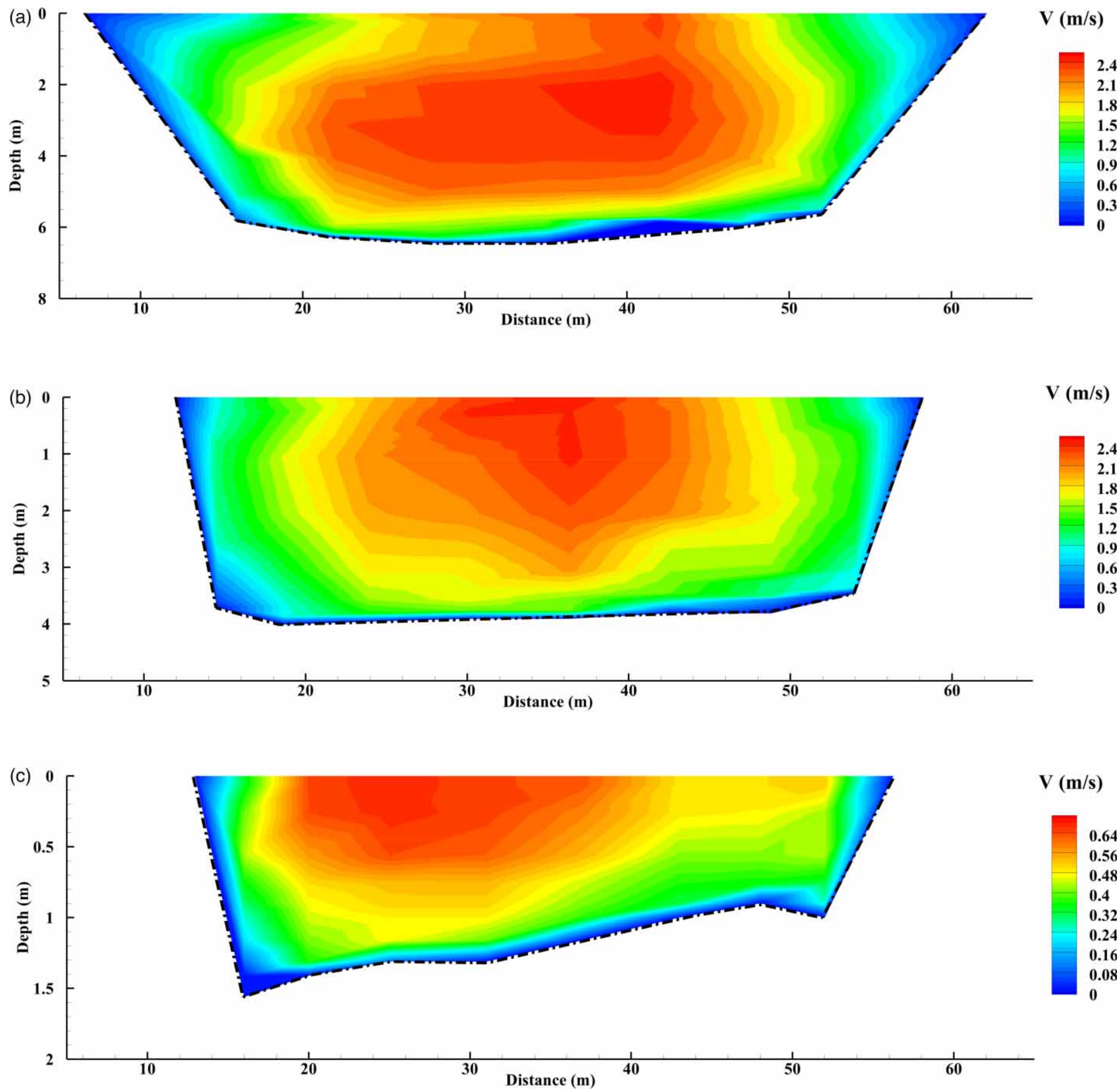

Figure 6 | Ponte Nuovo (Tiber River): cross-sectional distribution of the velocity: (a) High-flow conditions (Nov. 1996), (b) Moderate-flow conditions (Mar. 2000), (c) Low-flow conditions (May 2003).

Gualtieri *et al.* (2017) reported an average magnitude of $0.09 < M_2$ (1/m) < 0.37 at the confluence between Rio Negro and Rio Solimoes in the Amazon River. Other researchers calculated the minimum and maximum magnitudes of M_2 as 0.08 and 0.34 1/m (Fausch & White 1981), 3.1 and 40.7 1/m (Hayes & Jowett 1994), and 0.002 and 97.3 1/m (Crowder & Diplas 2000). The likeness of the identified ranges suggests the same flow patterns that may provide suitable habitats for the organisms such as fish. The difference between the magnitudes for different studies would be first because of different directions and distances between the velocity measurements and second because of the different flow kinematic conditions that make a complete comparison difficult. The results of a field study conducted by Kozarek *et al.* (2010) on Staunton River, Canada, showed that for brook trout, although velocity or depth characteristics are insufficient to explain fish habitat preferences in the complex flows created by boulders and other flow obstructions, fish density generally increases with increasing the flow complexity.

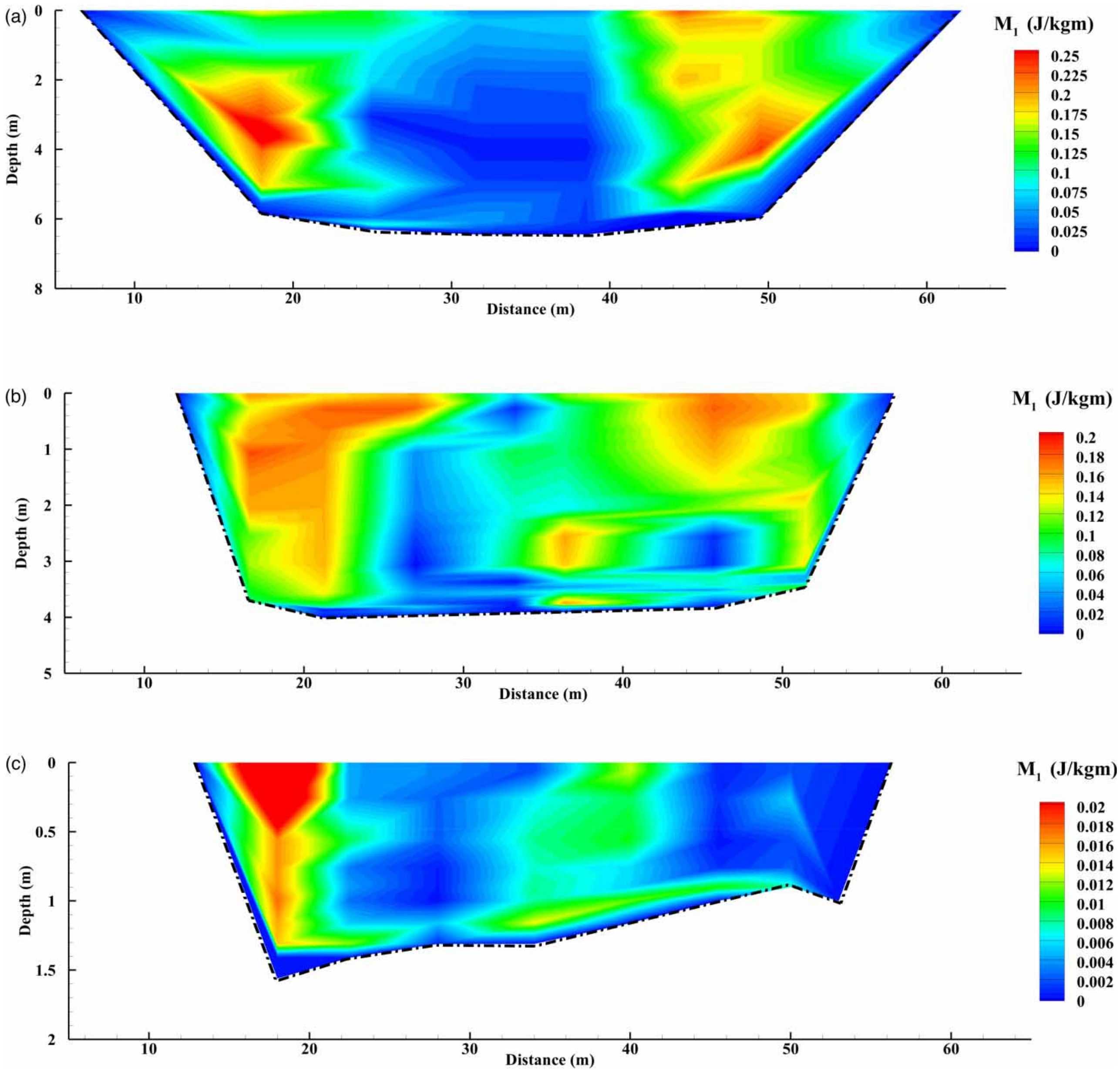

Figure 7 | Ponte Nuovo (Tiber River): cross-sectional distribution of parameter M_1: (a) High-flow conditions, (b) Moderate-flow conditions, (c) Low-flow conditions.

5. CONCLUSIONS

The hydraulic complexity metrics M_1 and M_2 are investigated for velocity datasets collected in a laboratory experiment as well as at gauged sites through the Tiber River in Italy. M_1 and M_2 enable us to calculate the kinetic energy used by aquatic organisms to move in the flow. Based on the laboratory data, the estimated parameters M_1 and M_2 adequately indicate the formation of high/low-velocity areas, along with the accelerated–decelerated zones, within each examined section. According to field observations, larger magnitudes of M_1 are linked to the zones with a larger change in velocity rates, which, for high and moderate flow conditions, it occurs at the centre. Furthermore, larger magnitudes of M_2 are observed at the left bank of the channel suggesting locations with larger kinetic energy consumption for aquatic organisms.

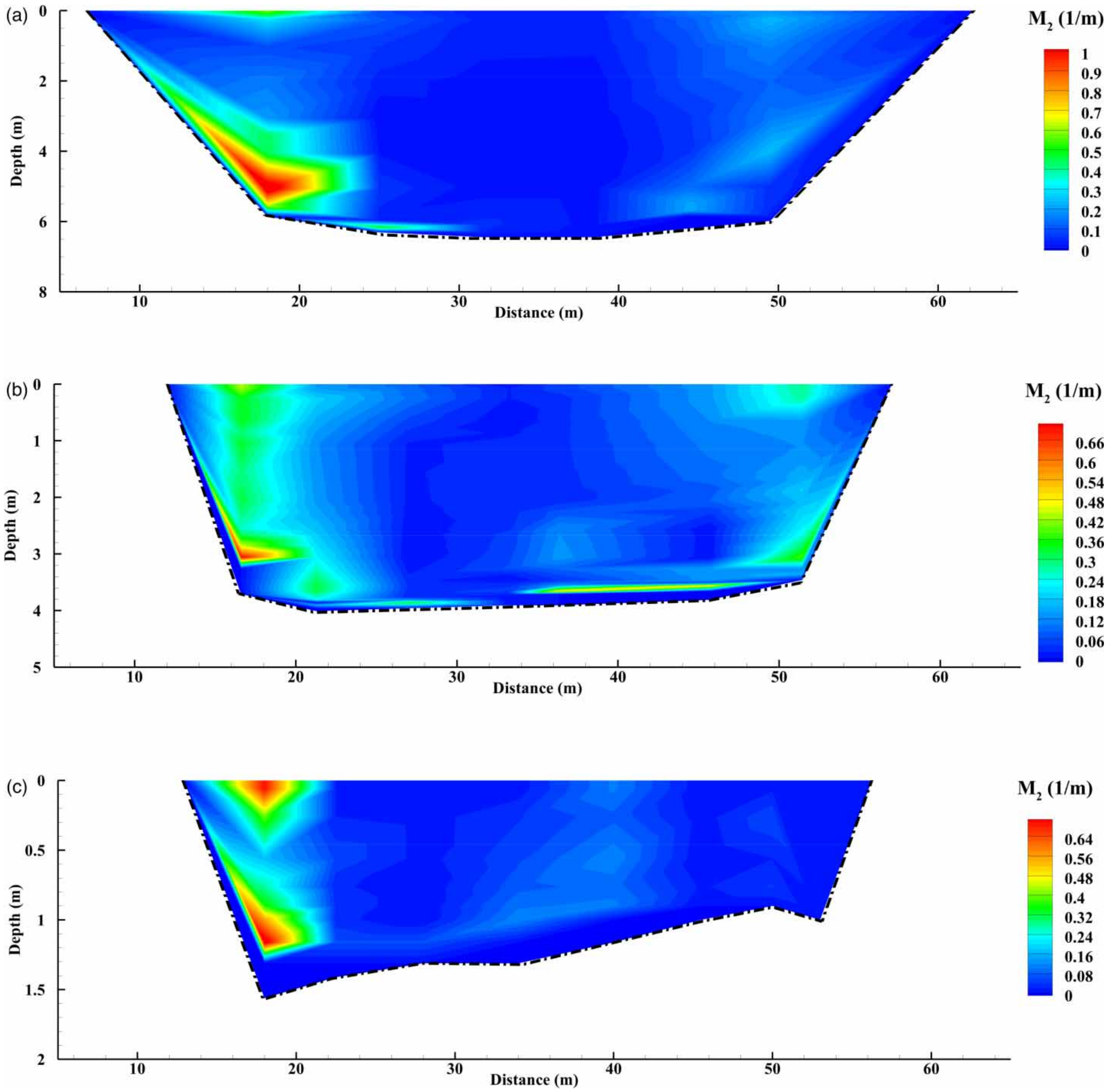

Figure 8 | Ponte Nuovo (Tiber River): cross-sectional distribution of parameter M_2: (a) High-flow conditions, (b) Moderate-flow conditions, (c) Low-flow conditions.

Overall, the findings suggest that the hydraulic complexity parameters may add some insights to explain the habitat heterogeneity as well as evaluate ecological and biological patterns in rivers with remarkable flood rates such as the Tiber River. As the next step of the present research, hydraulic complexity parameters will be calculated based on the application of Entropy theory considering either all measured surface velocities or only a single measured surface velocity.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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