A simple method to assess flood hazard at riverbed cross-sections applied to a site in the Italian Central Alps

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ABSTRACT

In mountain environments, urbanized areas are often, if not always, located along the main river, in the valley bottom: this can lead to hazardous situations when the river itself and its features are not accounted for in a proper manner. To avoid such situations, a proper hazard and/or risk evaluation is required, even more in the wider context of a changing climate. For these reasons, the present study proposes a simple and easy to reproduce method for a preliminary evaluation of the hydraulic hazard of rivers in an alpine environment. This approach is based on easy to access and public data. The method does not provide a complete description of the hydraulic conditions of a river but is simple and highly replicable: it is intended as a tool to quickly assess the hydraulic hazard of strategic locations. A suitable site in the Central Italian Alps was analyzed to test the goodness of this method.

KEY-WORDS: hydrological hazard, floods, Alpine region.

INTRODUCTION

In mountain environments, such in the Alps, it is common to find the most urbanized or industrialized areas along the valley bottom. Consequently, locations of high economic importance or densely inhabited areas lay close to or directly on the shores of rivers and torrents. While in the past most of the land was occupied by farmland, scenarios such as those just described become more and more common as the urbanized areas tend to expand: the human influence on the river channels dynamics is significant, as the wide distribution of protection works and artificial channels, required to keep the territory as safe as possible from floods, has altered the natural river processes (Gregory, 2006; Surian et al., 2009; Serrano-Notivoli et al., 2017; Horacio et al., 2019), aiming at fixing in place the position and stabilizing the behavior of something that is naturally and continuously changing. Nevertheless, the evaluation and mapping of hazardous scenarios associated with the presence of a river should be properly taken into account in land use planning; otherwise, significant negative consequences, damages and loss of human lives are to be expected (Mandarino et al., 2021).

In mountain regions, the main source of water for rivers and other waterbodies is the melting of the snow cover or the occurrence of intense or long rainfall events: it is, therefore, easy to see how the effects of climate change may have strong consequences in these areas, where the territory appears already significantly exposed to the adverse effects of channel dynamics because of the morphology of mountain valleys (De Jong, 2015; Molini et al., 2011; Schneeberger, 2015; Monforte et al., 2022). A well-timed approach to this kind of problem is always a good way to prevent significant damages in both the short and long term. With this in mind, the present work aims at providing a quick and easy to reproduce procedure for the evaluation of hydraulic hazard, relying on public databases and simple yet consolidated analytical methods, coupling them with a Geographic Information Systems (GIS) environment. A suitable case study located in the Central Italian Alps (Camonica Valley, municipality of Darfo Boario Terme) is proposed and analysed to evaluate the positive outcomes of this approach and its shortcomings.

GEOLOGICAL SETTING

The northern portion of the Oglio River catchment is located in the Central Italian Alps and practically coincides with the area occupied by the Camonica Valley (Brescia Province, Lombardy Region, Northern Italy): the valley stretches from the northern reliefs of Mt. Adamello group to Lake Iseo to the south, along a NE-SW direction. From a geological point of view, the southern portion of the valley is located within the Southern Alps Domain, while the northernmost portion is part of the Austroalpine Domain. The two tectonic domains are separated by the Insubric Line, which is known in the area by the local name of Tonale Line. From a geomorphological point of view, the area is characterized by the typical features of a glacial alpine valley, deeply influenced by slope instability and fluvial processes, especially in the northern portion. The geographical location of the study area is visible in Fig. 1, along with the position of the town of Darfo Boario Terme, where the closing position of the catchment considered in this study is located. This municipality is the most populous of the entire valley, and due to the morphology of the valley bottom, the urban area is mostly located close or very close to the Oglio River. In this area, the industrial sector is also significantly developed: all these factors make the area a suitable site to investigate hydraulic hazard, due to the high value of the elements at risk and their significant level of exposure. For this reason, three hydraulic sections were chosen for their position near residential or industrial areas, or because of the presence of strategical infrastructures. It should also be noted that the selected area has been recognised as hazardous by the local and regional administration: in fact, all three hydraulic sections are located within the perimeter of the frequent scenario for floods, defined as having a recurrent period (*Tr*) of 20 years and a high level of hazard (class *H*) by the Piano di Governo del Rischio Alluvioni (PGRA), that is the official flood hazard management tool of the regional administration (Regione Lombardia, 2022). The PGRA is also portrayed in Fig. 1.

MATERIAL AND METHODS

The basic idea behind the approach proposed in this paper is to identify hazardous hydraulic cross-sections in the cheapest and simplest way possible, minimizing the need to gather new data and information, relaying instead mostly on public databases. The simplicity of the method derives from it being based on well-known and consolidated empirical formulas to define the various quantities involved in a hydraulic hazard evaluation: these approaches provide a simple yet effective description of rainfall, peak discharge, and flow rate at a given cross section, requiring a small number of input

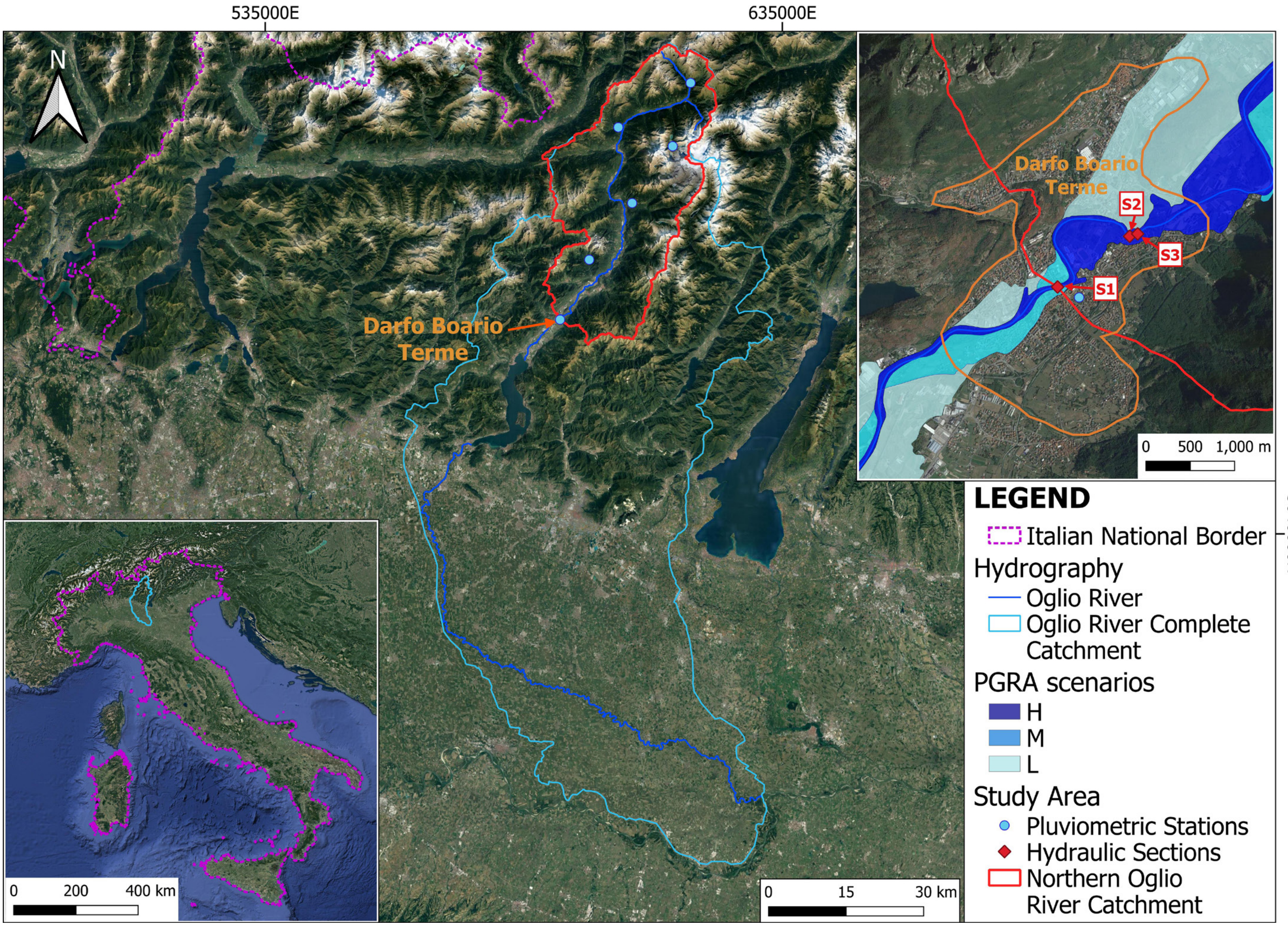

Fig. 1 - Geographic localization of the study area in Northern Italy, with the entire Oglio River catchment and its northern portion highlighted; the position of the pluviometric stations, of the town of Darfo Boario Terme and the three hydraulic sections (S1, S2 and S3) are also visible, alongside PGRA flood hazard polygons.

variables to be quantified. Moreover, the input variables can be easily derived from the data available in public databases.

The first step consists of the definition of the rainfall regimen of the studied area (i.e., the catchment identified by the considered cross-sections). The parameter traditionally used to describe this is the distribution through time of intense rainfall phenomena. To assess the effect of intense precipitation over the northern portion of the Oglio River catchment, and its consequences in terms of high discharge, the recorded rainfall data were analysed following the method proposed by Gumbel (1941). Once the rainfall phenomena have been described properly, the maximum expected discharge produced by the catchment can be quantified: this step is crucial, as this parameter quantifies the natural process that can potentially be hazardous; the maximum expected discharge was computed relying on the Metodo Razionale (Turazza, 1880; Peruginelli, 2011). The first input data required in this phase are, therefore, the morphometric features of the Oglio River, followed by the land cover classification. The last step of the process consists of the comparison between the maximum expected discharge and the amount of water that can flow through a given cross-section: this value, defined as the admissible flow rate, is quantified with the most common analytic approach described in Chow (1959).

Pluviometric analysis

Gumbel's (1941) approach links the intensity of an event to its probability of not being exceeded. When this probability value is expressed as a function of reference return periods, the intensity can be quantified through probability curves described by the following equation:

$$h = a\, t^{b}$$

where *t* is the duration of the event, *a* and *b* are characteristic features of a given catchment.

The parameter describing rainfall intensity (i_c) is usually expressed in terms of mm of rain (*h*) over a reference time interval. This time interval is set equal to the concentration time (t_c), calculated employing Giandotti's formula, which was specifically devised for this kind of studies (Giandotti, 1934): concentration time is defined as a function of catchment elevation, area and river length, which can all be extracted from the DTM once the study area is identified through the morphological analysis of the regional DTM itself (Regione Lombardia, 2015). To evaluate *a* and *n*, and therefore *h*, the analysis of a large enough database of rainfall measures spanning a sufficiently long period of time is required: this data was provided by the regional agency of environmental protection (ARPA Lombardia, 2020) for the period between 2005 and 2020 and measured in six stations located across the entire catchment analysed; the position of the stations is visible in Fig. 1. This analysis has been conducted for six return periods (*Tr*) of 10, 20, 50, 100, 200 and 500 years. Once *h* is known, the critical rain intensity (i_c) can be calculated, as it is defined as the ratio between *h* and t_c.

Gumbel's method is still considered today the standard approach to describe phenomena such as intense rainfall, although over very long return periods the accuracy of the approach decreases (De Michele et al., 2005). Given that in this study no return period higher than 200 years was considered, no correction of the method is required.

Maximum discharge evaluation

As anticipated previously, to quantify the maximum expected discharge produced by the northern Oglio River catchment, the Metodo Razionale (Turazza, 1880; Benini, 1990; Peruginelli, 2011) was employed; the expected discharge (Q_e) is defined as:

$$Q_e = k \cdot i_c \cdot C \cdot A$$

where *k* is a constant used to provide coherence between units of measurement, i_c is the rainfall intensity in mm/hour, *C* an adimensional coefficient describing surface runoff with respect to the global waterflow on the basin surface, and lastly, *A* the catchment area in km^2.

The expected discharge is, therefore, a function of only three parameter: the advantage of such a relation is of course the low number of parameters to quantify. The assumptions it relays on, though, is equally important: it is assumed that the rainfall event of critical intensity occurs over the entire catchment area, which is a significant simplification of how real extreme rainfall events work. The values for the discharge obtained in this way are indeed higher than those provided by more in-depth approaches, as this method is clearly cautionary. The choice of employing the Metodo Razionale is heavily weighted by the ease with which its variables can be quantified even for large or very large catchments. In fact, the catchment area is known, as the river catchment itself was extracted from the DTM. The method to quantify rainfall intensity has already been introduced in the previous paragraph, therefore only the third variable, the *C* coefficient, still needs to be quantified.

To do so, a two-step process was performed: the value of the coefficient was calculated as a weighted mean over the area of six land use classes: urban areas, farmland, grassland, vegetated areas, ice and waterbodies, and rock outcrops. The first step consists in mapping each of these classes using the publicly available land use data (Regione Lombardia, 2018): this data is derived from the analysis of orthophotos (aerial and from satellite) and is available at a 1:10.000 scale. A value of *C* was assigned to the first four classes, with reference to the values proposed by Benini (1990), while the value attributed to ice and waterbodies was set to 0. To assign the *C* value of rock outcrops (sixth class), the second step was employed: the shapefiles of the bedrock provided by the CARG geological maps (Servizio Geologico d'Italia, 2012, 2011a, 2011b, 2008), which are available at a 1:25.000 scale, were reclassified identifying only three lithologic families (silicatic, carbonatic and evaporitic rocks); in this way, it was possible to quantify the contribution of the different processes involved in the interaction between these groups of rocks and surface runoff. To each of these three families, a *C* value was given, then a global value for all rock outcrops was calculated as an average weighted over the area covered by each lithology. Once each of the six classes had a defined *C* coefficient, the global value for the entire northern portion of the Oglio River catchment was calculated. With all the required parameters known, it was possible to quantify discharge for each of the six *Tr*.

The simplicity of this method produces results that are intended only as preliminary and cannot be used, for example, to properly design mitigation works.

Admissible flow rate evaluation

The amount of water that can pass through a hydraulic section depends on the area of that section (*S*) and the velocity of the flow. To quantify the average flow velocity (*V*), the more commonly employed analytic expression is the one proposed by Chézy in the XVIII century and later modified by Manning (1895) in the XIX century. The relation, as described in Chow (1959), is as follows:

$$V = \frac{1}{n} \cdot R^{\frac{2}{3}} \cdot i^{\frac{1}{2}}$$

where *R* is the ratio between the area of the section (*S*, in m^2) and the perimeter that contains water (P_w, in m), *i* is the gradient (in m/m), and *n* a coefficient that describes the characteristics of the riverbed close to the section; if flow velocity is measured in m/s, *n* is measured in s/m$^{1/3}$. This factor can be quantified empirically using the approach proposed by Cowan (1956), where five partial factors (n_0 to n_4) describe the material of the riverbed, its surface regularity, variation in shape and size of the section, presence of obstructions and vegetation: these five partial factors are summed and then multiplied by a sixth coefficient (m_5) that describes the sinuosity of the river. The gradient (*i*) can be estimated by employing analytic expressions (Benini, 1990; Chow, 1959) or extracting such value from the DTM: in this study, *i* was quantified using the Taylor-Schwartz formula (Chow, 1959). Lastly, the surface of the section (*S*) and its perimeter (*Pw*) are obtained from topographic surveys carried out with a laser telemeter on-site. Once these parameters are known, the maximum acceptable discharge (Q_{max}) for each hydraulic section can be quantified.

The relation proposed by Chézy is more than sufficiently precise for the scopes of the method here discussed, considering the significant simplifications assumed in the previous steps of the method, as presented above. Moreover, the only parameters that require to be quantified through direct measures on the field, i.e., *R* and *n*, do not involve complex measurements, further adding to the simplicity of the methodology. It must be said, though, that the evaluation of the Manning's *n* coefficient is somewhat subjective in comparison to all the other passages of the approach.

RESULTS

Rainfall data covering the 2005-2020 period measured in the six considered stations were analysed as described in section 3.1. The first step consists in calculating the *a* and *n* coefficients for the pluviometric probability curve. These values were obtained by plotting the curves derived from measured data for each of the six considered *Tr* for every available station: given that the six considered stations cover practically all the northern Oglio River catchment area, the coefficients were then averaged, and global values were obtained. This needs to be done because the approach proposed by Gumbel (1941) considers rainfall events that cover the entire basin analysed. The resulting values are shown in Tab. 1.

Table 1 - The average values for a and n for the entire northern Oglio River catchment, derived from the measured data.

Tr	Average values	
[years]	***a***	***n***
10	28,8	0,40
20	31.6	0,40
50	35.4	0,40
100	38,1	0,40
200	40,9	0,39
500	44,6	0,40

The northern portion of the Oglio River catchment covers an area of 1.149 km^2, with an average elevation of 1.678 m and a total stream length of 80 km. The closing section has an elevation of 212 m. With this data available, the value of the concentration time (t_c) was obtained as described in section 3.1. Lastly, it was then possible to evaluate the amount of rain (*h*) expected for each *Tr*, and the respective rainfall intensity (i_c). The results are summarized in Tab. 2.

Table 2 - Expected rainfall (*h*) and rain intensity (i_c) for the calculated concentration time (t_c) for the six return periods.

Tr	h	t_c	i_c
[years]	[mm]	[hours]	[mm/hours]
10	31,18	8,33	3,74
20	34,05	8,33	4,09
50	37,76	8,33	4,53
100	40,54	8,33	4,87
200	43,29	8,33	5,20
500	46,96	8,33	5,64

Following the procedure exposed in section 3.2, the global *C* coefficient was evaluated. Fig. 2 depicts the Oglio River basin as its surface was classified in terms of this coefficient. Tab. 3 summarizes the steps of the approach for the determination of the global *C* value.

Table 3 - Value of *C* for the six land use classes, the three rocks families and the global weighted average.

Land use class	Area [km^2]	C
Urban area	27,09	0,90
Farmland	7,07	0,70
Grassland	216,51	0,62
Vegetated	613,72	0,36
Silicatic Rocks	217,90	0,82
Carbonatic Rocks	46,40	0,72
Evaporitic Rocks	0,12	0,52
Ice and Water	17,05	0,00
TOTAL	**1.145,86**	**0,52**

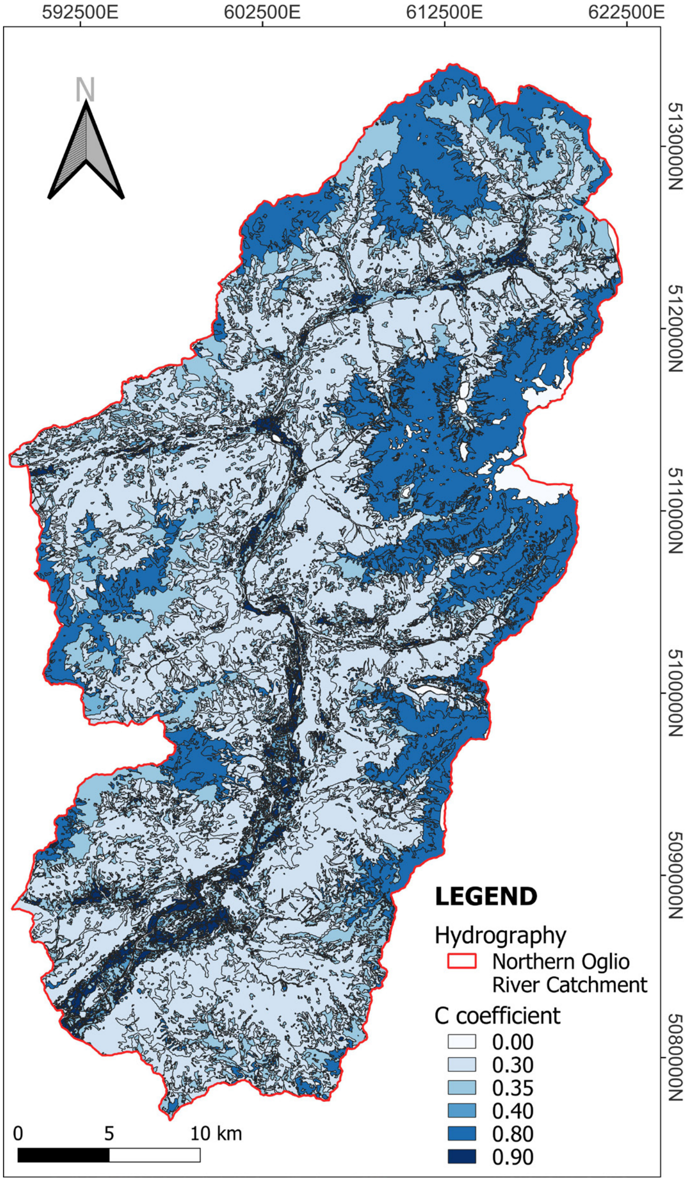

Fig. 2 - Values of the C coefficient in the studied catchment.

Fig. 3 - Pictures of section S1 (top), S2 (middle) and S3 (bottom).

It should be noted that the total area covered by the land use classification here employed (1.145,86 km²) is approximately 3 km² lower than the actual basin surface. This corresponds to a neglectable error of approximately 0,25%, most likely due to the different source data employed to define the catchment, which was extracted from the DTM, and the land use maps, delimited by the official border of Lombardy region; in some sectors the official border does not perfectly follow the morphologically defined Oglio River catchment perimeter.

With all the parameters required available, the equation describing the expected discharge (Q_e), as presented in section 3.2, was solved: Tab. 4 summarizes the results.

The last step consists in quantifying the maximum flow the three hydraulic sections can withstand (Q_{max}), as detailed in section 3.3. The three sections are depicted in Fig. 3 and schematized in Fig. 4. As can be seen, section S1 is located at a bridge, while sections S2 and S3 are positioned respectively at a river bend and just upstream. The Manning coefficient *n* evaluated

Table 4 - Value of the expected rainfall intensity (i_c) and discharge (Q_e) at the closing section of the northern portion of Oglio River catchment for each of the six *Tr* considered.

Tr	i_c	Q_e
[years]	[mm/hours]	[m³/s]
10	3,74	622,32
20	4,09	679,60
50	4,53	753,65
100	4,87	809,13
200	5,20	864,02
500	5,64	937,27

as proposed by Cowan (1956) is equal to 0,073 for section S1, 0,062 for S2 and 0,048 for S3. With all the parameters required, the mean flow velocity (*V*) and subsequently the maximum acceptable discharge (Q_{max}) were evaluated for each section. Tab. 5 shows the results.

Table 5 - Quantification of flow velocity (*V*) and maximum acceptable flow rate (Q_{max}) at each hydraulic section. *S* is the area of each section.

Section	n	R	i	V	S	Q_{max}
	[s/m$^{1/3}$]	[1/m]	[m/m]	[m/s]	[m^2]	[m^3/s]
S1	0,073	4,51	0,014	4,42	285,5	1.250,84
S2	0,062	6,77	0,014	6,72	494,3	3.321,76
S3	0,048	3,82	0,014	5,96	171,8	1.024,33

As a preliminary check, hydraulic hazard arises only in those situations where Q_{max} has a lower value than Q_e. Therefore, to verify that none of the three hydraulic sections considered in this study are associated with hydraulic hazard, the two values obtained in the previous paragraphs (Table 4 and 5) are confronted: Section S1 has a Q_{max} of approximately 1.250 m^3/s, which is larger than the maximum expected discharge (for *Tr* = 500 years) of 937 m^3/s; the difference amounts to 33% of Q_e. Section S2 has a Q_{max} of approximately 3.320 m^3/s, which is larger than the maximum expected discharge (for *Tr* = 500 years) of 937 m^3/s; the difference amounts to 254% of Q_e. Section S3 has a Q_{max} of approximately 1.024 m^3/s, which is larger than the maximum expected discharge (for *Tr* = 500 years) of 937 m^3/s; the difference amounts to 9% of Q_e. All sections are thus verified.

DISCUSSION

As seen, none of the three sections point out hydraulic hazard, but the results are quantitatively different. First of all, it is worth noting that section S1, located where a bridge crosses the river, has an ample margin between its Q_{max} and Q_e. This is mostly related to how wide (58,0 m) the hydraulic section is, even if considering the obstruction produced by the bridge structure. It should also be noted that, as visible in Fig. 4, the right portion of the section is occupied by vegetation. This fact is described by Manning's coefficient, which has the highest value of all three sections. Section S2 has the highest Q_{max} of all three sections, mostly because of how wide it is (75,5 m). This hydraulic section is the only one to have the m_5 coefficient lower than 1: this was chosen to account for the presence of a turn of the river towards NW. The turn is expected to reduce flow velocity, as it induces turbulence because of the curvature. The simple model proposed here does not seem to describe a significant reduction of flow velocity, though: this is likely associated with how wide the cross-section is. Lastly, section S3 has the lowest Q_{max} of the three sections: it's indeed the least wide (41,5 m), but it's also the section where resistance to flow is described as the lowest (*n* = 0,048).

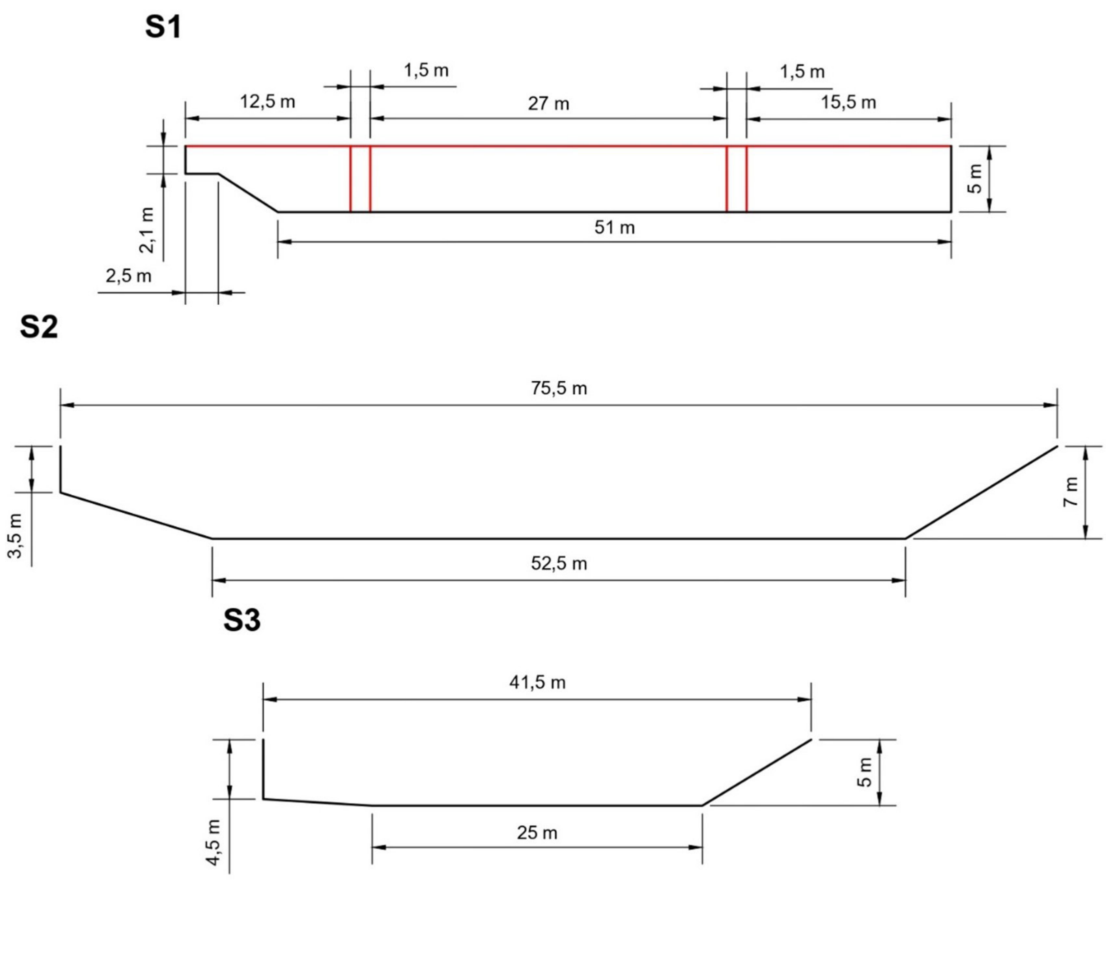

Fig. 4 - Schematic representation of section S1 (top), S2 (middle) and S3 (bottom).

In the broader context of changing climate, it is important to address this kind of situation: the calculations described in this study show that section S3 has a small margin of tolerance, given that if Q_e increases by less than 10% of its expected value, this section would be associated with a significant risk, considering the dense residential fabric of the surrounding area. To avoid such an occurrence, many techniques could be employed: from structural works such as reinforcing the riverbanks with embankments or the identification of suitable sites for retention basins along the river, to non-structural works involving the maintenance of the river itself, removing the sediment excess or the vegetation visible in the considered hydraulic sections. All of these approaches to the problem require a significant understanding of both the conditions of the riverbed and the dynamic of waterflow and channel processes. These features are not considered within the aims of the methodology here presented and, therefore, the proposal of flood risk mitigation techniques is beyond the scope of this study.

CONCLUSIONS

The study here presented aimed at evaluating the hydraulic hazard of the town of Darfo Boario Terme (BS), with reference to three sections chosen along the Oglio River for their proximity to residential or industrial areas with a dense urban fabric, or because of the presence of strategic infrastructure. The analysis performed quantified the expected discharge at the closing sections and the maximum acceptable discharge that those sections could withstand. The results show that among the three hydraulic sections, only S3 has a very low margin, considering that with an increase of less than 10 percent of the expected discharge value, this section would not be verified.

Although the approach employed in this study is simple and very easy to replicate, it is based on assumptions that significantly simplify the reality of events such as extreme rainfall and floods. These simplifications can lead only to rough estimations: therefore, the data here presented should be intended as a quick preliminary analysis, aiming at identifying critical locations where more in-depth and sophisticated investigations should be performed. Consequently, this approach cannot lead to suggestions on possible mitigation techniques or works to be used where the methodology identifies critical locations. Nevertheless, the simplicity of the process makes it feasible even for studies involving large areas and long rivers, thanks to the highly repeatable nature of the approach and the availability of input data required.

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