Comparison of Digital Terrain Models for estimating water volumes in a river through GIS tools

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Abstract

This work demonstrates the potential of exploiting LiDAR-based high resolution Digital Terrain Models (DTMs) to estimate water volume proxies by the mean of standard GIS tools, in a river stretch. Such approach may result profitable to integrate rapid analyses and reach timely information about the quantity of water contained in a river portion. This paper addresses the case study of Po River, in Italy, leveraging official databases to recover necessary data. Cross-sections are extracted from several DTMs and are used, in combination with hydrometric records collected along the river stretch, to estimate water volumes. Among the analyzed models, LiDAR-based DTMs, such as the 2x2 m resolution DTM used in this study, provided particularly accurate reconstructions of riverbed morphology. The findings show a substantial coherence with the river's seasonal variations and the volume trends reflect the environmental conditions faced by the Po River in the period of reference, ranging from severe drought to flood events. Furthermore, noticeable correlation between the estimated volumes and water surface extent evaluated in a previous work (Conversi et al., 2024) are shown.

1. Introduction

Riverine ecosystems are among the most exposed to climate change and its consequences. Specifically, they suffer from different types of phenomena, from droughts to floods caused by heavy rainfall, which, as shown by Barendrecht et al. (2024) appear to be phenomena having a mutual interaction within involved territories. The intensity and frequency of such events are increasing at an alarming rate. As shown by Arnell et al. (2014), the global flood risk is projected to reach 187% of what would be the expected risk in the absence of climate change by 2050. This means that as the years go by, such phenomena will affect larger areas, including zones that have not been particularly prone to flood damage in the past. The recent European Climate Risk Assessment (European Environment Agency, 2024) reports that on a worldwide basis, Europe results to be the fastest-warming continent, with critical peaks of extreme events expected to involve southern and western regions in the next years. Furthermore, the report highlights the crucial role played by waterbodies and their ecosystems in countless aspects of today's society, first of all referring the massive dependence that EU economy has upon such areas. Apart from the most direct and intuitive consequences of extreme events over the territories (e.g. casualties, economic losses, need to restore pre-event conditions), particular attention should be devoted to the impact that such phenomena have on the waterbodies themselves. Prolonged dry period, for instance, result in groundwater levels reduction, aquifer depletion and decrement of river flows, which may foster nutrients accumulation and, as a result, evolve into algae blooms threatening local biodiversity (Amorim & Moura, 2020). The issue of water quality is then becoming a problem European countries have to deal with, and the mentioned report (European Environment Agency, 2024) urges effective actions toward the so-called "water resilience", so to improve the capability of water bodies to resist and mitigate the impacts of extreme meteorological phenomena.

These conditions emphasize the necessity of efficient monitoring of river waters, also oriented to collect data and support the development of models to be used for estimating possible outcomes on the territories, thus providing tools to manage possible crises. Studies on the digitalization and analysis of rivers often combine the use of GIS software with Remote Sensing instruments to gather critical information on key aspects of interest, such as water levels, surface water extent, and volumetric measurements. Among the others, LiDAR (and more generally bathymetric sensors) have been widely used to explore the conformation of the riverbed, thus providing interesting results in the monitoring of constantly changing surfaces, such as gravel beds characterized by erosion and deposition phenomena (Moretto et al., 2012). Shifting the focus to the volume of water within a given river stretch, the analysis is typically performed through hydraulic modelling. However, in the absence of such models, high-quality survey data can serve as a valuable resource them to obtain a quick proxy for water volume, as shown e.g. for lakes by Hollister & Milstead (2010). The ability to derive such information instantaneously, even if approximate, can be extremely useful, e.g. enabling flood emergency operators to anticipate ground conditions before arriving at the affected areas.

The current work envisages the possibility of obtaining a tool to support Public Administration (PA) riverine monitoring, with particular focus on the volume changes on a selected stretch of a river. A test case for river volume computation has been considered, taking into account the requirements of a PA, thus considering only data provided through institutional databases and software that are currently available for Italian PA offices. The main concept behind this idea is to exploit commonly used GIS tools to obtain a rough estimation of the evolution of water volumes in an area of interest, as a support tool for monitoring and crisis management, in case of extreme events. The considered methodology will be presented in this paper, capable of providing useful insight by taking advantage of two main sources of information, such as hydrometric records, from which the water level of the stream at a given date can be derived, and Digital Terrain Models (DTMs), which will be used to extract information on the morphology of the riverbed. This study explores the possibility of using different DTMs to extract cross sections, as shown by Gichamo et al. (2011) for the global DEM case. Among others, models built using bathymetric LiDAR (also known as "green LiDAR"), which can provide accurate surface reconstruction even at 30-50 m depth for clean waters, will be taken into account (Cavalli & Tarolli, 2011). Once the geometry of the bed is known and the water height is available, GIS-based processing will be applied to estimate the volume of water within the area of interest. Results will be shown for a case study, providing also a comparison with the estimation of the water surface extent.

2. Study case

The study case chosen for this study is the largest Italian river, namely the Po River. It crosses from West to East Northern Italy, flowing in between Alps and Apennines, to the Adriatic Sea, in between of Veneto and Emilia Romagna regions; its Delta was included in 2015 among UNESCO's "Man and the Biosphere" program, thanks to the huge range of habitats which permit the development of a unique biodiversity (UNESCO, 2015). Its watershed, shown in Figure 1, covers more than 80.000 km^2 of Italian territory and in its northern areas also touches France and Switzerland (Autorità di bacino distrettuale del fiume Po, 2018).

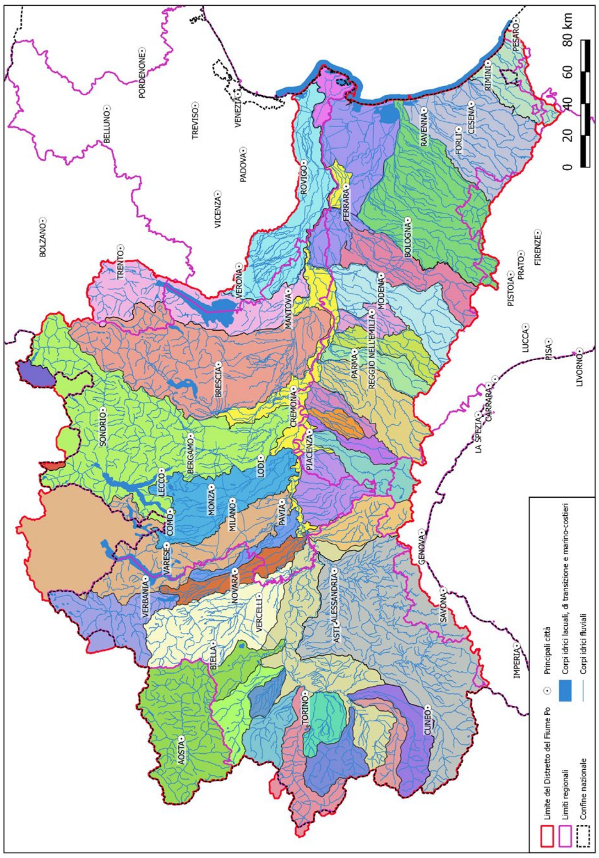

Figure 1. Po River watershed, from (Autorità di bacino distrettuale del fiume Po, 2018).

The amount of population living in the Po valley, more than a third of Italian citizens (Suwanu Europe, 2018), and the impact that the activities related to this area have on the Country economy (agriculture, livestock production, hydroelectric power generation) clearly highlight the relevance of Po River as a national crucial asset. Furthermore, this territory represents a litmus test for the effects of climate crises, being in a climatic hotspot in which global warming consequences result more pronounced (Liberti, 2023). Indeed, the rate of extreme hydrogeological events affecting the plain is increasing over recent years, showing how Po River is a perfect example for studies on drought-flood interaction, which takes into account the hydrological processes taking place in an area exposed to drought conditions and its capacity to respond to a flood, resulting in increased or reduced impacts depending on the specific conditions (Barendrecht et al., 2024). In recent years, the valley was affected by the most intense drought crisis since historical data are recorded (Monteleone & Borzì, 2024), culminating in summer 2022. The following year, while the territory was recovering from the dry conditions, it was involved in several flood events. In particular, in May 2023, two different storms within a few weeks led to widespread damage in the river valley, causing €700 million damage and 17 fatalities (Bernet, 2023). Such events are no longer isolated cases, as shown by two other floods that also occurred in the same regions in April and October 2024, proving the necessity of in-depth studies to develop abilities for facing such extreme and recurrent events. This emphasizes the need for gathering reliable data and obtain a better territorial knowledge and understanding. Within the current study it is relevant to consider which kind of public data are available for such a relevant area as Po River valley is.

3. Datasets

In this work, data coming from the river monitoring, such as hydrometric levels, as well as topographic products, specifically different types of DTMs, have been considered. Only authoritative datasets have been taken into account, and these are presented in the following.

3.1 River hydrometric monitoring network

The official Interregional Agency for the Po River (AIPo) is a public entity providing engineering and environmental services to authorities and stakeholders involved in the management and exploitation of Po River. The agency's mission is articulated on different areas of research: civil hydraulic projects devoted to improving river conditions (e.g. disaster mitigation infrastructures), navigation support, hydrogeological event forecasting and management, and riverbed characterization over morphology and hydrodynamic (AIPo, 2025a). Such results are complemented by the collection of data that can be exploited for monitoring river conditions. A dense network of hydrometer-instrumented sections covers the whole river course, with record of centimetric precision, collected with several frequencies, up to 5 minutes. All the recordings are then stored and made available by AIPo by the mean of a GIS-based WebApp showing, for each station, the geolocation, the value of hydrometric level and its trend. Furthermore, additional information can be reached, such as the hydrometer altitude and the historical records of events that overcome pre-defined alert thresholds (AIPo, 2025b). AIPo, in conjunction with the management authority of Po River catchment (AdBPo), also conducted several topographic surveys along the river, aimed at collecting information on the morphology of the riverbed. Specifically, through the official geoportal (AIPo, 2025c), AIPo offers an archive of historical data on cross-section and riverbanks characterization, providing results of multiple topographic survey campaigns, in form of planimetric data, embankment profiles and geometry of the fluvial section. This dataset was considered in the current study as a reference for the sections of interest, to be compared with those extracted by digital terrain models, as it will be detailed in the following. It is important to note that, although the hydrometric records can also be consulted on the topographically surveyed sections, there are some discrepancies between the two datasets. In short, all sections instrumented with a hydrometer are included in the cross-section geometry database, but not vice versa. The actual number of sections with hydrometric records is relatively small with respect to the total number of sections surveyed. This creates a limitation for exploring water volume along broad stretches of the river, as the essential information on water level is only provided on sections that are spaced quite far apart. It was then decided to specify this study in the surroundings of an instrumented section, expanding the area of interest to a number of cross-sections in its surrounding. The group of sections to be considered was extracted from an area that was considered in a previous study (Conversi et al., 2023), located in the Spessa Po site, in Pavia province, Lombardy Region. Figure 2 shows in the upper part a section of the Po river, where in red it is possible to see the surveyed cross-sections, for which the geometry is available, while in the yellow circle the Spessa Po section (coded *S7D*) is highlighted, as it is the only one with provided hydrometric records. The pink polygon at the bottom part of Figure 2 corresponds to the chosen area of interest, embedding one section upstream (*S7C*) and two sections downstream (*S8* and *S8A*) with respect to the availability of hydrometric records.

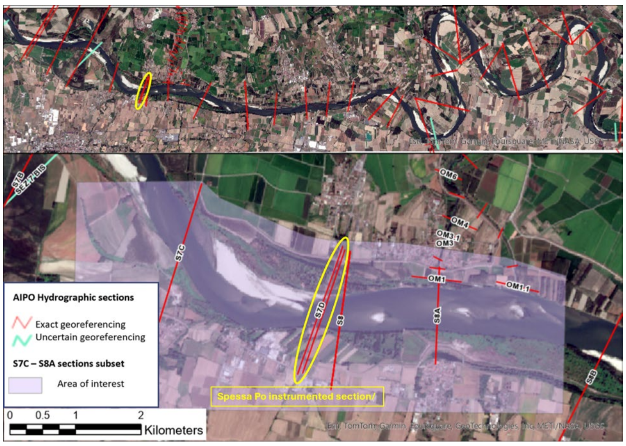

Figure 2. Overview of the instrumented cross-sections in the Po River stretch of interest.

3.2 Digital Terrain Models

As for river cross-sections characterization, also the second group of essential data to be considered in the current study, DTMs, was extracted by institutional databases. In the recent past, indeed, Italian Public Administrations started their process of digitalization, evolving, for the interest of this study, in the compulsory publication of territorial geodata, under prescribed technical requirements (Ministero per la Pubblica Amministrazione e l'Innovazione, 2012). This process resulted in the predisposition for each Regional institution of an open database, accessible by citizens and researchers through different geoportals and online catalogues. As a part of this process, also a National geoportal was created, containing both data inflow from local administrations and layers covering all the Country. Considering the National, Regional and local sources, a set of terrain models was identified, and they are hereby listed in Table 1. For the sake of simplicity, in the following, each model will be named basing on its ground resolution (e.g. DTM20 is made of a 20 x 20 m grid).

DTM 20	
Provider	*Regione Lombardia*
Coverage	Whole regional territory
Altimetric precision	Function of the original data, at least few meters
Reference date	1994
DTM 2	
Provider	*AdBPo*
Coverage	Po River surroundings between *confluenza Pellice* and *confluenza Ticino*
Altimetric precision	0.3 / 0.2 m
Reference date	2004
DTM 5	
Provider	*Regione Lombardia*
Coverage	Whole regional territory
Altimetric precision	0.3 m – 2 m
Reference date	2015
DSM 1	
Provider	*Ministero dell'Ambiente e della Sicurezza Energetica*
Coverage	National territory, depending on regional data availability
Altimetric precision	0.15 m
Reference date	2013

Table 1. Overview of the selected terrain models.

DTM 20 is retrieved from Lombardy Region geoportal and it is referred to data acquired in multiple campaigns over the territory between 1982 and 1994, represented as contour lines and elevation points, within the official topographic map of the Region, in scale 1:10.000. These data were then interpolated to obtain the terrain model, resulting thus in a variable altimetric precision, not quantified by the data providers, function of the density of measurements points over the territory (Regione Lombardia, 2014).
DTM 5, published on Lombardy Region geoportal, is a multi-resolution product, with an altimetric precision ranging from 0.3 m in urban areas, to 2 m in forestal ones. This characteristic depends on its nature of being an hybrid model, mainly based on interpolation of data extracted from to the official cartography (elevation points, contour lines, breaklines) and integrated with 1 m x 1 m resolution LiDAR data over streams and, in some limited portions, with an upscaled version of DTM 20 (Regione Lombardia, 2015).
DTM 2 is provided by the Interregional Agency for the Po River. It was specifically tailored on the description of Po River surroundings. It reaches high altimetric precisions, with respect to the ground resolution of 2 m, because it was entirely derived from airborne laser-scanner flights. Two different sensors (Optech ALTM 3033, Toposys Falcon II) equipped with GPS were used; raw data were processed with suitable software to recognize and removes «High» and «Low» inconsistent points, so to realize a Digital Surface Model (DSM). Pixels representing vegetation and buildings were filtered and holes

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interpolated. A validation was performed on several known altimetric sections by expert operators (Autorità di Bacino distrettuale del fiume Po, 2004).
Lastly, DSM 1 was realized as a part of an extraordinary National plan for environmental Remote Sensing, by the mean of LiDAR scanning (Optech ALTM Gemini, ALTM 3100EA Pegasus, working on Near Infrared). It aims to cover the whole Italian territory, but actually the datasets present some consistent data lack; nevertheless, it preserves a high altimetric precision, estimated in 0.15 m (Corradeghini,2018), over small 1 m x 1 m pixels (Ministero dell’Ambiente e della Sicurezza Energetica, 2013).

4. Selection of the model to be used in the case study

The riverbed morphology is well known only in the specific locations addressed by the topographic surveys. In order to obtain a proper volume analysis, a continuous surface is needed, such as a DTM. The geometries of the cross-sections provided by AIPo are crucial to this study, because they represent the reference to which information extracted from DTMs should be compared. By means of thr QGIS *Profile tool* plugin (Tourigny, 2018) cross-sections were extracted from DTMs manually tracing the location of *S7C*, *S7D*, *S8* and *8A*. A comparison among surveyed sections geometries and extracted profiles is shown In Figure 3 for Section *S7C*.

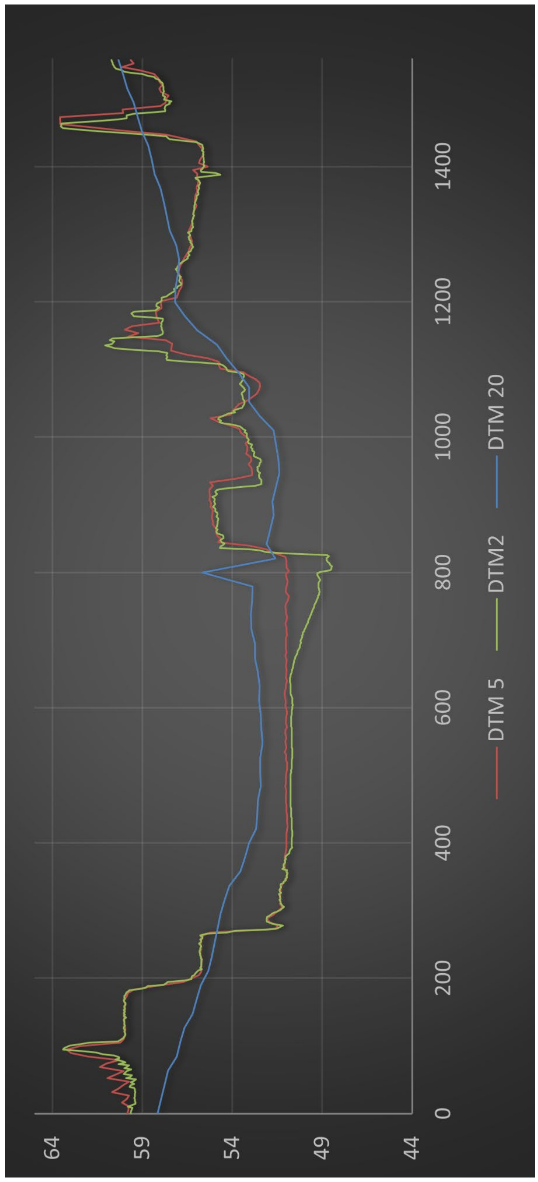
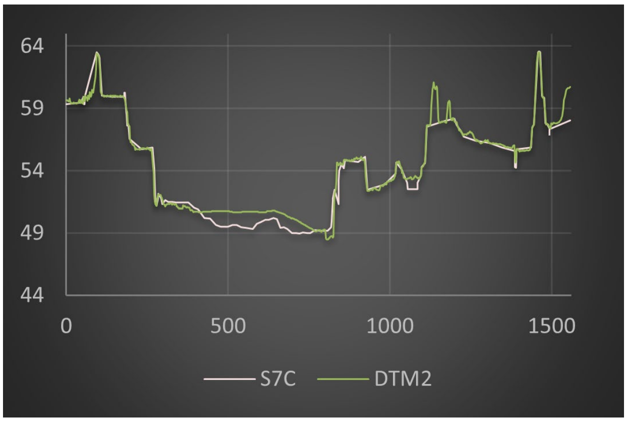


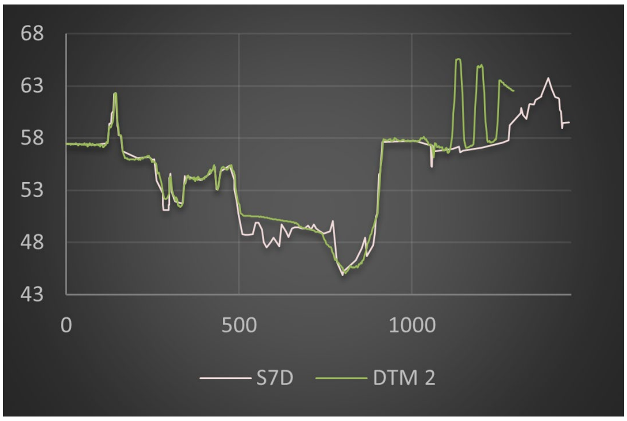
Figure 3. Comparison of profiles extracted in correspondence of section *S7C* from DTM 20, DTM 5 and DTM 2.

First, it is evident that DTM 20 cannot provide a relevant contribution, because its resolution is too coarse to extract a profile that reproduces accurately the morphology of the riverbed. As expected, DTM 5 results to be coarser in describing the evolution of the profile, as seen in the visible spikes. These spikes probably indicate the presence of objects that have not been removed during the processing phase of DTMs, or reflect errors in the interpolation. Most importantly, it is evident that DTM 2, only based on LiDAR acquisition provides a more accurate representation of the the riverbed, while DTM 5 results in a flat surface, thus showing that water represents a challenge for the model. The enhanced result of DTM 2 is in line with the capability of LiDAR pulses to penetrate water up to few meters, when considering green light pulses (Mader et al., 2022), as also proven by Kinzel et al. (2007) in case of shallow sand-bedded river surveying. DTM 2 resulted then in the most suitable model for the study, particularly given issues with the other LiDAR-based model, which is DSM 1. Indeed, While DSM 1 offered a smoother embankment profile, the specific radar instrumentation used to

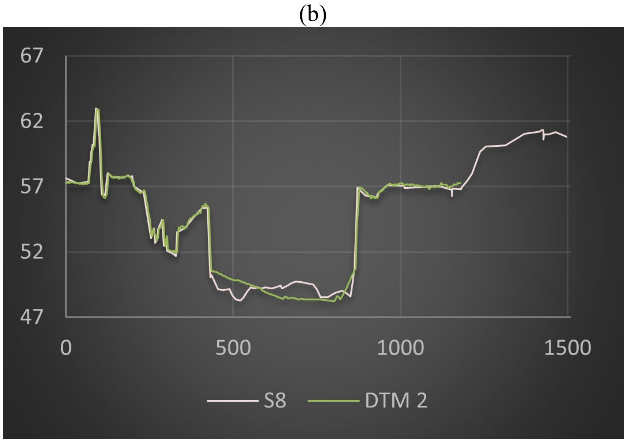
derive the model was inadequate for penetrating water, resulting in a flattened surface. In addition, this model suffers from a significant data gap, including a relevant portion of the case study area.
Figures from 4a to 4d demonstrate the overall consistency of the results in the sections of interest for DTM 2, in which it is clearly recognizable the relevant characteristic of such model to map the riverbed, unaffected by the presence of the water. As expected, it is not possible to obtain a perfect 1:1 correspondence between a field-mapped profile obtained with specific instruments and the profiles extracted from DTM. However, this degree of approximation is satisfactory for the scope of the current work.



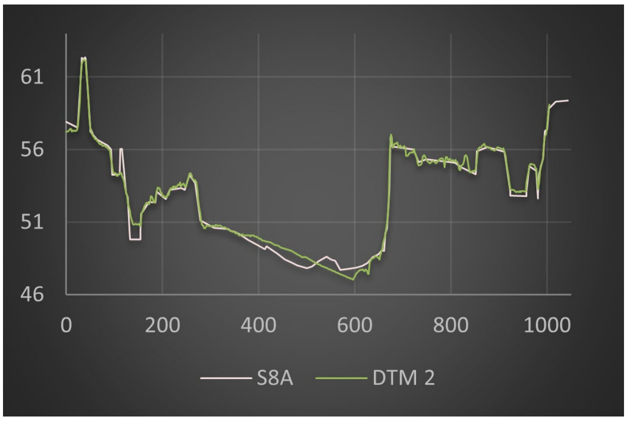
(a)



(b)



(c)



(d)

Figure 4. Cross-sections derived from the chosen terrain model, superimposed to the known profiles provided by Po River authorities in sections *S7C* (a), *S7D* (b), *S8* (c), *S8A* (d).

5. Volume estimation and results discussion

Before assessing the water volume for the considered river stretch, it should be pointed out that the analysis will be performed under a simplifying assumption. Since the hydrometry is recorded only at section *S7D*, we assume that this water level is representative of the entire river portion considered. This assumption is justified by the relatively short length and negligible slope of the river stretch analysed and by the study's objective, which is not to reconstruct the river hydraulic profile but to estimate the overall volume of water within the river stretch of interest.
The estimation of water volume is performed through a specific ArcGIS Pro tool (Esri, 2025), which allows to calculate the volume underlying a certain height, giving as input a terrain model. Thus, the water surface is simplified as a planar surface that intersects the DTM 2 at a given level.
In order to explore the results of the proposed methodology and test the reliability of the chosen datasets, the water volume is estimated on multiple dates to cover diverse environmental and climatic conditions. The values used for testing are derived from Conversi et al., (2023, 2024), in which the same Po River stretch was analyzed as a case study for applying an automated methodology to estimate water surface extent by integrating optical and radar satellite imagery. This approach allows the integration of surface data as additional information, enabling a cross-check of the results' consistency.

Late spring (May/June) and summer (August) dates are tested, over a reference period of 7 years, from 2016 to 2023. As mentioned, the *S7D* hydrometer was used to collect the information on water level, corresponding to the average level in the date of the image acquisition; as specified in the mentioned work, each imagery set was collected over a maximum time window of few days, depending on data availability, so to have a mosaicked image completely covering the area of interest.
Figure 5 reports the water volume estimation. Late spring volumes are larger than summer ones, mainly due to rainfall events and water discharge from melting snow, combined with the high temperatures in August which foster evaporation. Furthermore, as mentioned, the study area experienced several extreme hydrological events during the considered period, the estimated volume reflects these conditions. The decreasing trend starting in 2021 can be attributed to various factors,

including rainfall anomalies and warmer temperatures leading to poor snow accumulation in southern Alps and thus to poor snow melting contribution (Toreti et al., 2022). These factors, combined with a significant lack of summer rainfalls triggered a severe drought period, whose consequences are detectable until early 2023. As previously addressed, the Po River valley is prone to drought-induced floods, which occurred in May 2023, where the calculated volume growth coincides with the increase in rainfall, up to the peak reached after the double-flood event.

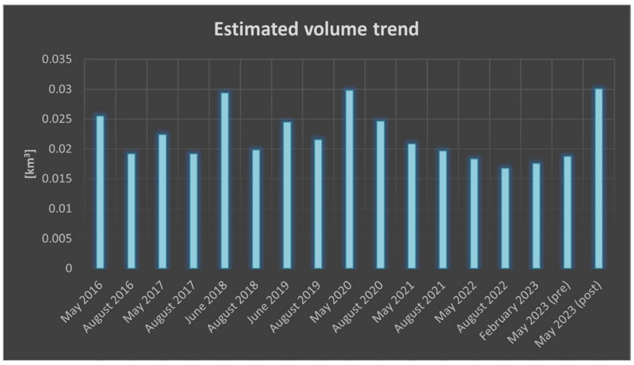


Figure 5. Trend of the estimated volumes in the multitemporal analysis.

Aiming to furtherly corroborate the results of the study, it is of interest to compare the volume outcomes with other available parameters. If it is true that the volume was directly dependent on water table height and then it is not particularly meaningful to test volume estimate against the corresponding fluctuation of the hydrometric level, the same cannot be said for areas. Obviously, it is expected that an increment of volume will also affect the surface covered in water, given the shape of the profiles, not presenting "vertical" steps. Then, the volume estimations were compared to the results of the previously mentioned works obtained from remote sensing imagery processing (Conversi et al., 2023; Conversi et al., 2024), as a cross-check of the quality of both the applied procedures. As the graph in Figure 6 shows, a substantial coherence was found, with a simple linear correlation showing an R^2 equal to 0.845.

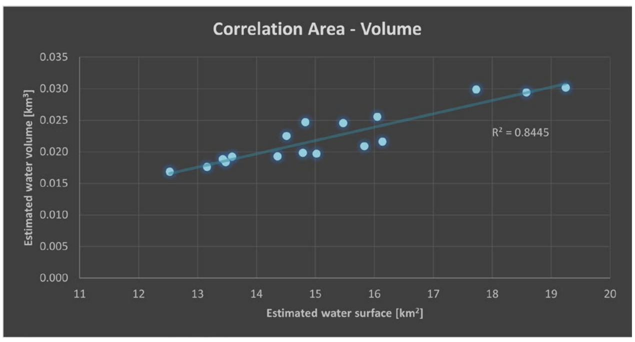


Figure 6. Linear regression of estimated volume against water surface, mapped with (Conversi et al., 2024) methodology.

6. Conclusions

This study aims to address the upcoming necessity for Public Administration of a tool for supporting river ecosystems monitoring and management to face extreme events and increase water resilience, so to improve the ability of territories to absorb the impacts of phenomena such as drought periods and floods. In particular, the goal is oriented towards estimating the volume of water in a delimited stretch of a river. The work aims at verifying the applicability of available DTMs for rapid volume estimation that could be effectively replicated through common tools, such as GIS software. The case study of a portion of Po valley area was selected, as it is a perfect site to explore drought flood interactions, due to the abundance of such phenomena in recent past. Regional and national databases were explored for obtaining reliable hydrometric records and digital models for the riverbed characterizations. Several DTMs were compared and a LiDAR-based one was selected to be used as a base for cross-sections extraction. The volume of water flowing into a defined stretch of the Po River was then estimated with GIS processing, considering the volume between the water surface, whose level was obtained from the hydrometers, and the riverbed profile derived from the DTM. A multitemporal analysis was performed, and the results showed substantial consistency between the estimated volume trends and the known seasonality of the river. Furthermore, a comparison was made with water extent proxy calculated based on satellite image processing. The two derived quantities were then compared, showing a good correlation (R^2=0.845).

Although the proposed methodology requires strong simplifying assumptions, the results seem promising, especially if considering them as a proxy, which may just constitute a rapid assessment of volumetrics under specific conditions, to be supplemented by investigations. The proposed GIS-based approach can be considered useful for rapid responses of systems behaviour near hydrometer-instrumented sections when a detailed LIDAR based DTM is available. A denser monitoring network would allow for water level interpolation between cross-sections (Vetter et al., 2011), providing richer data for DTM-based volume estimation.

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The map proposed in the work contain modified Copernicus Sentinel data [2021 – 2022].

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