UNIVERSITÀ DEGLI STUDI DI PADOVA

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

MASTER THESIS IN WATER AND GEOLOGICAL RISK ENGINEERING

Application of the D-CASCADE model in the Po River: Estimating the impact of using different transport formulas on the sediment fluxes and budget

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ACADEMIC YEAR 2023/2024

Dedication

This work is dedicated to my mother, whose unwavering support and encouragement have been the foundation of my journey. I also extend my heartfelt thanks to my family for their understanding, patience, and belief in my endeavors. Your endless encouragement and faith in me have been instrumental in every step of this research. This work is dedicated to you with profound gratitude and love.

Abstract

This study investigates sediment transport dynamics in the Po River basin through comparative simulations utilizing different sediment transport formulas in the D-CASCADE model. Two simulations were conducted with identical network parametrization but varying sediment transport formulas: Engelund & Hansen (1967) and Wilcock & Crowe (2003).

The mobilized volume and sediment budget were analyzed, revealing similar trend behavior but differing in magnitude between the two formulations. This sensitivity analysis highlighted the impact of sediment properties and discharge on simulation outputs, particularly in upstream areas where sediment size ranges diverge. Validation against observed data and satellite images demonstrated the model's capability to capture system dynamics, but with some discrepancies in specific reaches.

The study underscores the need for considering local geomorphological features and hydraulic conditions when assessing sediment transport dynamics. Furthermore, it highlights the influence of anthropogenic interventions, such as dams and instream sediment mining, on river morphology and sediment transport patterns, emphasizing the complexity of river system responses to human activities.

Overall, the research provides insights into the present-day, and possible future sediment transport and connectivity patterns of the Po River network and their correlation with historical morphological evidence.

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1. INTRODUCTION

Fluvial systems are dynamic natural systems where water flows through river channels, playing a crucial role in shaping Earth's surface, influencing various geomorphic processes, and supporting ecosystems (Fryirs, 2013; Schmitt et al., 2016). These natural systems facilitate the transfer of the majority of water and sediment fluxes globally from land to oceans and encompass channels, tributaries, floodplains, and associated landforms through which water moves within a drainage basin (Fryirs, 2013).

The dynamics of fluvial systems are driven by interactions between water, sediment, vegetation, and the underlying geology. Water flow within fluvial systems can vary in velocity, discharge, and sediment load, forming distinct channel patterns, landforms, and habitats along river corridors (Bizzi et al., 2021; Cossart et al., 2018). Fluvial processes such as erosion, transportation, and sediment deposition contribute to the continuous evolution of river channels and surrounding landscapes.

In this context, human activities have a significant direct and indirect influence on this evolution. Anthropic interventions such as reforestation, channelization, and dam construction, but also consequences of climate change have had significant impacts on sediment supply to river channels around the globe. These activities have altered sediment fluxes, leading to notable changes in channel morphology (Brenna et al., 2024; Surian & Rinaldi, 2004). In the case of the Italian rivers, these human activities have collectively contributed to a remarkable decrease in sediment supply to river channels, leading to channel adjustments such as narrowing, incision, and changes in braiding intensity over the last two centuries (Surian et al., 2009).

Within this scenario, the Po River, the largest river in Italy, has been significantly impacted by various anthropic pressures and human activities, leading to complex morphological changes in its channel patterns (Brenna et al., 2024; Surian et al., 2009). These changes have been influenced by factors such as river training works for navigation, in-channel mining, construction of dams, and land use changes in the catchment area, and as a consequence, the river has experienced sediment starvation, channel incision, and narrowing, evolving from multi-thread configurations to single-thread sinuous patterns (Brenna et al., 2024).

That said, a key idea for understanding sediment transport dynamics and geomorphic evolution in fluvial systems is sediment connectivity. This concept refers to the degree to which sediment sources, pathways, and sinks within a river network are linked and interact (Najafi et al., 2021). It encompasses the processes that control the movement of sediment from its origin in the landscape to its deposition in downstream areas. This concept is important in recognizing the spatial patterns of sediment distribution, comprehending sediment cascades, and locating areas where sediment accumulates and erodes, reducing uncertainties in sediment transport (Tangi et al., 2022). By studying sediment connectivity, researchers can better understand how disturbances or perturbations in the landscape may impact sediment transport processes.

A direct consequence of these processes is the channel geometry and morphology, which as stated by Church (2006), is strongly influenced by bed material transport. According to him, when considering the morphological processes of river channels, it is more appropriate to categorize sediments into bed material and wash material. Bed material refers to relatively coarse sediment that comprises the bed and lower banks of the river channel, playing a significant role in shaping the channel's morphology, and, on the other hand, wash material consists of fine sediment that, once mobilized, moves downstream (Wilcock et al., 2009).

That said, the assessment of bed material transport is crucial for maintaining the stability of the channel, considering that changes in bed material transport can lead to channel aggradation, degradation, or shifts in channel patterns (Wilcock et al., 2009). In addition, understanding bed material transport is essential for establishing sediment budgets and predicting river channel changes over time because it helps assess the balance between sediment supply and transport capacity (Church, 2006).

Currently, assessing the sediment budget and potential alterations in river morphologies could be performed through the application of diverse methods and considerations to estimate the movement of sediment that forms the bed and lower banks of the channel (Church 2006). For instance, it is possible to conduct field surveys to measure sediment characteristics such as size distribution, bed roughness, and sediment transport rates. Although is more accurate, field measurements require significant time, effort, and resources to collect sediment samples, perform the surveys, and analyze the data. Another widely used method is to utilize sediment transport equations to estimate bed material transport rates based on flow velocity, sediment size, and channel characteristics (Church, 2006). Especially for large river systems or remote locations, formula predictions require less effort, and provide the ability to predict transport under conditions other than the present. For example, sediment transport rates can vary temporally due to changes in flow conditions, seasonal variations, and sediment supply, so conducting field measurements at a single point in time may not capture these temporal variations accurately (Church, 2006; Wilcock et al., 2009).

Over the last decades, several process-based models have been developed to simulate the hydro-sedimentary processes, their interactions and predict the morphological evolution of rivers (Pinto et al., 2012). Conventionally, traditional morphodynamic models focus on detailed modeling of local-scale river processes with high accuracy but are limited to short and well-studied river reaches due to high computational demands and data requirements (Tangi et al., 2022).

For network-scale applications, morphodynamic models need to consider the connected or disconnected nature of sediment transport that occurs across an entire river basin (Tangi et al., 2022), which currently is possible due to recent advancements in remote sensing technologies have enabled the characterization and interpretation of geomorphic processes at the scale of entire river networks, leading to the development of novel numerical models for network-scale sediment connectivity (Bizzi et al., 2019; Lammers & Bledsoe, 2018).

According to Tangi et al. (2022), these network-scale morphodynamic models incorporate empirical sediment transport equations and pre-defined boundary conditions as inputs to represent large-scale sediment transfer processes. Unlike traditional models that focus on local-scale morphodynamic processes using hydraulic and channel geometry interactions, network-scale models trade off some accuracy to simulate sediment connectivity patterns among different components of the river network over longer periods and larger areas (Bizzi et al., 2021).

Therefore, when developing or utilizing a morphodynamic model for network-scale applications, the correct choice of the sediment transport formula is vital. This decision may significantly impact both the accuracy and performance of the model. An appropriate widely accepted sediment transport formula, which reflects the sediment transport processes occurring in the specific river system, leads to more reliable results (Syvitski et al., 2010). Besides that, enables researchers to assess and compare results across different river systems or modeling approaches, considering that such models must be applied under conditions similar to those for which the model was developed (Wilcock & Crowe, 2003). In addition, when the model is used for forecasting future scenarios or for river management decision-making, especially for network scales, the choice of sediment transport formula becomes even more critical, taking into account the difficulties in considering the wide range of hydromorphological conditions in a river network (Schmitt et al., 2016).

Several innovative methods have been suggested to investigate different aspects of network sediment connectivity without the high computational expenses and data requirements associated with physically-based sediment transport models (Schmitt, 2017). In this context, the Catchment Sediment Connectivity and Delivery (CASCADE) model, developed by Schmitt et al. (2016), is a network-scale sediment connectivity model developed to analyze sediment connectivity in river networks. In this approach, the sediment transport in the river network is represented as cascades, each originating from a specific sediment source and traveling through the network to the outlet node (Tangi et al., 2019). Also, these cascades can deposit sediment along their path based on transport capacity and sediment flux, providing a detailed understanding of sediment movement within the network.

Every cascade is distinctively characterized by its point of origin and carries a specified sediment volume, which may experience partial or complete deposition as it advances downstream, interacting with other cascades in the process (Tangi et al., 2022). As a result, CASCADE allows for evaluating connectivity rates between individual sediment sources and downstream reaches. This facilitates the computation of statistical properties associated with the connectivity among different sediment sources and sinks (Schmitt et al., 2016).

Maintaining all the properties and concepts of the CASCADE model, the D-CASCADE is a new dynamic, network-based sediment connectivity model that can explore also the temporal representation of sediment processes and can trace the position and movement of cascades over time, as well as across space (Tangi et al., 2022). The spatiotemporal evolution assessment of sediment supply provided by this approach is fundamental to predicting and understanding morphological changes in river basins and considering the impact of natural processes or human activities on river morphology

(Brenna et al., 2024).

Therefore, according to Tangi et al. (2022), the D-CASCADE model has the capability to explore the impacts of diverse and varying drivers of change, which differ in their magnitude, spatial distribution, and timing. Another important characteristic of the model is that components can be included in the framework to model local processes that the 1D structure of D-CASCADE cannot capture (Tangi et al., 2022), such as the reproduction of variations in channel width. As a result, the D-CASCADE demonstrates adaptability across various research objectives, output specifications, and data accessibility.

That said, the primary objective of this study is to evaluate the influence of the sediment transport formula on the sediment budget within the D-CASCADE model application on the Po River basin, in Italy. Specifically, the aim is to assess how variations in the sediment transport formula impact the magnitude of sediment deposition and erosion as computed by the model. To achieve a comprehensive understanding, the secondary objective is to establish correlations between the outcomes of the sediment budget, considering both deposition and erosion and observable patterns within the river system. This analysis will contribute valuable insights into the model's performance and ability to simulate real-world sediment transport dynamics, thereby enhancing the understanding of sediment connectivity in the Po River, Italy.

The thesis was structured as it follows, with the aim of providing a comprehensive analysis of the study performed. The initial sections are devoted to detailing the data sources utilized and the methodologies employed in the study. Following this, the presentation of results and discussions forms the central core of the thesis, where findings are systematically presented and interpreted considering the objectives. Finally, the concluding section encapsulates the key findings, contributions, and limitations of the study, drawing together the threads of the research journey.

2. DATA AND METHODS

2.1. Study area

The study area of this study is the Po River basin (Figure 1), which is the longest in Italy, with a total length of over 650 km and a drainage area of 75,000 km^2, from the foot of the Monviso mountain in the Piedmont region to the Adriatic Sea in the Emilia Romagna region, dissecting seven Italian regions and about 3200 municipalities (Bozzola & Swanson, 2014). The related river network is about 6750 km and 31 000 km long, for natural and artificial channels, respectively (Montanari, 2012). Due to these factors, the Po River exhibits a complex hydrological system, gathering water from the majority of northern Italy and its mountainous regions.

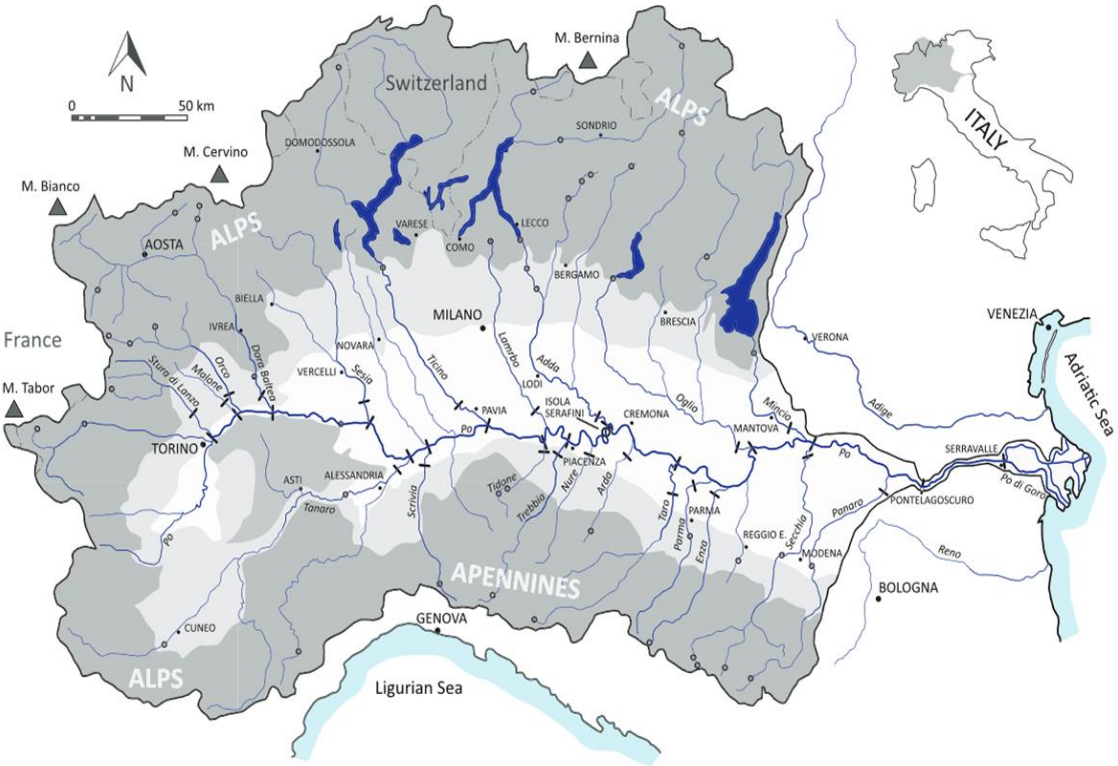

Figure 1 - Localization map of the Po River basin, in Italy. Source: Adapted from Brenna et al., 2022.

The Po River basin exhibits a varied topography, encompassing mountains, hills, and plains, and also heterogeneous soil texture, including sand, loam, and clay (ISTAT, 2006). The mean annual precipitation is about 1200 mm, and the average daily discharge at the catchment outlet is 1,470 m^3/s, with a maximum recorded peak flow of 10,300 m3/s at Pontelagoscuro (close to the city of Ferrara) in 1951 (Zanchettin et al., 2008; Montanari, 2012).

The basin is home to approximately 16 million people, and the economic activities within the basin contribute to around 40% of the annual Italian GDP (Bozzola & Swanson, 2014). Agriculture is a significant economic activity in the region, with about 35% of the Italian agricultural production coming from the Po River basin, being irrigation commonly used to supplement natural rainfall, with about 80% from surface water sources and the remaining 20% extracted from aquifers (ISTAT, 2006). Equally important, the Po River basin is habitat to diverse ecosystems, including wetlands, forests, and riverine habitats that support a wide range of plant and animal species. The basin's biodiversity is important for maintaining ecological balance and supporting wildlife conservation efforts (Bozzola & Swanson, 2014).

In anthropological terms, the Po River, and its tributaries, have historically served as important transportation routes, facilitating trade and commerce in the region (Brenna et al., 2024). Navigable waterways in the basin have played a crucial role in the transportation of goods and people, helping to build historic cities, towns, and archaeological sites located along its banks (Hatinguais, 2019). The basin's cultural significance is reflected in its art, architecture, and traditions, attracting tourists and visitors from around the world.

Over the years, the Po River has been significantly impacted by various anthropic pressures and human activities, leading to complex morphological changes in its channel patterns (Brenna et al., 2024). These changes have been influenced by factors such as river training works for navigation, in-channel mining, construction of dams, and land use changes in the catchment area, which caused sediment starvation, channel incision, and narrowing, resulting in the evolution from multi-thread configurations to single-thread sinuous patterns (Surian & Rinaldi, 2004).

This perturbation in sediment availability led to rapid incision of the active channels during the 1970s, notably in the primary channels protected by groins (Brenna et al., 2024). Human-induced sediment depletion through activities like in-channel mining and the construction of the Isola Serafini Dam drove substantial lowering of riverbeds and incision, reduction in morphological complexity, channel narrowing, and variations in the planimetric shape of the river, consequently inducing morphological alterations in the river system (Surian & Rinaldi, 2004).

2.2. Data

2.2.1. Discharge

The discharge data is essential to the D-CASCADE model as it informs key aspects of hydrological processes, sediment transport dynamics, and channel morphology within river networks (Tangi et al., 2019). By incorporating discharge data, the model can simulate how flow rates influence sediment transport pathways, erosion, and deposition, enhancing the representation of sediment (dis)connectivity (Schmitt et al., 2016).

Additionally, discharge data is crucial for model calibration, allowing researchers to validate the model's performance and improve its accuracy in simulating sediment transport processes. The use of discharge data enables scenario analysis, where different flow conditions can be explored to assess their impacts on sediment dynamics, connectivity, and channel behavior (Nelson et al., 2003). Furthermore, accurate discharge data enhances the model's predictive capabilities, enabling the forecasting of future changes in sediment transport and channel morphology under varying hydrological conditions, and providing valuable insights for river basin management and decision-making (Syvitski et al., 2010).

That said, the discharge data for each reach simulated were computed by the Flood-PROOFS probabilistic forecasting system which utilizes a rainfall-runoff model called DRiFt, which has been modified to account for the presence of dams and other hydraulic structures (Laiolo et al., 2014). This system integrates real-time MODIS sensor data, snow depth measurements and initializes soil moisture conditions based on an Antecedent Precipitation Index (API) and satellite-based estimates of soil moisture, enhancing its predictive capabilities (Laiolo et al., 2014).

The values of discharge associated with each reach, for a period spanning from 2019 and 2021 used in the simulations, (Figure 2) have been provided by the International Center for Environmental Monitoring (CIMA) foundation, which is collaborating with UNIPD in other ongoing research projects.

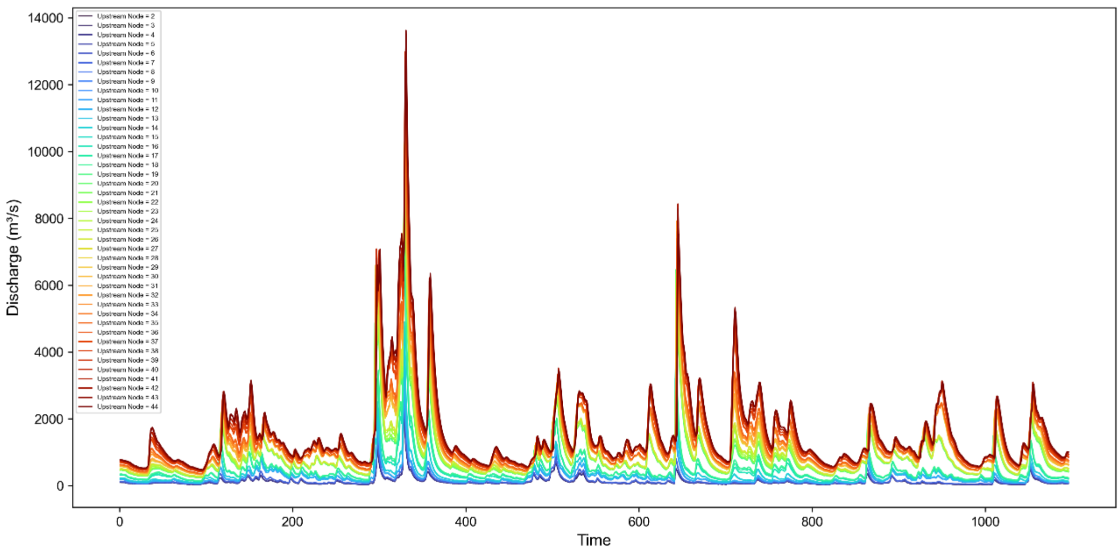

Figure 2 - Distribution of discharge over time along all reaches used for the D-CASCADE simulations.

2.2.2. Width

The determination of the active channel width in the Po River basin was performed by a manual vectorization process across all reaches, utilizing satellite imagery from 2021. This procedure required a delineation of the extent of the active channels within the basin, and the division of the area by the length of the respective reach. In the context of sediment transport modeling in river networks, the active channel refers to the portion of the river channel where sediment transport processes are actively occurring (Church, 2006). It is the part of the channel that is currently transporting sediment due to the flow of water.

By outlining the boundaries of the watercourses and the features that compose the active channel visible in the satellite images, it is possible to accurately capture the width of the active channels across various segments of the river network. This manual vectorization process ensured that the measurements were comprehensive for the entire basin, allowing for a thorough assessment of the spatial distribution and variability of active channel widths. Through this approach, a detailed understanding of the morphological characteristics and dynamics of the river system within the Po River basin was achieved, contributing valuable insights for hydrological and environmental analyses. Figure 3 below shows the width distribution along the Po River network.

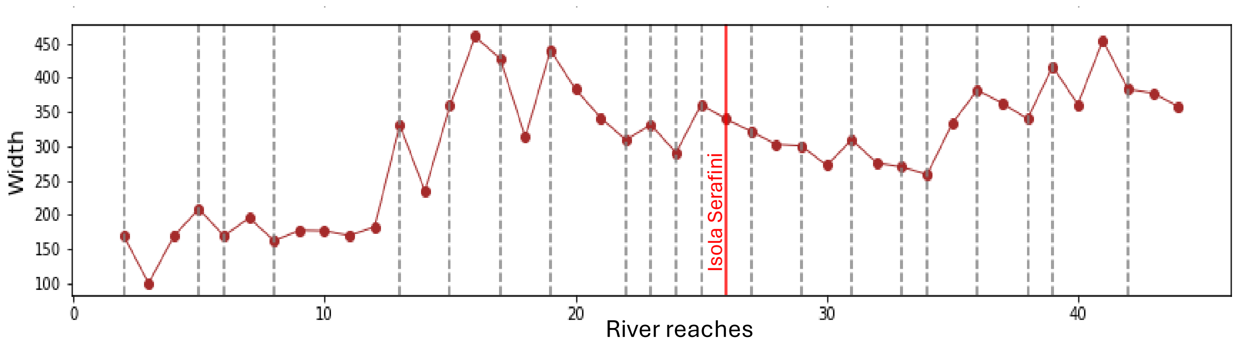

Figure 3 – Computed width based on the active layer for each reach along the Po River.

2.2.3. Grain-size distribution

The grain-size distribution data is essential for the model to be able to simulate the movement of sediment particles of varied sizes, their deposition patterns, and their impact on channel morphology over time. Grain-size distribution data also plays a crucial role in estimating sediment budgets, understanding connectivity dynamics, and calibrating the model to improve its ability to replicate real-world sediment transport processes.

For this application, the distribution of grain size was derived from field sediment grain size measurements of the Piano di Gestione dei Sedimenti (PGS), organized by the Autorità di Bacino Distrettuale del fiume Po (AdbPo) (2005-2008), from more recent (2012) updates of the same PGS plan, as well as from data collected by UNIPD projects in 2022-2023. The distribution of the D50 is shown in Figure 4, below. The D50 is a critical parameter as it provides a measure of the central tendency of the grain size distribution (Schmitt et al., 2018b). It is commonly used to characterize the average size of sediment particles in a sample and is essential for understanding sediment transport processes, erosion rates, deposition patterns, and overall sediment dynamics in river systems. In the context of the D-CASCADE model, the D50 plays a significant role in determining sediment transport capacity, channel morphology changes, and the spatiotemporal evolution of sediment (dis)connectivity within river networks.

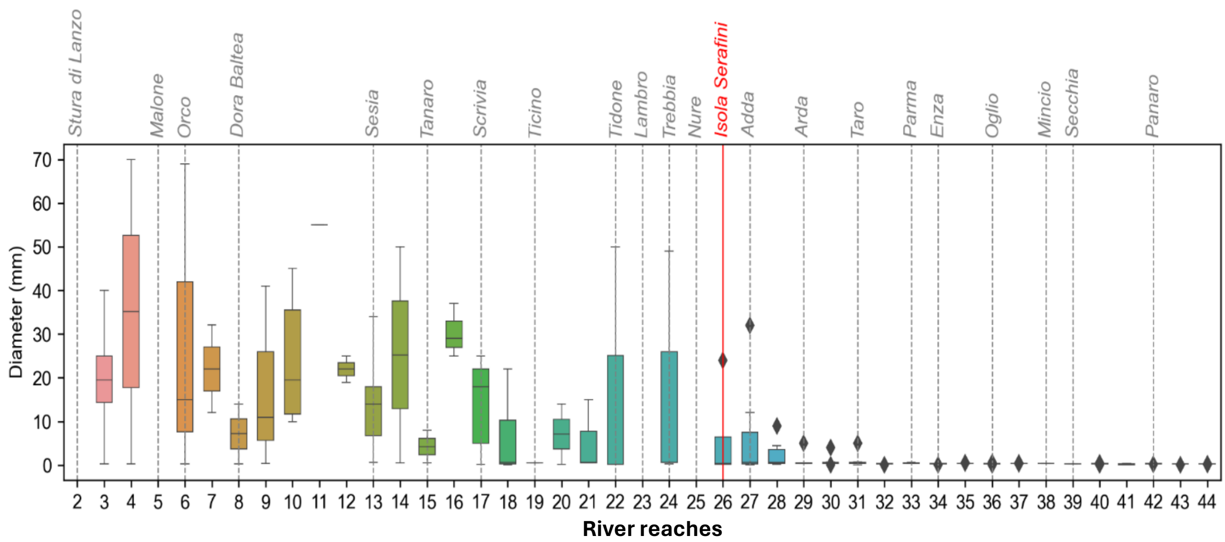

Figure 4 - Distribution of the D50 along all the reaches used for the D-CASCADE simulations.

2.2.4. Slope

The derivation of slope data necessary for the application of the D-CASCADE model necessitated a multi-step methodology due to data constraints. Initially, slope values were sourced from a downstream segment of the network via a hydraulic simulation conducted by a UNIPD project using the HEC-RAS software. However, this data was limited in scope and did not cover the entire network. To address this deficiency upstream, a polynomial regression of degree 3 was implemented to model the elevation profile using a Digital Elevation Model (DEM) with a spatial resolution of 1 meter (Figure 5). This regression enabled the derivation of slope values up to a designated node, identified as node 13. Subsequently, beyond node 13, slope values from the UNIPD project were adopted. By integrating data from both sources and employing regression techniques, a comprehensive representation of slope distribution throughout the network was achieved, enhancing the accuracy of sediment transport simulations within the morphological model.

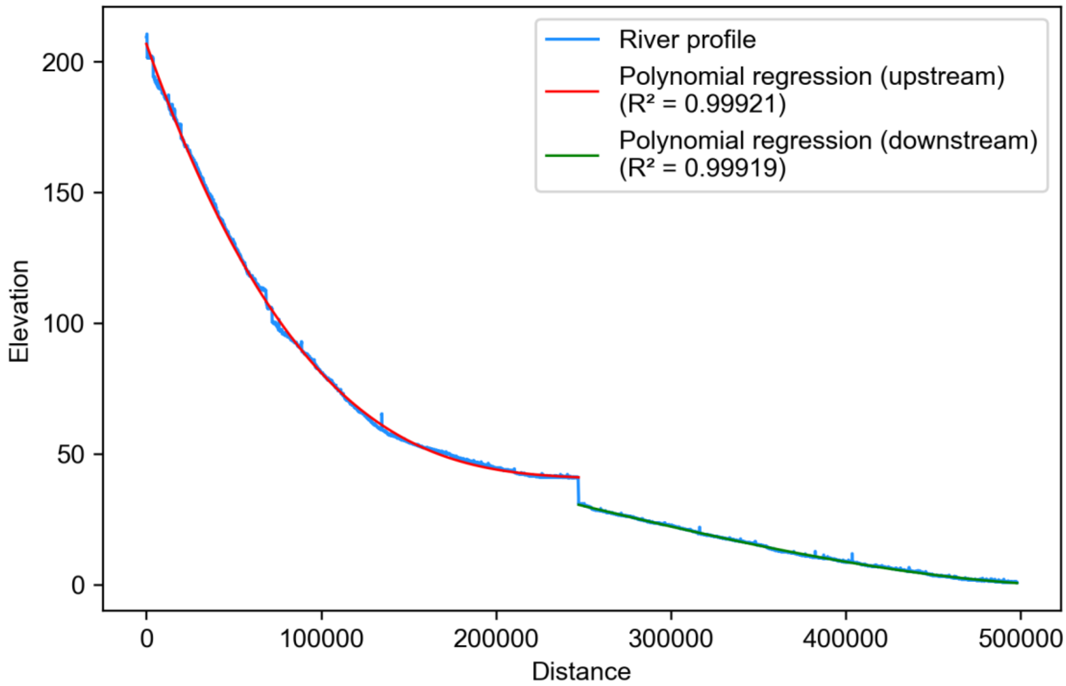

Figure 5 - Polynomial regressions with degree 3 used to describe the elevation profile of the Po River basin.

Since the Isola Serafini dam significantly altered the elevation profile in the middle part of the network, it was necessary to split the regression into two parts to better represent the shape of the profile, as shown in Figure 5 above. That said, the equations representing the first and second parts of the polynomial regression, respectively, are shown below (Equations 1 and 2).

$$-1.89 \cdot 10^{-3}X + 7.29 \cdot 10^{-9}X^2 - 9.50 \cdot 10^{-15}X^3 + 2.07 \cdot 10^2 \quad (1)$$

$$-1.02 \cdot 10^{-4}X - 2.92 \cdot 10^{-10}X^2 + 4.64 \cdot 10^{-16}X^3 + 6.66 \cdot 10^1 \quad (2)$$

The slope profile obtained through the combination of the two mentioned sources is shown in the Figure 6 below. Since the slope stands out as a notably sensitive parameter within the model, minor inaccuracies can trigger significant alterations in sediment transport predictions. Traditional approaches, relying solely on slope calculations between two points, are susceptible to considerable inaccuracies due to their dependence on the precise placement of these points (Baar et al., 2018). Recognizing this limitation, it was adopted a more precise methodology considering the numerical hydraulic data and employing polynomial regressions on elevation from the 1-meter DEM only for the missing values to determining the slope profile. By integrating these advanced techniques, the model can achieve a higher degree of precision in slope estimation, thus enhancing the reliability and validity of sediment transport predictions.

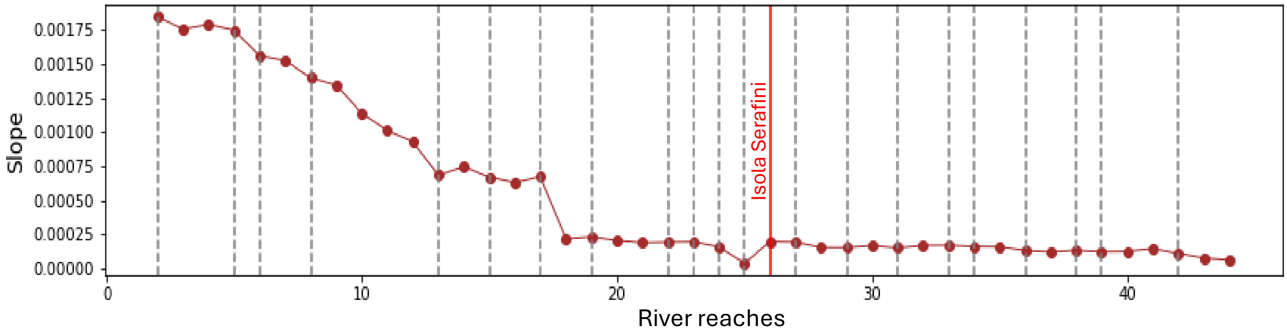

Figure 6 – Slope profile of the Po River considering the values from the polynomial regressions (from upstream node 2 until the 13) and the hydraulic simulated slopes (from upstream node 13 until 44).

2.2.5. Validation reports

The model application underwent validation on the Po River using data from the three years spanning 2019 to 2021, selected due to the availability of validation data. Given the scarcity of sediment budget data for Italian rivers, including the Po River, two primary data sources were utilized as reference points for the validation process. The first was the study performed by Schippa (2021), which focused on the bed and suspended sediment load measurements, performed on a specific Po River site under four different water discharges. The second was the data of the mean annual sediment budget for the Po River, calculated over 23 years (1982-2005), by the PGS project (AdbPo, 2012). This is the only information available on the entire Po River scale.

2.3. D-CASCADE model

The D-CASCADE model is a dynamic, network-based sediment (dis)connectivity model designed to investigate the spatiotemporal evolution of sediment supply and delivery across river basins (Tangi et al., 2022). The model integrates concepts of network modeling with empirical sediment transport formulas to quantify sediment connectivity patterns within river networks. As stated by Tangi et al. (2022), the D-CASCADE model setup consists of two main phases: initialization and the main D-CASCADE loop, characterized as follows.

During the initialization phase, the necessary input data for the model is defined, and the structure of the simulation is delineated. This includes representing the river network as a graph with nodes and reaches (Figure 7), where each reach represents a section of the river network with specific geomorphic and hydraulic features. All the steps related to the initialization are reported below (Tangi et al., 2022).

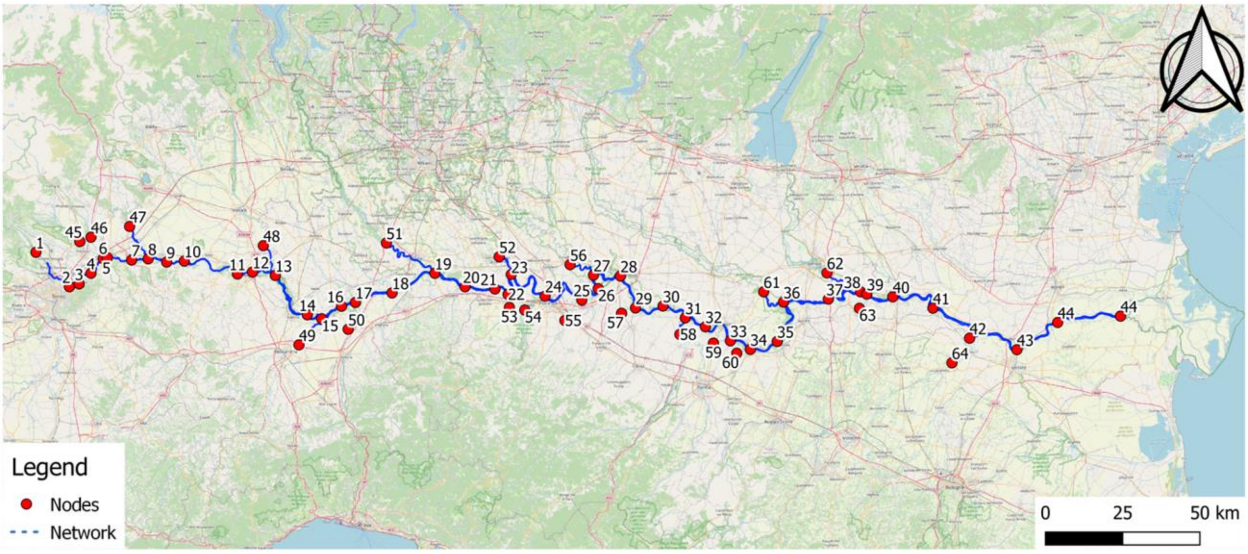

Figure 7 - Simulated Po River network with the main tributaries included. The numbers highlight the reach nodes defined by uniform hydraulic, geometrical, and geomorphological properties.

- Definition of the input data required for model execution;
- Delineation of the structure of the simulation;
- Representation of the river network as a graph composed of nodes and reaches;
- Definition of each reach as a section of the river network between two nodes with homogeneous geomorphic and hydraulic features;
- Definition of boundary conditions of the simulation, such as its time horizon;
- Definition of the size and composition of the sediment classes according to the composition of the material transported and the level of detail desired;

- Reach features are classified as static, dynamic, or modeled based on their characteristics and temporal variability.

Regarding the main D-CASCADE loop, this phase incorporates the core components and procedures of the model. During the loop the dynamic framework of the model operates, tracing the movement of sediment cascades over time and space. The main D-CASCADE loop is essential in the model framework and consists of a series of operations that are repeated for each reach and at each timestep, including the definition of mobilized sediment, changes in geomorphic features, and sediment delivery (Tangi et al., 2022).

In the context of defining mobilized sediment, the overall volume of sediment that is mobilized and carried downstream during each timestep consists of cascades that are either received from upstream in the previous timestep, held in the deposited layer, or a combination of both. The deposited layer is conceptualized as a series of distinct tiers stacked on top of each other, where each tier is composed of a single cascade. This modeling structure ensures that newly deposited cascades form a tier above the previously deposited material (Tangi et al., 2022). At the same time, entrained sediment is removed from the upper tiers of the deposit.

The amount of sediment mobilized in a reach at a given time is determined by the sediment transport capacity, which is the maximum sediment discharge passing through a section allowed by the hydromorphological characteristics of the reach under consideration (Tangi et al., 2022). This instantaneous transport capacity is calculated using empirical formulas, such as Wilcock and Crowe (2003) and Engelund and Hansen (1967), and converted to daily transport capacity to determine the mobilized volume in each timestep. The cascades in the active layer are mobilized from the top layer until the defined volume is reached or the active layer is emptied. In contrast, the unmobilized volume is stacked in the storage layer to form the new deposit layer.

Figure 8 below shows the passages that define the mobilized sediment volume for a specific reach, where the colors of the tiers indicate the reach of provenance in the network. According to the definitions made by Tangi et al. (2022), in (b) the model extracts the incoming cascades and deposit layer in the timestep, in (c) the deposit is divided into active and substrate layers, in (d) the model calculates the transport capacity for the sediment in the active layer, according to the layer Grain Size Distribution (GSD). Finally, in (e) the mobilized volume and new deposit layer are defined.

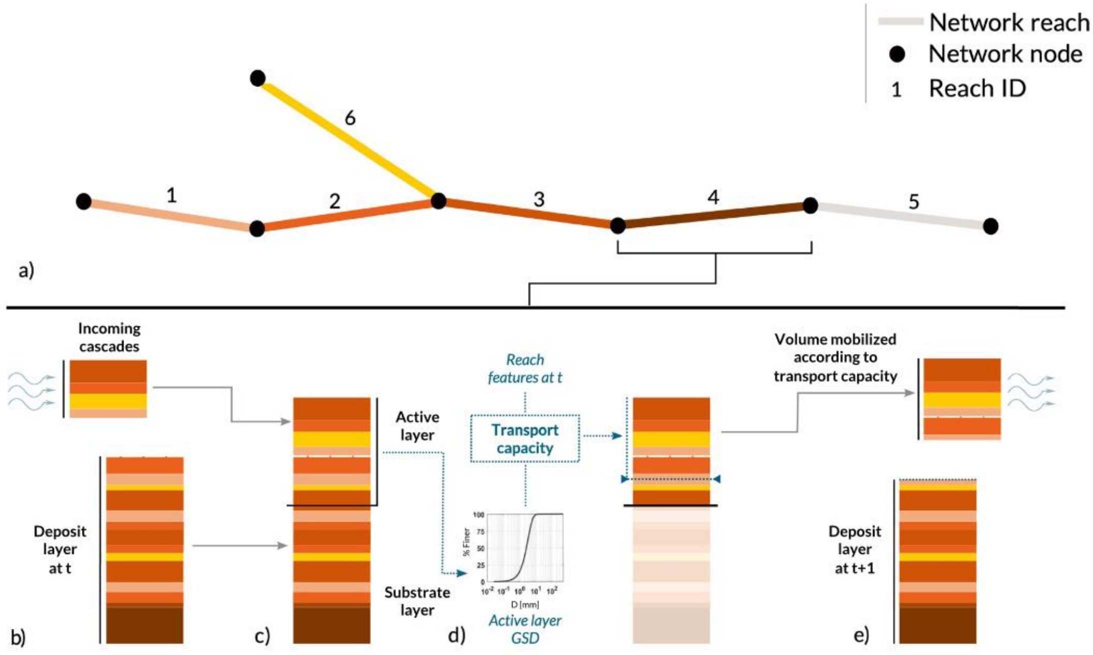

Figure 8 - How the mobilized sediment volume is defined in a reach in a single model timestep. Source: Tangi et al., 2022.

To simulate the sediment budget in the D-CASCADE model, the following data are required (Schmitt et al., 2016; Tangi et al., 2022):

- River network data, represented as a graph of nodes and reaches;
- Reach features, including static features (fixed for the entire simulation), dynamic features (values that may change in each timestep), and modeled features (changes simulated in each timestep);
- Initialization of sediment volumes routed through the network, either derived from material initialized in the reaches or as external, user-defined sediment contributions;
- Boundary conditions of the simulation, such as the time horizon, numerical precision in measuring sediment volumes, and the provenance and quantity of sediment routed in the model;
- Sediment transport formulas that are best suited for the specific study environment;

- Information on sediment transport capacity, sediment velocity, and how they can alter spatial and temporal patterns of sediment (dis)connectivity.

Regarding the reach features, the key inputs used for the simulations are the channel slope (m/m), length (m), active channel width (m), grain size distribution (mm), discharge (m^3/d), Manning's coefficient, and sediment deposit (m^3).

A good parametrization in the D-CASCADE model plays a crucial role in influencing the accuracy and reliability of the model outputs. A proper parametrization ensures that the model accurately represents the physical processes and interactions within the river network, and this leads to more realistic simulations of sediment transport and connectivity dynamics (Schmitt et al., 2016). Besides that, a good parametrization enhances the model's predictive capability, allowing it to forecast future trends of sediment (dis)connectivity dynamics with greater confidence, being essential for understanding how river systems may evolve.

In addition, proper parametrization enables sensitivity analysis, where the impact of different parameters on model outcomes can be assessed. This helps in understanding the relative importance of various factors influencing sediment transport processes simulated.

On the other hand, the sediment transport formula used in the D-CASCADE model also has a significant influence on the accuracy and behavior of sediment transport simulations within river networks. The sediment transport formula determines how sediment is mobilized, transported, and deposited within the river network, so different formulas can represent various sediment transport processes, such as bedload transport, suspended sediment transport, and channel erosion, leading to a more comprehensive representation of sediment dynamics (Wilcock et al., 2009).

Besides that, the choice of sediment transport formula affects the calibration and validation of the model. By selecting an appropriate formula that aligns with observed sediment transport processes, the model can be calibrated better to match real-world data (Church, 2006), improving its reliability and accuracy. As it is tested in this study, the sediment transport formula is a key parameter in sensitivity analysis, allowing modelers to assess the sensitivity of model outputs to variations in the formula. Understanding how changes in the formula affect model results can provide insights into the importance of different sediment transport processes.

2.4. Sediment transport formulas

A comparative analysis of two sediment transport formulations within the D-CASCADE model was performed, aiming to elucidate their respective efficacy in predicting sediment dynamics. The formulations chosen were the Engelund and Hansen (1967) and Wilcock and Crowe (2003), each renowned for its distinctive approach to sediment transport modeling. The Engelund and Hansen formula is tailored towards scenarios dominated by fine sand, offering a robust framework for simulating sediment transport in such conditions. Conversely, the Wilcock and Crowe formula is renowned for its suitability in scenarios where a mixture of gravel and sand prevails, providing an effective means of modeling sediment transport dynamics in these environments.

2.4.1. Engelund and Hansen, 1967

The Engelund and Hansen (1967) equation is a widely used empirical formula for calculating sediment transport in alluvial streams. The equation provides an estimate of the sediment transport rate based on the flow conditions and sediment characteristics. The formula was derived based on extensive flume observation data, using relatively uniform sand sizes between 0.19 mm and 0.93 mm, through empirical observations and theoretical considerations related to sediment movement in rivers (Engelund & Hansen, 1967).

They collected data on sediment transport rates under various flow conditions, channel slopes, and sediment characteristics to understand the factors influencing sediment movement and combined with theoretical principles of fluid mechanics and sediment transport to develop a mathematical relationship that could describe the sediment transport process in rivers (Engelund & Hansen, 1967). The Engelund and Hansen (1967) formulation is shown below (Equation 7).

$$gs = V^2 \left(\frac{\tau b}{(\gamma s - \gamma)\, d50}\right)^{\frac{3}{2}} \sqrt{\frac{d50}{g\,(\frac{\gamma s}{\gamma} - 1)}} = V^2 (\tau^*)^{\frac{3}{2}} \sqrt{\frac{d50}{g\,(\frac{\gamma s}{\gamma} - 1)}} \qquad (7)$$

Where:
gs = Sediment transport;

γ = Unit weight of water;
γs = Unit weight of sediment;
V = Average channel velocity;
τb = Bed shear stress;
τ^* = Dimensionless Shields Number;
$d50$ = Median particle size.

2.4.2. Wilcock and Crowe, 2003

The surface-based equation of Wilcock and Crowe (2003) was developed from coupled observations of flow, transport, and bed surface grain size using five sediments with varying sand content in a laboratory flume (Wilcock et al., 2001).

The model incorporates a hiding function that helps resolve discrepancies observed in earlier models (Wilcock et al., 2001). The hiding function accounts for different grain sizes on the bed surface and their influence on sediment transport rates (Wilcock and Crowe, 2003), by considering the full-size distribution of the bed surface, including sand, the model can capture the nonlinear effect of sand content on gravel transport rate, which was not fully addressed in previous models (Wilcock and Crowe, 2003). The hiding function is given by Equations 3 and 4, below.

$$\tau_{ri}^* = \tau_{rm}^*(\frac{di}{dsm})^b \qquad (3)$$

$$b = \frac{0.67}{1+exp\ (1.5 - \frac{di}{dsm})} \qquad (4)$$

Where:

τ^*ri = Reference shear stress for a specific grain size

τ_{rm}^* = Base reference shear stress

These equations are used to adjust the reference shear (τ^*ri) for the specific grain size class using the base reference shear ($\tau * rm$) for the median grain class, the ratio of the grain class particle size (di) on the surface to the median mixture surface grain size, and the hiding factor, b. The reference shear is a function of the sand content (FS) of the bed surface (in percent), as shown below, in Equation 5.

$$\tau^*rm = 0.021 + 0.15\epsilon^{-20Fs} \qquad (5)$$

That said, the Wilcock and Crowe equation is based on the ratio of the shields number (τ^*) to a "reference shields" number (τ_{ri}^*), making it a sort of excess shear stress (Wilcock and Crowe, 2003). They defined the transport rate as two functions of the dimensionless shear ratio, as shown below (Equation 6).

$$W_i^* = \begin{cases} 0.002\left(\frac{\tau^*}{\tau_{ri}^*}\right)^{7.5} & if\ \frac{\tau^*}{\tau_{ri}^*} < 1.35 \\ 14\left(1 - \frac{0.894}{\sqrt{\frac{\tau^*}{\tau_{ri}^*}}}\right)^{4.5} & if\ \frac{\tau^*}{\tau_{ri}^*} \geq 1.35 \end{cases} \quad (6)$$

Where:
τ^*= Bed shear stress;
$\tau^* ri$ = Reference shields number.

According to Wilcock and Crowe (2003), where there is a small amount of sand on the surface, sand nestles between larger gravel clasts, which reduces the bed shear it experiences. In this way, coarse clasts reduce the transport of fine particles to occur only when a large grain is mobilized. In contrast, gravel transport increases with sand content. As the sand content of the bed surface increases, it 'lubricates' the bed, depositing between surface gravels and reducing the framework integrity.

Given that both equations are empirical, they present limitations in effectively forecasting sediment transport rates across diverse conditions. In each scenario, these formulations might fail to incorporate intricate flow patterns, sediment interactions, or variations in channel dynamics, potentially leading to inaccuracies in representing the transportation of coarse sediments. As outlined in this section, the Wilcock and Crowe formula is suitable for rivers with a mixture of sand and gravel, unlike the Engelund and Hansen formula, which caters to finer sediment ranges.

In the case of the application of the mentioned sediment transport equations in the D-CASCADE model, both of them may not fully account for the spatial heterogeneity of sediment transport processes within a river network. The application of both formulas at a network scale may cause an oversimplification of the complex sediment transport dynamics that occur at different locations within a river network, leading to uncertainties in estimating sediment transport rates.

3. RESULTS

3.1. Results

As mentioned in the objectives, two different simulations were performed with the same network parametrization (Figure 6), but changing the sediment transport formula, varying through Wilcock and Crowe (2003) and Engelund and Hansen (1967).

Comparing the two results in terms of mobilized volume (Figure 9), both formulas presented similar trend behavior but differed in magnitude. Firstly, exploring the sensitivity of each formula, each formulation considered different sediment transport processes, including assumptions about factors such as sediment size distribution, flow velocity, and channel morphology.

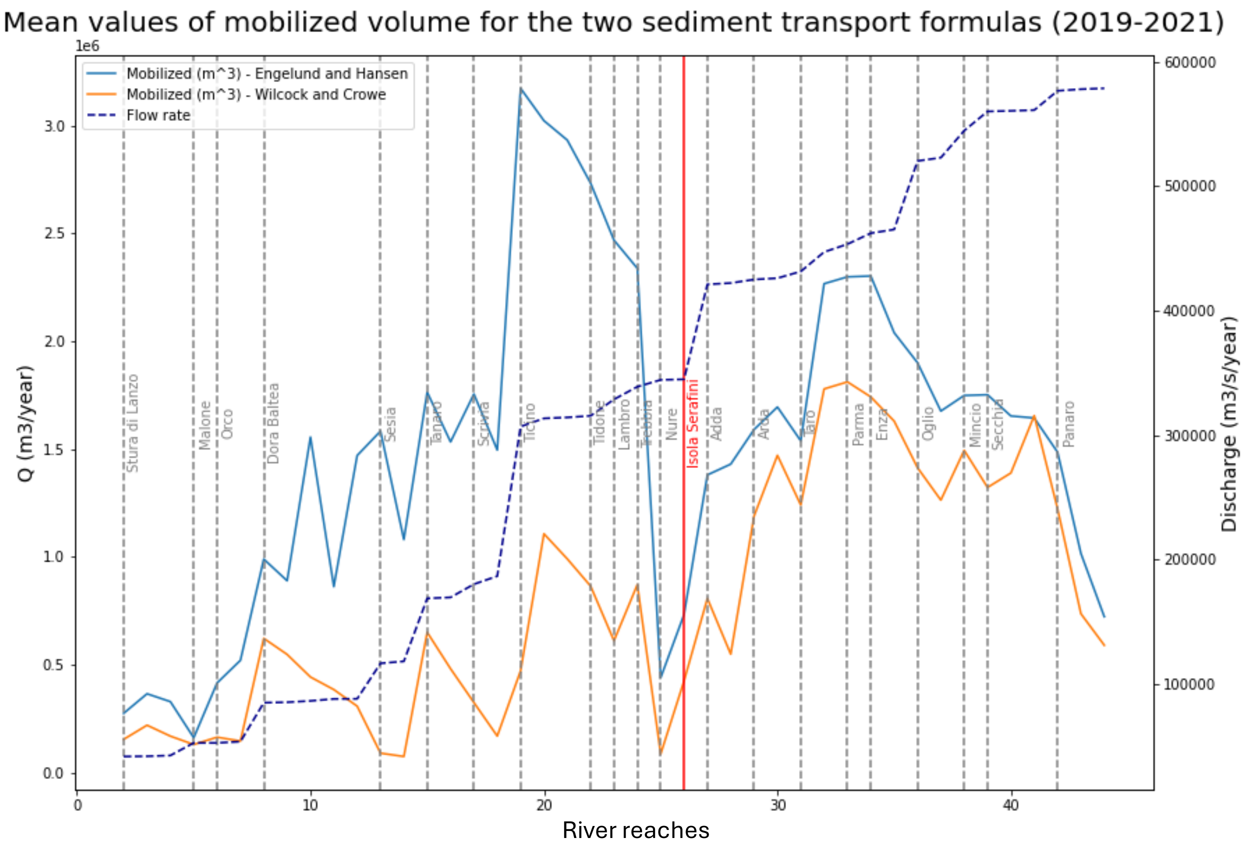

Figure 9 - Comparison between the mobilized volume simulated using Wilcock and Crowe and Engelund and Hansen.

Although both sediment transport formulations are used to compute bed material transport, they better represent different sediment grain sizes, as mentioned in the methodology section, so it is acceptable a higher mobilization for the Engelund and Hansen, as observed in Figure 9 above. So, probably the sediment properties in the upstream part of the Po network do not align well with the assumptions of both formulas, considering that both were calibrated or designed to prioritize certain sediment properties over others, which can result in contrasting estimates of mobilized volume.

In addition, it is noticeable the influence of discharge on both formulations, especially on Engelund and Hansen. The highest peak of mobilization, occurred on node 19, coincided with an increase of discharge, being the average mobilized sediment around 3,500,000 m^3/year (Figure 9). Additionally, the largest disparities in simulation outputs are primarily concentrated in upstream areas, where the sediment size range applicable to the formulas diverges. This discrepancy is less relevant in downstream reaches, where the difference becomes less pronounced, with both formulations presenting results of comparable magnitudes. This observation highlights the nuanced interplay between discharge, sediment characteristics, and formula applicability, emphasizing the need for careful consideration of these factors when assessing sediment transport dynamics in river systems.

Concerning the sediment budget of the study area within the model, this value is computed as the delta volume, calculated as the difference between the sediment entering (transported volume) and exiting (mobilized volume) the specified reach (Bizzi et al., 2021). The consistency in the trend of the delta volume among the two sediment transport formulas demonstrates the model's coherence in describing sediment dynamics according to the parametrization. This consistency implies that the model can effectively replicate sediment transport processes but is differing in terms of magnitude (Figure 10).

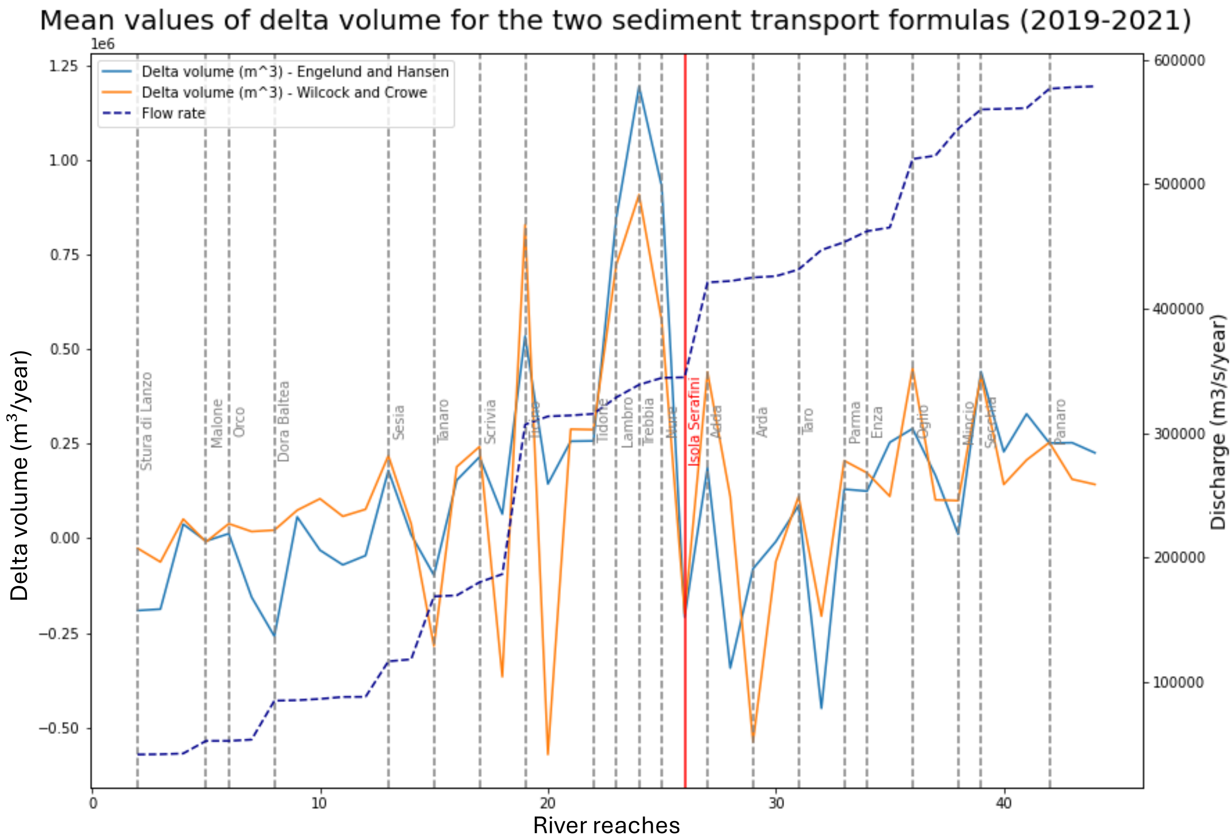

Figure 10 - Comparison of the delta volume (sediment budget) simulated using Wilcock and Crowe and Engelund and Hansen.

A similar behavior was observed for the values of elevation change (delta z) for the entire period of simulation (Figure 11), where the largest discrepancies are located on the upstream part of the network, probably due to variations in how Wilcock and Crowe and Engelund and Hansen formulas account for sediment properties that can impact the sediment transport predictions and subsequent bed elevation changes in the river network.

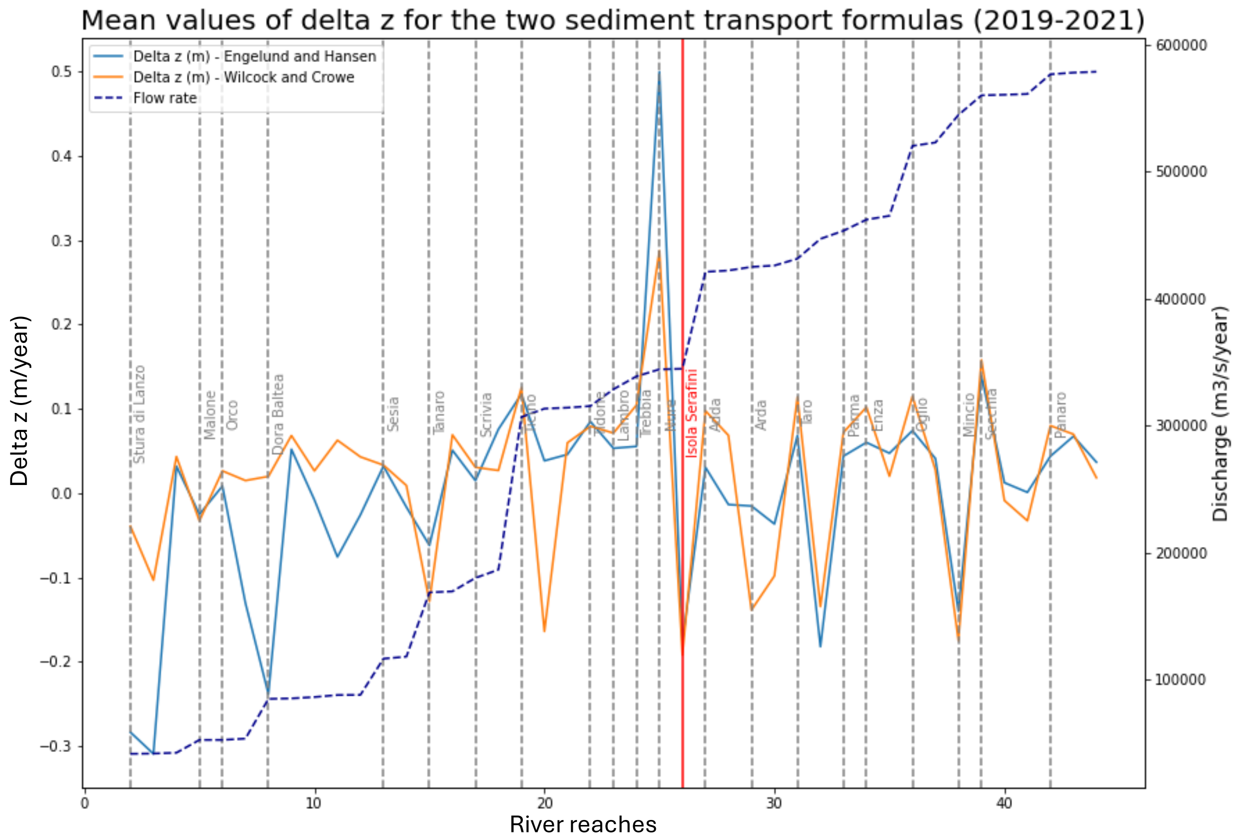

Figure 11 - Comparison between the difference in elevation from the initial condition (before the simulation) simulated using Wilcock and Crowe and Engelund and Hansen.

The fact that different sediment transport formulas lead to similar delta volume and delta z trends suggests that the model may not be highly sensitive to the choice of sediment transport formula for the downstream part of the Po River basin. However, the fact that the magnitude is varying could imply that this model aspect together with the boundary conditions has a greater impact on the overall sediment transport outcomes.

As for the mobilized volume the largest discrepancies, especially in terms of erosion prediction, were located in the upstream part of the network for the delta volume and delta z. The large difference in erosion was placed in node 20, while for deposition the highest discrepancy is placed in node 24. Since the largest discrepancies are distributed in specific reaches along the network, these differences may be due to the geomorphological features of individual reaches, including channel slope, width, and bed material, which can influence sediment transport dynamics (Schmitt et al., 2016). Differences in how the sediment transport formulas account for these local channel characteristics may also result in varying predictions for delta volume in specific reaches.

In addition, the hydraulic conditions within specific reaches, such as the presence of hydraulic structures, constrictions, or variations in water depth, can affect sediment transport behavior (Wilcock et al., 2009). Since the model does not take into account the direct effects of bridges or dams that are present in the Po River network, the sediment transport formulas may interpret these hydraulic conditions differently, resulting in distinct predictions for delta volume in certain reaches.

However, although the direct impact of the dams is not directly computed, some physical effects were compassed by considering the changes in slope derived from a Digital Elevation Model (DEM) with good spatial resolution. As mentioned before, the 1-meter DEM has accurate elevation data that captures the topographic features relevant to sediment transport modeling in the D-CASCADE framework, so it is possible to observe a deposition in the reach before the Isola Serafini dam (node 25), and erosion in the reach where the dam was placed (node 26).

Considering this potential, nodes 2 and 3 are located downstream of dams, so it is acceptable to observe sediment starvation caused by this type of structure resulting in erosion and sediment depletion downstream, potentially lowering the bed height in these reaches, as shown in Figure 11, especially for the simulation using the Engelund and Hansen formula. In terms of delta volume, dams can disrupt the natural sediment budget of river systems by trapping sediment upstream and reducing sediment supply downstream (Brenna et al., 2024). That said, not considering dams in the model can misrepresent sediment budgets, leading to errors in predicting sediment transport, erosion, and deposition patterns.

3.2. Validation

3.2.1. Mean annual sediment budget (PGS 1982-2005, AdbPo)

The mean annual sediment flux computed in the PGS project (AdbPo, 2008), computed between 1982 and 2005, and updated in 2012 is shown in Figure 12, below. The portion of the data used for validation of the simulations performed comprehends the reaches between the Taro and Panaro rivers, which are tributaries of the Po River.

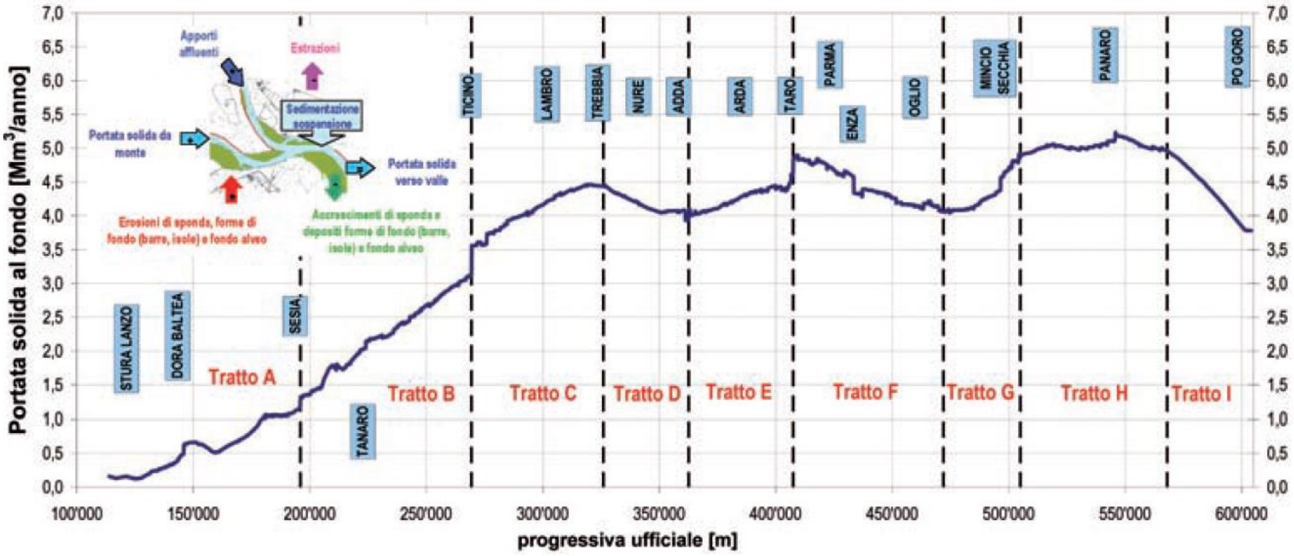

Figure 12 - Average annual transport budget solid to the bottom computed between 1982 and 2005. Source: AdbPo, 2008.

The observed data from the PGS project, presented values of mobilized sediment ranging between 4,000,000 and 5,000,000 m^3/year, while the simulations ranging between 1,500,000 and 2,300,000 m^3/year for the simulations utilizing Engelund and Hansen formula, and 1,200,000 and 1,750,000 m^3/year for the results obtained with the Wilcock and Crowe formula (Figure 9). The fact that both observed and simulated sediment fluxes have the same order of magnitude can thus be considered a satisfactory result for this type of analysis (Table 1).

Source	Range of mobilized volume (m^3/year)
PGS project	4,000,000 – 5,000,000
Engelund and Hansen (1967)	1,500,000 – 2,300,000
Wilcock and Crowe (2003)	1,200,000 – 1,750,000

Table 1 – Comparison between the range of values of mobilized volume (m^3/year) for the PGS project and the D-CASCADE simulations using two different sediment transport formulas.

3.2.2. Site-specific observations (Prof. Schippa - UNIFE, 2021)

Compare model outputs with observed data from a specific reach, enabling an assessment of the model's accuracy in replicating real-world conditions. By validating simulations, researchers can identify discrepancies between model predictions and actual measurements, helping to refine and improve the model's performance. That said, the simulated values were extracted from the same location, between nodes 33 and 34 (Figure 13), and under the same water discharge conditions of the observed data.

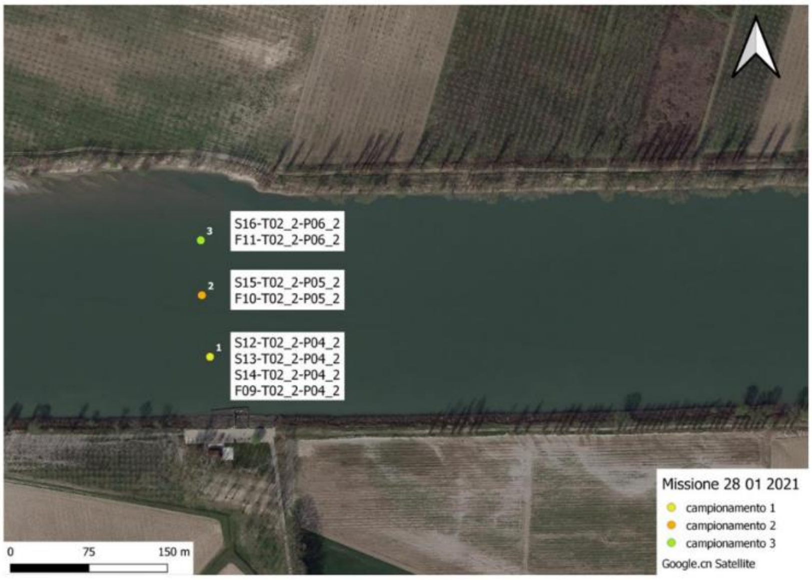

Figure 13 - Sampling points of solid transport at the bottom and in suspension located between nodes 33 and 34. Source: Schippa, 2021.

The measured data (suspended sediment flux and bed load) from Schippa (2021) were performed on four different dates (13/11/2019, 10/12/2019, 28/1/2021, and 10/2/2021), under four different water discharges that varied between 1327 and 1877 m^3/s. The sampling showed great variability and non-linearity of the relation between the total sediment flux and water discharge, with a measured total sediment flux that ranged between 10 and 26 g/s/m (Figures 14 and 15), where the highest flux was recorded for the lowest water discharge (1327 m^3/s).

Data	Portata Boretto	Campione/misura	Certificato lab. Geot.	Codice campione in campo	Inizio (ora)	Durata campion amento	D50	Peso secco	Ghiaia	Sabbia	Fraz. Fine	Flusso
	(mc/s)				(ora)	(s)	(mm)	(g)	(%)	(%)	(%)	g/s/m
28/01/21	1327	F09-T02_2-P04_2	921/06_21	F33	12:54	1200	0.56	1887.71	0.20	99.80	0.00	**20.64**
28/01/21	1327	F10-T02_2-P05_2	922/06_21	F34	13:28	1200	0.38	1742.69	0.10	99.50	0.40	**19.06**
28/01/21	1327	F11-T02_2-P06_2	923/06_21	F36	14:20	1110	0.34	2212.02	0.00	99.80	0.20	**26.15**

Figure 14 - First sample measurements for the three points of solid transport at the bottom and in suspension. Source: Schippa, 2021.

Data	Portata Boretto	Campione/misura	Certificato lab. Geot.	Inizio (ora)	Durata campion amento	D50	Peso secco	Ghiaia	Sabbia	Fraz. Fine	Flusso
	(mc/s)			(ora)	(s)	(mm)	(g)	(%)	(%)	(%)	g/s/m
10/02/21	1877	F12-T02_2-P04_3	939_08/21	11:00	900	0.62	928.96	0.90	99.10	-	**13.55**
10/02/21	1877	F13-T02_2-P05_3	940_08/21	11:40	900	0.45	1378.12	0.20	99.30	0.50	**20.10**
10/02/21	1877	F14-T02_2-P06_3	941_08/21	12:15	900	0.36	812.59	0.10	99.90	-	**11.85**

Figure 15 - Second sample measurements for the three points of solid transport at the bottom and in suspension. Source: Schippa, 2021.

The simulated sediment flux was very variable ranging between 20 and 31 g/s/m, for the Wilcock and Crowe application and 12 and 36 g/s/m for the Engelund and Hansen, for discharges varying from 1328 and 1862 m^3/s. Both are within the same variability window of the observations (Table 2).

Source	Range of discharge (m^3/s)	Range of mobilized volume (g/s/m)
Schippa (2021)	1327 – 1877	10 – 26
Engelund and Hansen (1967)	1328 – 1862	12 – 36
Wilcock and Crowe (2003)	1328 – 1862	20 – 31

Table 2 – Comparison between the range of values of sediment fluxes (g/s/m) for the site-specific observations and the D-CASCADE simulations using two different sediment transport formulas.

Given that both applications displayed a comparable scale of observed data in the two validation reports, it can be concluded that the model effectively captures the fundamental dynamics and behaviors of the system.

3.3. Comparison of the simulated sediment budget with satellite observations

Since the simulation performed using the Engelund and Hansen sediment transport formula presented the results closer to the validation reports, this application was utilized to compare the model outputs in terms of the elevation of erosion or deposition, with satellite images, which provide detailed spatial and temporal information about the Earth's surface, capturing features at different scales.

The temporal resolution is necessary for justifying correspondences between model outputs and satellite images, especially considering the short-period application of three years. By simulating erosion and deposition processes over comparable time intervals as captured by the satellite data, it was possible to observe that the D-CASCADE model was capable of following changes in sediment budget over time. Consistent temporal resolution ensures that the model can replicate the temporal patterns of sediment transport and landscape evolution, leading to better agreement with the temporal dynamics observed in satellite images.

The simulation of the D-CASCADE model was compared to satellite images by analyzing the delta z values (Figure 16). These values represent the average height of the delta volume (m^3) calculated by the model divided by the area of the active channel width (m^2).

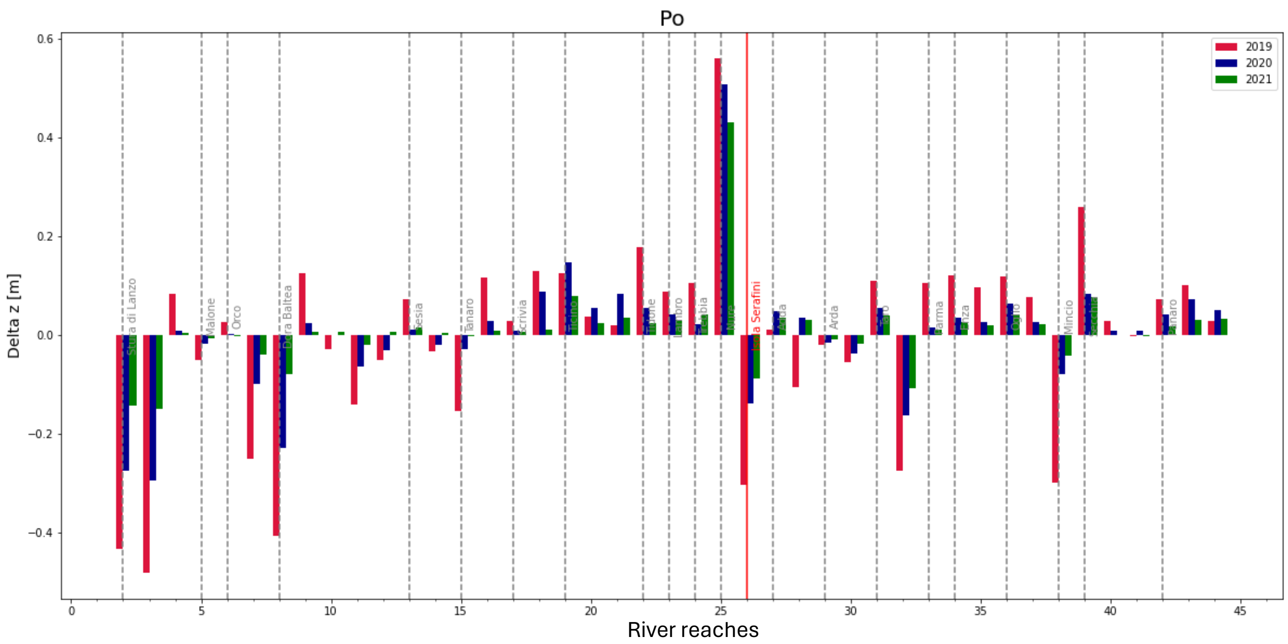

Figure 16 - Delta z values for each reach of the Po River.

Figure 17 below shows the correlation between the simulations of the reach between nodes 19 and 20 and the satellite images. The simulations indicated a trend of deposition over the three years considered, which fitted the images considering that the increasing in the exposed sediment bars could be a indication of deposition. The reach presented an average deposition of around 12 cm per year, being 13 cm in 2019, 15 cm in 2020, and 8 cm in 2021 (Figure 16).

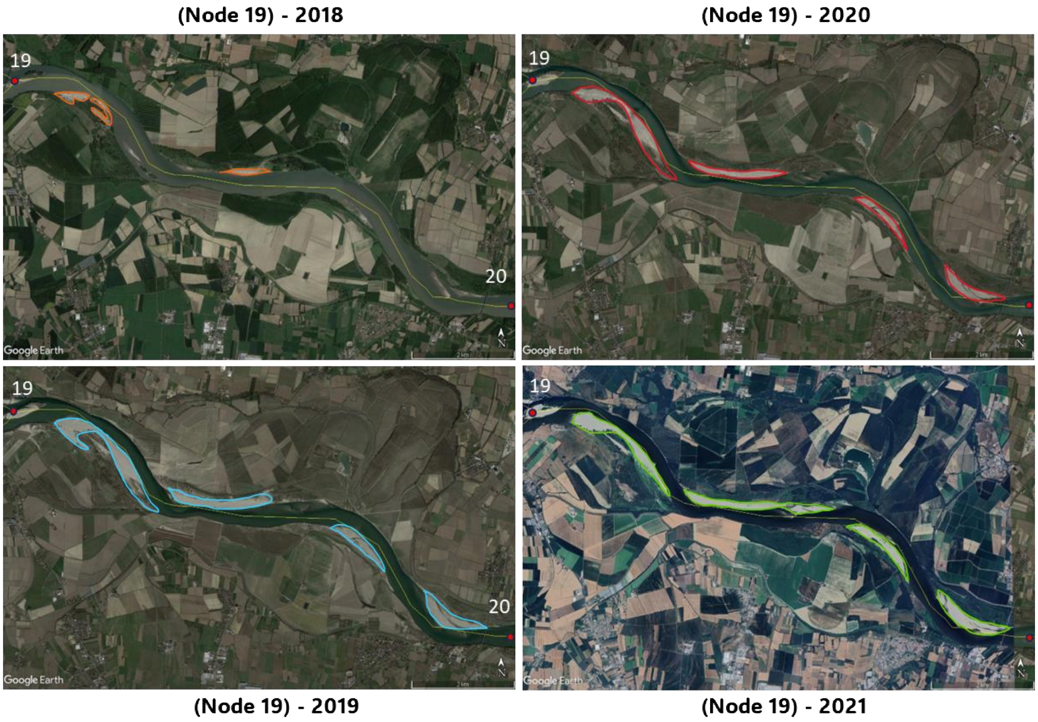

Figure 17 – Observable variations of sediment budget in reach between nodes 19 and 20, which could indicate deposition during the same period of simulation.

Nonetheless, the trend of deposition for this reach is relevant only for the short timescale simulated. Historically, this section of the Po River has suffered adjustments, including incision and narrowing (Brenna et al., 2024; Surian and Rinaldi, 2003). The adjustments observed in the last 20 years (Figure 18) correspond to the historical morphological evolution reported by Surian and Rinaldi (2003) in the Italian rivers, in the past century. According to Figure 18 below, this reach suffered the adjustment going from a transitional morphology shown in B (2003) to the condition represented in E (2023), which corresponds to a slight or moderate incision combined with channel narrowing, that leads to a single-thread configuration, with the presence of bars (Surian & Rinaldi, 2003).

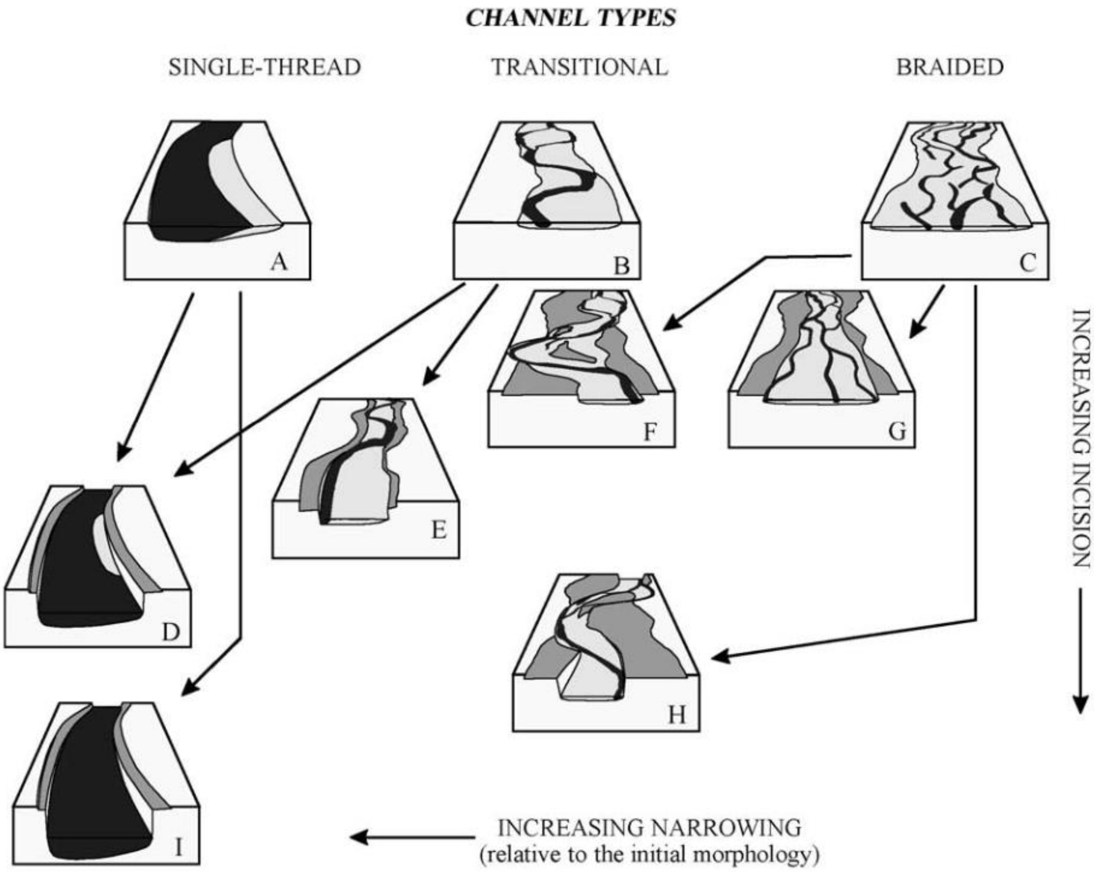

Figure 18 - Classification scheme of channel adjustments for Italian rivers starting from three initial morphologies (A, B, and C), and the recent evolution of the reach between nodes 19 and 20. Source: Surian & Rinaldi, 2003.

Another example of correspondence between the model output and satellite image was the reach between nodes 31 and 32 (Figure 19). In this reach, the simulation indicated a deposition in 2019 of around 11 cm, 5 cm in 2020, and 4 cm in 2021. Based on these findings, the data indicates an average sediment deposition of 7 cm per year. This could lead to various future processes, such as increased flood risk due to reduced channel capacity, resulting in geomorphic adjustments along the river network.

Figure 19 - Observable variations of sediment budget in reach between nodes 31 and 32, which could indicate deposition during the same period of simulation.

However, as shown in the previous example, this trend of deposition does not match the historical evolution of the reach. According to Brenna et al. (2024), this specific reach underwent significant morphological changes during the last century, with observable alterations in channel width, pattern, and complexity, as shown in Figure 20. The reach exhibited a modification in its channel morphology, indicating a response to various perturbations acting on the river system. Some of these perturbations were sediment starvation resulting from upstream anthropic activities such as dam construction, gravel extraction, and land use changes (Brenna et al., 2024). These activities disrupted the natural sediment supply, leading to a reduction in sediment fluxes and availability.

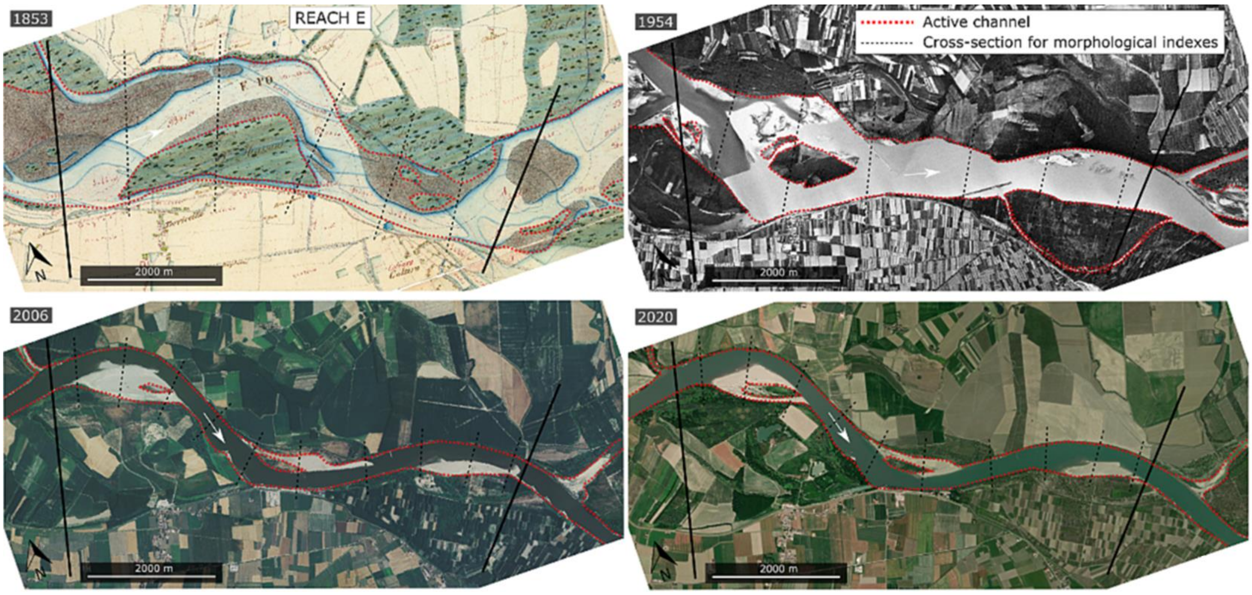

Figure 20 - Morphological evolution of the reach between nodes 31 and 32. Source: Brenna et al., 2024.

The same occurred in reach between the nodes 28 and 29. The computed sediment budget indicates a stable trend, where the average sediment budget was almost negligible, close to -1 cm per year (Figure 21), which does not align with the erosion trend observed in the last century (Brenna et al., 2022). This trend could indicate the maintenance of the natural morphology of the river channel, including the formation of bars, islands, and meanders, which are necessary for sediment transport and hydraulic diversity (Church, 2006). This stability trend may also indicate resilience to natural events such as floods and droughts, as well as human-induced disturbances, by maintaining equilibrium between sediment supply and transport capacity.

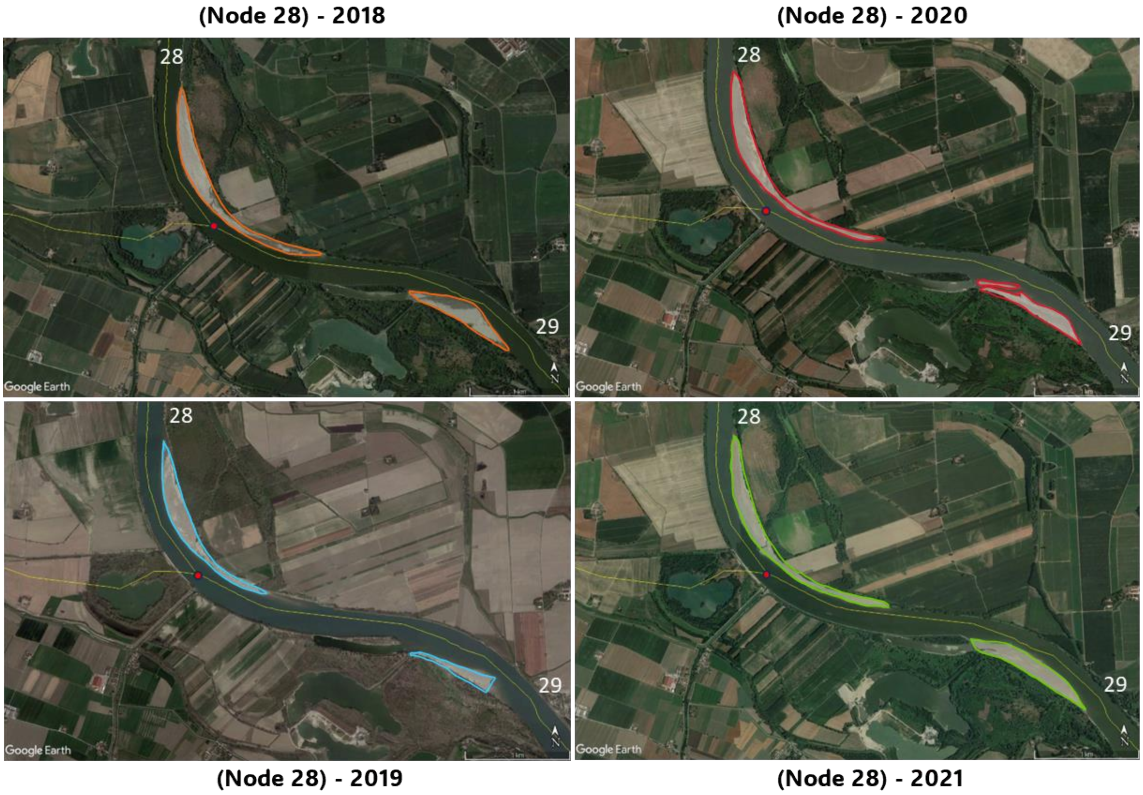

Figure 21 - Observable variations of sediment budget in reach between nodes 28 and 29, which could indicate stability during the same period of simulation.

As stated by Brenna et al. (2022), the decrease in the active channel width suggests a reduction in coarse sediment fluxes, which is typically associated with erosion processes leading to channel narrowing and reduced sediment transport capacity, as shown in Figure 22, below.

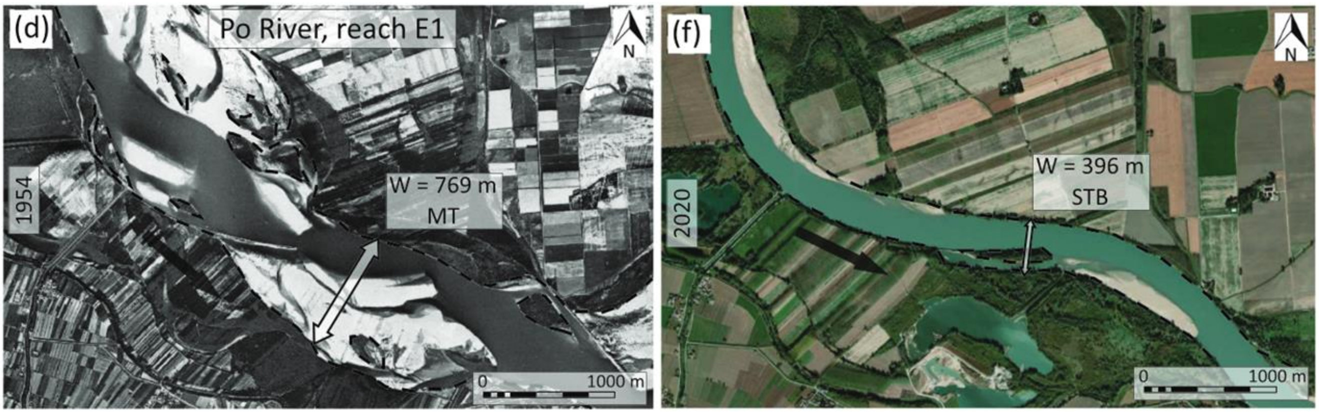

Figure 22 - Morphological evolution of the reach between nodes 28 and 29. Source: Brenna et al., 2024.

Although the historical trend for the Po River, such as for various Italian rivers, is the occurrence of erosion and narrowing primarily attributed to diverse human interventions such as instream sediment mining, dam construction, channelization, and land-use changes (Brenna et al., 2024; Surian & Rinaldi, 2003), the final morphologies of this reaches do not necessarily represent the last stage of channel evolution (Surian et al., 2009). Even though these activities disrupted the natural sediment balance in the recent past, recent evidence in some rivers (Piave, Brenta, and Taro Rivers) seems to suggest that other kinds of adjustment, such as widening and aggradation, could follow the main phase of adjustment characterized by incision and narrowing (Surian et al., 2009).

4. DISCUSSIONS

Since both sediment transport equations have been validated and calibrated using flume observations, the uncertainties on the application in a real case study may lead to overestimation or underestimation of the simulations, indicating a need for recalibration or refinement for the study area adopted. Besides that, it is needed to take into account the applicability of each formula to the specific conditions of the Po River basin, recognizing that differences in sediment types, flow regimes, or channel geometries could contribute to discrepancies in predicted sediment transport rates.

Moreover, the limitations of each formula in accurately representing sediment transport processes, include factors such as the neglect of certain sediment interactions, flow complexities, or channel variations. That said, the conduction of a sensitivity analysis to identify key parameters driving differences in predicted sediment transport rates, aids in understanding which factors have the greatest influence on model outputs. Additionally, quantifying the uncertainty associated with each formula and its inputs, considering measurement errors, variability in environmental conditions, or inherent limitations of the formulas themselves is essential.

For the simulations performed, the results using the Engelund and Hansen formula showed a higher correlation with the validation data and the analysis of the satellite images, so the derivation of this formula might align more closely with the sediment dynamics, flow conditions, and channel characteristics of the modeled reaches of the Po River, resulting in a closer match to observed data.

In comparison with the observed data used for validation, the underestimation of the sediment flux regarding the data from the PGS project could be associated with the use of a mean daily water discharge as a modeling input. A mean daily value means that on that same day, there could be lower and higher water discharge peaks. Given the non-linear response of the sediment transport to an increase in water discharge, the reduction of those peaks in the averaging process might lead to significant reductions in the total sediment loads.

In addition, considering that the D-CASCADE is codified to simulate daily sediment fluxes, the choice of using a mean daily water discharge is assumed to be the most sensible. Higher (for example, daily maximum) water discharge peaks could be used to assess the upper boundary of possible daily sediment fluxes. Another factor that might contribute to lower simulated sediment fluxes compared to the values reported by the PGS project is the potential difference in hydrological conditions between the two periods being compared. Given that the simulations spanned from 2019 to 2021, while the observed data from the PGS report ranged from 1982 to 2005, variations in hydrological patterns between these periods could significantly impact the analysis outcomes.

The similar trends and magnitudes of delta volume in the downstream reaches obtained across different sediment transport formulas may suggest that the overall behavior of sediment transport in the Po River network is consistent and can be generalized to some extent. This can be valuable for understanding sediment dynamics in similar river systems or under comparable conditions. While consistent results are encouraging, it is also important to conduct further analysis to understand why different formulas lead to similar outcomes in this part of the basin. Exploring the specific mechanisms and interactions that drive sediment transport in the model can provide insights into the underlying processes at play.

Regarding the discrepancies in the upstream reaches between the two sediment transport formulations, the sediment characteristics in the upstream reaches of the Po River network, such as grain size distribution, sediment composition, and sediment sources, can influence how the formulas estimate sediment transport. If the sediment properties align more closely with the assumptions of one formula, it can result in differences in the computed sediment budget (delta volume) per reach, compared to the other formula. That said, a coherent approach could be to partition the network according to the best fit with the sediment transport formulas.

Adapting sediment transport formulas based on the sediment grain size distribution allows for greater flexibility in modeling various sediment types and behaviors along the river network, which enables the model to make more robust predictions about sediment behavior under varying conditions. In addition, using formulas that are specifically calibrated for different grain size distributions ensures that the model captures the nuances of sediment movement, deposition, and erosion accurately, leading to a more realistic representation of sediment dynamics.

Comparing the results of the D-CASCADE model with satellite images of varying temporal resolutions is crucial for assessing temporal dynamics, identifying sediment transport events, analyzing long-term trends, link sediment transport fluxes to real morphological changes, ensuring model robustness, especially for application at the network scale. By validating the model with temporal satellite observations, it was possible to improve its capability to represent short-term simulations, such as the one performed in this study, long-term trends, and the full range of temporal variability in sediment transport processes, ultimately enhancing the reliability of the model in predicting sediment dynamics over time.

The comparison in the period of simulation showed a good correlation between the patterns of erosion and deposition observed in the satellite images with the model outputs, especially for the reaches in the downstream part of the Po network. However, it showed a discrepancy between the period of simulation adopted (3 years), and the historical trend for the same reaches.

Although short-term simulations may capture transient sediment processes within a limited timeframe, masking the overall historical trend observed, the morphological changes over the past century on the Po River associated with incision and narrowing due to various human interventions and disturbances (Brenna et al., 2024), may not be the final morphology stage of channel evolution (Surian & Rinaldi, 2003). That said, additional adjustments, such as widening and aggradation, may occur after the primary phase suggesting that the Po River network is a dynamic system that can undergo further changes beyond the initial adjustments, emphasizing the need for continued monitoring and research to understand the complete evolution of river channels.

That said, the analysis performed in the present study offers a recent point of view, focusing on present-day sediment transport and connectivity patterns and their correlation with morphological evidence. This approach not only highlights the novelty and strength of the simulations performed but also underscores its significance in providing evidence-based insights into current trajectories of sediment dynamics, which is not commonly present in literature for the study area. This distinction emphasizes the value and relevance of this assessment in advancing the understanding of sediment dynamics in the present, and potentially in the future context.

In this scenario, the D-CASCADE model demonstrates strong applicability in predicting future trends of sediment budgets within river systems by integrating network modeling with empirical sediment transport formulas to simulate spatiotemporal variations in hydrological regimes, sediment grain sizes, and transport processes (Tangi et al., 2022). Its capability to accurately reproduce historical morphological changes and sediment transport pathways enables the model to project future sediment dynamics by incorporating historical drivers of change and running multiple scenarios to forecast sediment transport trajectories at the river reach scale.

Designed for strategic decision-making, D-CASCADE provides indicators of sediment connectivity alteration and supports management decisions related to sediment dynamics, making it a valuable tool for informing river basin health. The model's adaptability, flexibility, and potential for integration with other models enhance its predictive capabilities (Tangi et al., 2022), allowing for hypothesis testing in data-scarce environments and the exploration of complex sediment connectivity processes to predict future trends in sediment (dis)connectivity dynamics and support decision-making at larger scales.

5. CONCLUSIONS

The comparative analysis of two different sediment transport formulations in the application of the D-CASCADE model within the Po River basin highlighted the nuanced dynamics of sediment transport and deposition processes. Through simulations employing both the Wilcock and Crowe (2003) and Engelund and Hansen (1967) formulas, it became evident that while both formulations exhibited similar trend behaviors in terms of mobilized volume, there were notable differences in magnitude. These differences probably originate from the distinct sediment transport processes considered by each formula, emphasizing the importance of understanding their underlying assumptions regarding factors such as sediment size distribution, flow velocity, and channel morphology.

Figure 9 illustrates the comparison between the mobilized volumes simulated using the two formulas, highlighting how they better represent different sediment grain sizes. The Wilcock and Crowe formula proves more suitable for mixed-size sediments, while the Engelund and Hansen formula is more aligned with fine sand. This discrepancy is particularly pronounced in upstream areas, where sediment size ranges diverge, leading to varying estimates of mobilized volume. Moreover, the influence of discharge on both formulations, especially on Engelund and Hansen, highlights the complex interplay between hydraulic conditions, sediment characteristics, and formula applicability.

The evaluation of sediment budgets, depicted in Figure 10, reveals a consistency in trend between the two sediment transport formulas, implying the model's coherence in describing sediment dynamics. However, disparities in magnitude suggest that the choice of sediment transport formula, along with boundary conditions, significantly impacts sediment transport outcomes, particularly in the upstream reaches of the basin.

Further examination of erosion and deposition patterns, as indicated by delta volume variations, exposes the influence of geomorphological features and hydraulic conditions within specific reaches. Notably, the presence of hydraulic structures like dams can disrupt natural sediment budgets, leading to errors in predicting sediment transport dynamics. While the model does not directly account for the effects of dams, changes in slope derived from Digital Elevation Models offer insights into deposition and erosion patterns surrounding these structures.

The comparison of average elevation differences (Figure 11) underscores the impact of sediment properties and local geomorphological characteristics on bed elevation changes. Variations in how sediment transport formulas interact with these factors result in discrepancies, particularly in upstream reaches. Furthermore, the presence of dams introduces additional complexities, influencing sediment starvation and subsequent erosion downstream.

Using an inappropriate sediment transport formula can lead to inaccuracies in model outputs, potentially resulting in misleading conclusions about sediment transport patterns, erosion rates, and deposition locations within the river network. Therefore, selecting the correct sediment transport formula is essential for ensuring the model's validity and enhancing the understanding of sediment connectivity and river system dynamics (Tangi et al., 2019).

The comprehensive evaluation of sediment dynamics within the Po River basin, utilizing the Engelund and Hansen sediment transport formula, in conjunction with satellite imagery, has provided valuable insights into the morphological evolution and sediment budget of the river system. By comparing model outputs with observed data from satellite images, particularly focusing on erosion and deposition trends, this study has advanced the understanding of the complex interplay between natural processes and anthropogenic influences shaping river morphology.

The analysis revealed a significant correspondence between simulated sediment budgets and satellite images, indicating the model's capability to replicate real-world sediment dynamics over short timescales. Notably, simulations demonstrated trends in specific reaches, which did not align with historical morphological evolution as documented in previous studies. However, it is essential to recognize that while the model captures short-term trends, long-term morphological adjustments may deviate from historical patterns due to changing environmental conditions and human interventions. Moving forward, continued monitoring and modeling efforts, informed by advances in remote sensing technology and hydrological modeling techniques, will be essential for capturing the evolving dynamics of river systems and informing effective management strategies.

The use of the D-CASCADE model, like any modeling approach, comes with inherent uncertainties that can impact the accuracy and reliability of its predictions. For instance, the accuracy and availability of input data such as sediment grain size distribution, hydrological data, and geomorphic parameters may lead to biased simulations and affect the model's predictive capabilities. In addition, the grid-based structure of D-CASCADE typically represents the river network in a simplified manner, with discretized grid cells that may not fully capture the intricacies of certain hydro-morphological processes (Tangi et al., 2022), so by incorporating add-ons, the model can account for specific phenomena or interactions that require a more detailed representation.

Besides that, uncertainties can arise from the simplifications and assumptions made in the model structure and algorithms. Assumptions about sediment transport processes, channel morphology evolution, and connectivity dynamics may not fully capture the complexity of real-world systems, introducing uncertainties into the model outputs. Addressing these uncertainties requires sensitivity analyses, uncertainty quantification methods, and robust validation procedures to improve the reliability and robustness of the D-CASCADE model for predicting sediment transport dynamics and (dis)connectivity processes in river networks.

In conclusion, the simulations performed in this study demonstrated significant potential in forecasting future patterns of sediment transport in the Po River basin. Through the integration of dynamic, network-based sediment (dis)connectivity modeling, D-CASCADE can replicate the temporal and spatial progression of sediment supply and distribution throughout a network scale, and its predictive capabilities can provide valuable insights for environmental planning initiatives, helping to inform strategies for sediment management, erosion control, and habitat restoration within river basins.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Simone Bizzi, and the entire research group for their invaluable guidance, mentorship, and unwavering support throughout this research journey. Their expertise, confidence, patience, and encouragement have been instrumental in shaping this study and my growth as a researcher. This work would not have been possible without the support and contributions of all those mentioned above. Thank you for being an integral part of this journey.

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