Modelling sediment transport at network scale and implications for river management: the case of the Po River (Italy)

Modélisation du transport de sédiments à l'échelle du réseau fluvial et implications pour la gestion des rivières : le cas du Fleuve Pô (Italie)

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RÉSUMÉ

Avec ses 17 millions d'habitants, la plaine du Pô héberge l'une des rivières les plus anthropisées en Europe. Etant donné sa forte population, il est nécessaire de comprendre et planifier les trajectoires en termes de flux de sédiments et changements morphologiques. Les données sur le transport de sédiments sont plutôt rares, et le dernier relevé à l'échelle du Pô date des années 2005-2006. Un nouveau plan de gestion des sédiments est en cours, cependant les données de bathymétrie et de flux de sédiments restent limitées. Récemment, le plus grand projet de restauration jamais proposé en Italie a été lancé, ayant pour but de réouvrir plus de 15 chenaux secondaires le long du Pô. Dans ce contexte, une meilleure compréhension de la dynamique des sédiments le long du Pô est requise pour une gestion plus efficace du fleuve. L'utilisation de la modélisation numérique à l'échelle du réseau fluvial peut constituer une aide à la décision. Cette étude présente l'application du modèle numérique DCASCADE au fleuve Pô. Nous estimons flux et budgets de sédiments, ainsi que la connectivité entre tronçons du fleuve, et nous évaluons la sensibilité du modèle à des paramètres incertains. Malgré le manque de données pour une validation approfondie, les flux simulés coïncident avec les dernières estimations de 2005-2006. Nous discutons comment mieux valider le modèle, c'est-à-dire, via l'utilisation de trajectoires morphologiques récentes, acquises de mesures de terrain (*DODs*) et d'images satellites.

ABSTRACT

With about 17 million inhabitants, the Po Plain hosts one of the most human-impacted rivers in Europe. Given the large population, it is crucial to understand and plan its trajectory, in terms of sediment fluxes and morphological changes. Information on sediment transport is very scarce and the last survey at the network-scale dates back to 2005-2006. A new sediment management plan is ongoing, but data on river bathymetry and sediment transport fluxes remain limited. In recent years, one of the largest restoration projects ever proposed in Italy was launched on the Po River, aiming to reopen over 15 secondary channels along its main stem. In this context, a better understanding of sediment dynamics across the Po River network is needed for a more effective management. This can be supported by the use of network-scale numerical models to make better-informed decisions. The present study applies the DCASCADE model to the Po River. We estimate sediment fluxes, budgets, and reach connectivity, and evaluate the sensitivity of uncertain model parameters. Despite lacking data for in-depth validation, the simulated fluxes are consistent with the last estimate carried out in 2005-2006. We further discuss plans for better validating the model, e.g. the use of recent morphological trajectories acquired from field measurements (*DODs*) and satellite images.

KEYWORDS

Geomorphic changes, large-scale modelling, Po River, river restoration, sediment connectivity.

Changements morphologiques, connectivité sédimentaire, Fleuve Pô, modélisation à large échelle, restauration des rivières

1 INTRODUCTION

The Po River is one of the most anthropized fluvial system in Europe. It has been subjected to remarkable anthropic pressures in the last century leading to geomorphic changes and channel adjustments, such as a significant decrease of active channel width in some portions of the river (Brenna et al., 2024). An important restoration project has recently started aiming at increasing river planform mobility thanks to the reopening of several secondary channels along the main stem. However, a thorough assessment of the river's current and potential future geomorphological evolution is missing.

To better understand and predict river geomorphic changes, it is crucial to analyze sediment fluxes and how they propagate along the network (i.e., how sediment sources and sinks are connected). Network-scale sediment numerical models are a precious tool for evaluating sediment connectivity and guiding the understanding of river sediment dynamics in its globality (Brierley et al., 2022). Using physical-based assumptions and simplified reach geometries, they can simulate long periods of time, providing quantitative insight into sediment volume movements and how they can change under different (e.g., hydrological) conditions. We apply the numerical network scale model DCASCADE to the Po River, to evaluate sediment dynamics and trajectories over the last 16 years.

2 METHODS

2.1 DCASCADE applied to the Po River

The DCASCADE (Dynamic CAtchment Sediment Connectivity And DElivery) model combines concepts of network modelling with empirical sediment transport formulas to quantify spatiotemporal sediment connectivity in river network (Tangi et al., 2022). It is a dynamic adaptation of the model CASCADE, which offers a static representation of sediment trajectories from source to sinks (Schmitt et al., 2016; Tangi et al., 2019). In the dynamic version, sediment layers can be formed and remobilized at further time steps. Multiple sediment sizes can be modelled for a more comprehensive representation of sediment mobilization and transfer processes.

The river network simulated represents the main stem of the Po River between Torino and the entrance of the Po delta (~500 km), and includes also the most downstream part (~7 km) of the main tributaries (Figure 1,c). It is subdivided into geomorphologically homogeneous reaches, defined also by uniform geomorphic attributes (slope, active width, initial grain size distribution) that were measured from satellite images, DEM, and fieldwork. Modelled daily discharge time series from 2008 to 2023 are used as input for each reach in the model. They were provided by the *CIMA* foundation (*International Center for Environmental Monitoring*) and generated using the model FloodProof (Laiolo et al., 2013). Since the Po River is gravel-bedded in the upper part and sandy in the lower one, we use Wilcock and Crowe's transport formula (Wilcock and Crowe, 2003).

2.2 Past bedload flux estimations

Very few direct sediment measurements are available for model validation in the Po River. In this study, we have yearly sediment fluxes estimated from field observations of erosion and deposition volumes between 1982 and 2002 (Sediment Management Plan, (AdBPO, 2008)). On a yearly average, these estimations indicate bedload volume between 4 and 5 million m^3 in the downstream part of the river (i.e., reaches 24-33, located between Taro and Panaro confluences).

3 RESULTS AND DISCUSSION

The yearly fluxes calculated with the model between Taro and Panaro are on average ~1.8 million m^3/y, with a significant variability depending on the year. The lowest year (2022) transports ~0.6 million m^3 of sediments, and the highest year (2014) ~3.7 million m^3 (Figure 1, a). Comparing to the *PGS* estimation between 1982 and 2002, the present estimations are coherent in terms of magnitude, even if they are slightly lower. It is important to note that differences may arise due to the two different periods we are comparing mostly in terms of hydrology (1982- 2002 vs 2008-2023). In addition, the use of daily discharge in the model does not allow to account for sub-daily peaks of discharge, which could be another reason for the observed underestimation.

The model also provides sediment budgets, indicating morphological trajectories per reach, either depositing, eroding, or equilibrium conditions (Figure 1,b). Considering the lack of sediment flux data over the modelled period (2008-2023), these trajectories can be used to validate the model, when compared to available information on in-channel elevation changes. Planimetric changes observed by satellite, now increasingly available, can also be a source of indirect information on the channel morphological change, for example, a change in active width over the years can indicate channel bed level change.

In parallel of this work, DoDs (DEM of Differences) are currently being generated using DEMs with bathymetry available for 2005 and 2021, providing net bed level change between the two surveys, which corresponds more or less to the period modelled with DCASCADE (2005-2021 vs 2008-2023). Sentinel 2 satellite data series from 2017 to now, with high temporal and spatial resolution (10m, every 5 days) are also available and automatically classified monthly by water, sediment, and vegetation cover inside the active channel (Bozzolan et al., 2023). By integrating both types of information, we aim at validating the DCASCADE simulations and generating a model capable to reproduce, within a structural uncertainty, the Po River sediment connectivity: source, sinks, provenances, and fluxes.

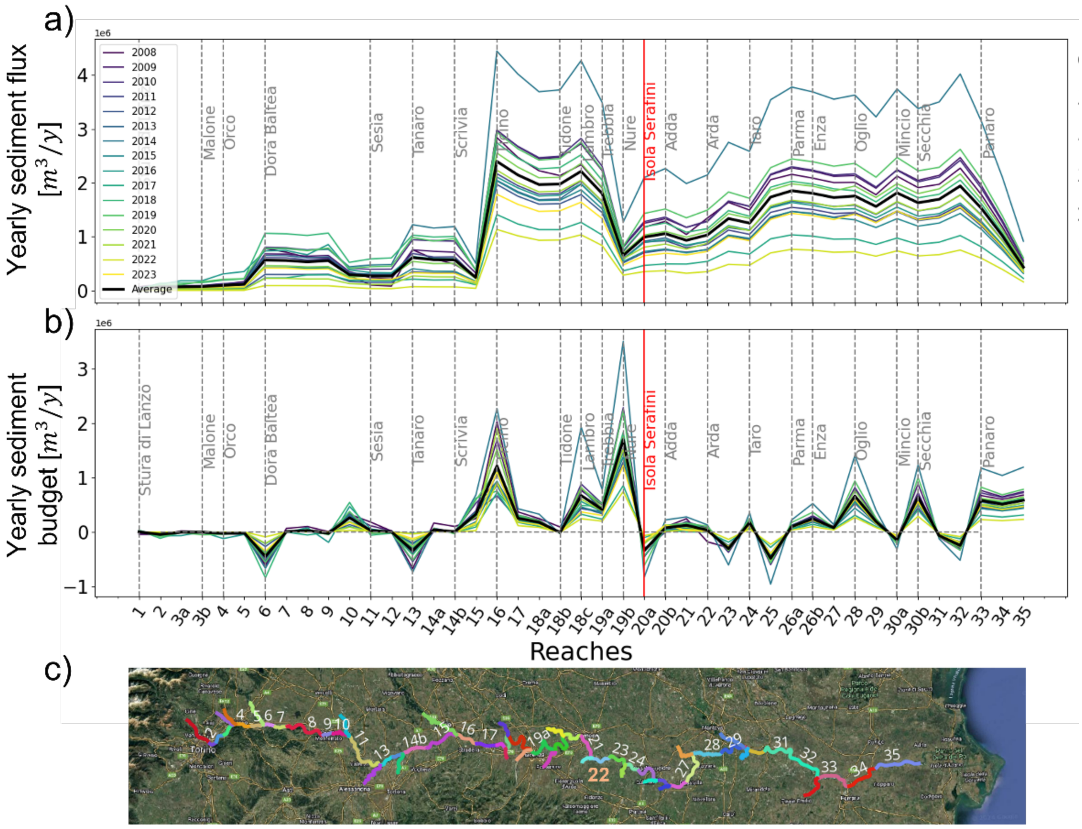

Figure 1: (a) Yearly total sediment fluxes and (b) sediment budget per reach along the main stem of the Po River, simulated with DCASCADE. In the sediment budget, positive and negative values indicate respectively net deposition and erosion. (c) The Po River network subdivided into geomorphologically homogeneous reaches.

Once confident of the model's input configuration and results, sediment transport simulations can be analyzed, for example, under different hydrological scenarios or to better identify those areas of the river network that most contribute to sediment (dis)connectivity. The model, in fact, enables the analysis of reach sediment properties through time (Figure 2), but also by provenance (Figure 3). Figure 3, for example, shows the provenance of the sediment transported during the simulation time in reach 22, which is located at the confluence of the Arda River (blue star in Figure 3). Results indicate that most sediments come from the reaches located just after the Isola Serafini dam (20a and 20b) but also significantly from the Ticino River, which is upstream of the dam (Figure 3). The identification of sediment sources and sinks, reaches trajectory, and sediment provenance along the Po River is key to support future river management and restoration measures, like the ongoing large restoration scheme planned in the Po.

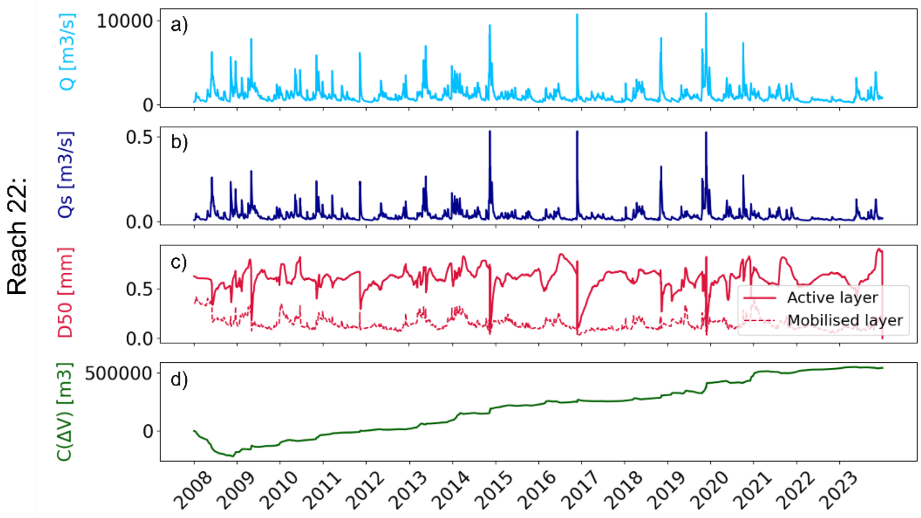

Figure 2: Time series of input discharge Q (a), simulated sediment flux Qs (b), simulated D50 in the active layer and in mobilized layer (c), and cumulative sum of sediment budget (d), in reach 22 (see Figure 3c). The active layer is the volume considered active in terms of transport, i.e. used to compute the transport capacity (here, the active layer is computed as twice the D90). The mobilized layer is the sediment volume that is entrained and transported across the reach.

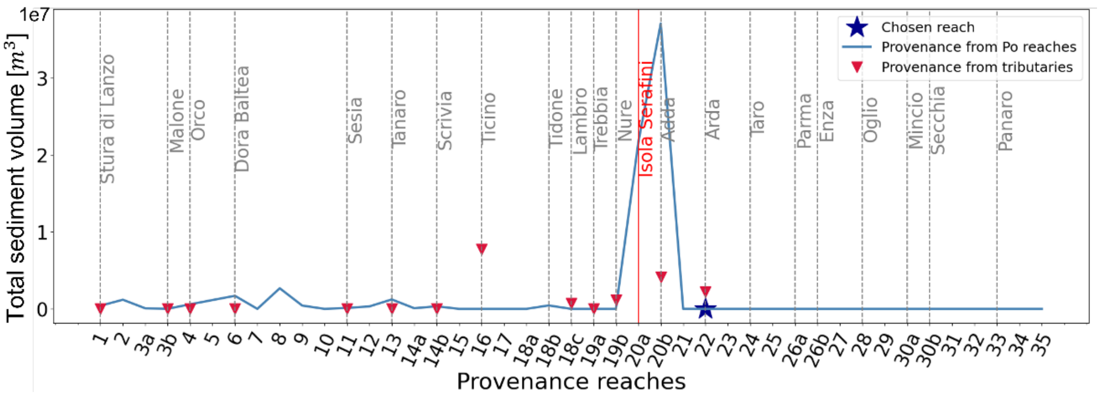

Figure 3: Total sediment volumes provenance, transported to reach 22 (chosen reach). The total is summed over the 16 years of the simulation. The blue line indicates volumes coming from the main stem. The red triangles indicate volumes coming from the tributaries.

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