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Restoring sediment continuity in large regulated rivers: a 2D-informed 1D morphodynamic framework applied to the Hungarian Danube

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Sustainable sediment management in large, regulated rivers requires modelling tools that can reliably predict long-term morphological trends while remaining computationally efficient for scenario testing. This study presents a simplified one-dimensional (1D) morphodynamic framework parameterized using effective flow conveyance and sediment transport widths extracted from a calibrated two-dimensional (2D) hydrodynamic model. The approach corrects a key limitation of conventional 1D models, which implicitly assumes that the entire cross-section is hydraulically and morphologically active. The method was applied to a 100-km gravel-bed reach of the Hungarian Danube, where sediment deficit caused by the upstream hydropower-plant impoundment and extensive training works have caused persistent bed degradation, reaching 5 m erosion at places. The model was validated against measured water levels, two multi-year bathymetric datasets, and a bedload rating curve derived from direct field measurements. Using total or constant channel widths substantially distorted predicted erosion–deposition patterns, whereas the 2D-derived effective widths reproduced both the magnitude and spatial distribution of observed bed changes. Long-term simulations (2005–2035) show continuing riverbed incision of ~0.8 m in the most active 20 km. A widening scenario (1.5× effective width), modelling the removal of river training works, reduced incision by ~50%, while targeted sediment feeding (10,000 m^3/yr) produced local mitigation with weaker downstream propagation. The study demonstrates that 2D-informed 1D morphodynamic modelling provides a transparent and computationally light decision-support tool suitable for evaluating sediment management strategies in large, engineered rivers.

KEYWORDS
1D model, Danube River, effective width, river morphodynamics, sediment management, sediment transport

1 Introduction

Hydromorphological alteration has become one of the most pervasive stressors affecting freshwater ecosystems across Europe. Decades of channelization, bank stabilization, hydropower development, dredging activities, and disconnection of floodplains have profoundly modified river corridors, reducing habitat diversity, altering sediment continuity, and diminishing ecological resilience (Walling and Fang, 2003; Gregory, 2006; Kondolf et al., 2014; Habersack et al., 2019). In many large rivers, the interruption of sediment supply and the confinement of channels have driven persistent bed degradation, with consequences that propagate well beyond geomorphology—affecting riparian vegetation, aquatic biodiversity, flood risks, navigational conditions, hydropower production, drinking water supply, recreational activities, nutrient dynamics as well as groundwater–surface water interactions. For instance, In the Danube River, the suspended sediment flux to the Black Sea has declined by more than 60% since the early 20th century due mainly to dam-induced sediment trapping and channel stabilization, contributing to reduced downstream sediment supply and ongoing delta and coastal erosion (Habersack et al., 2019). In the Rhine River, channelization and flow regulation have produced long-term sediment deficits and channel incision, with historical erosion rates of up to ~7 cm/yr, widespread floodplain disconnection, and persistent downstream sediment imbalance (Krapesch et al., 2024). In the Mississippi River, leveeing, channel cutoffs, revetments, and dike construction since the 1920s have reduced overbank inundation and floodplain sediment storage by >90% and suppressed bank erosion as a sediment source, while additional sediment deficits arise from dam construction on major tributaries, together driving long-term channel adjustment and reduced channel–floodplain connectivity (Kesel, 2003).

Recognizing these pressures, the Water Framework Directive (WFD; European Parliament and Council, 2000) and recent European river-restoration initiatives (European Commission, 2007; European Commission, 2022) emphasized the restoration of sediment continuity and hydromorphological functioning as essential components of achieving good ecological status. Measures such as channel widening, removal or modification of training structures, and sediment feeding are increasingly implemented to counteract incision, improve habitat conditions, restore dynamic processes that support biodiversity, enhance navigability, reduce flood risk, and improve channel–floodplain connectivity (e.g., Surian and Rinaldi, 2003; Ock et al., 2013; Peirce et al., 2021). Designing such interventions, however, requires an understanding of how regulated river systems evolve over decadal scales under ongoing sediment imbalance, and how different management options may modify these trajectories.

Numerical models play a central role in this decision-making process. While two-dimensional (2D) and three-dimensional (3D) models can capture local hydraulic and morphological complexity, their computational demand limits their application to long-term or basin-scale planning (e.g., Wu and Wang, 2004; Fischer-Antze et al., 2008; Siviglia et al., 2013; Török et al., 2020; Balouchi et al., 2024; Pomázi and Baranya, 2025). One-dimensional (1D) models remain indispensable for evaluating multi-decadal trends, yet conventional formulations assume that the entire wetted width participates equally in flow conveyance and sediment transport (Parker, 2004; El kadi Abderrezzak and Paquier, 2009; Lauer et al., 2016; Zhou et al., 2019). In large, trained rivers with groyne fields, and inactive lateral zones, this assumption does not hold and can lead to substantial errors in predicted sediment fluxes and morphological change (Camenen et al., 2011; Rindler et al., 2023).

To address this gap, a hybrid 1D–2D morphodynamic modelling framework is developed in this study in which effective flow conveyance and sediment transport widths are extracted from a calibrated 2D hydrodynamic model. This approach retains the computational efficiency of a 1D model while incorporating essential spatial information on active river corridors, enabling more realistic predictions of long-term sediment dynamics under regulated conditions.

This framework is applied to a 100-km gravel-bed reach of the Hungarian Danube—one of the most hydromorphologically stressed segments of the river system—where the combined effects of upstream hydropower, historical dredging, and intensive river training have produced substantial bed degradation and associated ecological impacts. The aims of this study are to: i) evaluate the performance of the hybrid modelling framework against bathymetric and sediment transport observations; ii) quantify long-term morphological trends under persistent sediment deficit; and iii) illustrate how the modelling framework can assess the impacts of potential restoration-oriented measures, including channel widening and sediment feeding, to mitigate hydromorphological stress and support more sustainable river functioning.

By linking process-based morphodynamic modelling with restoration-oriented scenario analysis, this study contributes tools and insights relevant for freshwater ecosystem management, highlighting pathways to reduce hydromorphological stress and improve the ecological condition of large, regulated rivers.

2 Methods

2.1 Case study

The study area is the Slovak–Hungarian reach of the Danube River, which is a free-flowing section of the river (Figure 1). Along this reach, the main channel width, at mean flow, varies between 200 and 500 m, with an average water depth of approximately 5 m. The mean river slope is 10 cm/km; however, within the study area, the Danube transitions from an upper-reach character to a middle-reach character (Török and Baranya, 2017), with the average slope decreasing from 20 cm/km to 7 cm/km. The riverbed material is predominantly gravel, with an average grain diameter of 0.009 m. Significant river regulation interventions have been carried out in this area since the late 19th century. The banks were stabilized using riprap, groyne fields were constructed, and flood protection levees were built in the floodplain (Nyiri and Török, 2024).

In the mid-20th century, extensive industrial gravel extraction took place, followed by the construction of two hydropower plants (HPP) near the upstream end of the study area in the early 1990s (Holubová et al., 2004). These interventions have led to the deepening of the riverbed, reaching up to 5 m in some places (Rákóczi, 2000). According to previous studies, over the last decades, the average riverbed degradation has been around 2 cm/year (Nyiri and Török, 2024). However, due to the complex bed topography and the interacting effects of the various interventions, bed degradation is not uniform, on some shorter sections, local aggradation has also been observed instead (Rákóczi, 2000; Török and Baranya, 2017). The deepening of the riverbed has resulted in several adverse effects, including the sedimentation of side branches, a decrease in groundwater levels, a lowering of water levels in tributaries, and the emergence of navigational issues (Habersack et al., 2019),

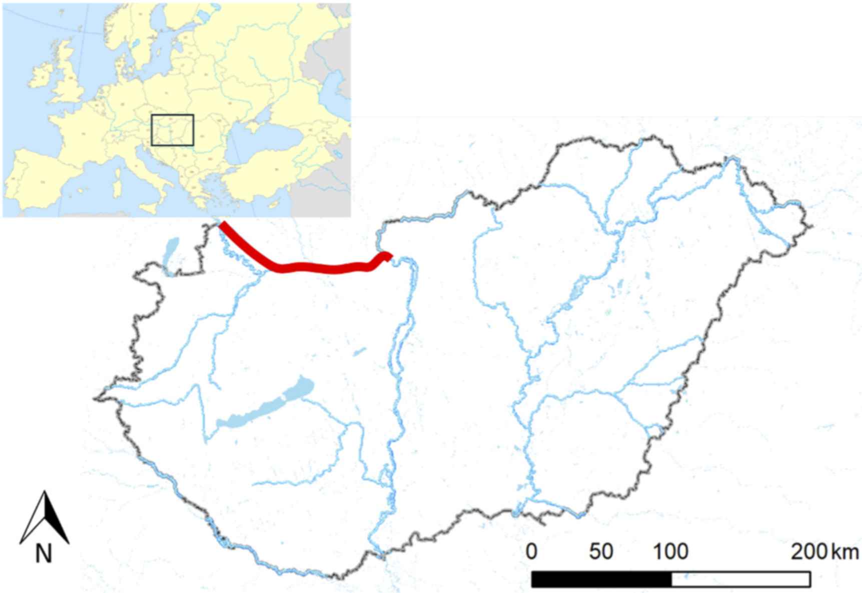

FIGURE 1
Study reach of the Danube River in Hungary (indicated with red).

making it a representative European large-river section for evaluating sediment-based restoration measures.

2.2 Model development

The modelling system couples a quasi-steady 1D flow module with a bedload-based 1D morphodynamic module for the Danube section between rkm 1710–1810. The novelty lies in parameterizing both flow conveyance and sediment transport using effective widths derived from a calibrated 2D hydrodynamic model. This preserves computational efficiency for multi-decadal simulations while incorporating key spatial information on hydraulically active channel zones.

2.2.1 Flow model

The modelling was done using a self-developed tool. For the flow analysis, a mathematically simple approach was used based on solving the one-dimensional gradually varied flow equation, coupled with a sediment transport and morphodynamic model, with the method suggested by Parker (2004). The novelty of the 1D model lies in its parameterization, which was derived from the results of a previously developed and validated 2D model for the study reach (Füstös et al., 2021). In the 1D framework, quasi-steady flow conditions along the entire study section are assumed. This approach is considered to be sufficient for this study because: i) long-term bed change is controlled primarily by cumulative transport capacity rather than short-duration dynamic effects; ii) the focus here is rather on decadal-scale trends and testing management scenarios—not event-scale morphological response. Eventually, this approach allows multi-decadal simulations at very low computational cost, essential for exploring multiple management scenarios.

The gradually varied water surface profile is calculated using Equation 1:

$$\frac{dH}{dx} = \frac{S - S_f}{1 - Fr^2} \tag{1}$$

where H is the water depth at the cross section, x is the longitudinal coordinate along the river axis, S is the bed slope, S_f is the energy slope, and Fr is the Froude number.

The Froude number is computed (Equation 2) based on the cross-sectionally averaged flow velocity U, gravitational acceleration g (9.81 m/s^2), and local water depth H:

$$Fr^2 = \frac{U^2}{gH} \tag{2}$$

The energy slope Sf is determined (Equation 3) using the Froude number and a dimensionless channel resistance coefficient C_f, to be calibrated:

$$S_f = C_f Fr^2 \tag{3}$$

As input data for the model, the bed elevation and width of each cross section must be specified. For each section, the channel width that best represents the bankfull conditions is assigned, as these discharges are considered the most morphologically active flows (Parker, 2004). While this bankfull width is prescribed as the initial geometric parameter, it is subsequently modified to an effective flow width based on hydraulically active zones, as described in the followings. Cross-sections are spaced at 500 m intervals and represented as simplified rectangular sections, allowing rapid morphology updates at each time step. This resolution is consistent with typical long-reach Danube modelling studies and reflects the scale at which sediment management decisions are taken.

A calibrated 2D hydrodynamic model (Füstös et al., 2021) was used to determine the effective width for flow conveyance, B_{eff}. The referred 2D flow simulations were performed using the Adaptive Hydraulics Modeling System (AdH), a depth-averaged finite-element solver of the shallow-water equations. The model was applied to the Danube reach between rkm 1811 and 1708 (Sap–Szob), including groynes, training walls, islands, and major tributaries, and was run for low-, mean-, and flood-flow conditions. The 2D model provided spatially distributed fields of water depth and depth-averaged velocity. Under typical mean-flow discharge (≈2,200 m^3/s), spatial maps of specific flow discharge $q = U\,H$ were extracted from the 2D model results, and these maps were subsequently used to determine the effective flow width (B_{eff}) at each 1D model cross section by excluding low-activity marginal zones where q < 1 m^2/s from the total channel width. This threshold was based on a preliminary analysis of 2D flow field showing negligible contribution to conveyance below this value.

Using the 2D model, the average bed elevation z and the effective channel width B_{eff} for each 500-m cross section were extracted. Two different methods were used to determine bed levels depending on the purpose of the simulation: i) for flow model calibration, water level data recorded during the historic low flow event of 2018 was used, and thus adopted the 2018 bathymetric survey as a basis; ii) for morphodynamic simulations covering changes from 2005, we used the 2005 bathymetric survey as the initial condition.

The flow velocity for each cross-section was calculated by Equation 4:

$$U = \frac{Q}{B_{eff}H} \tag{4}$$

2.2.2 Morphodynamic model

The morphodynamic module of the model is responsible for simulating the longitudinal and temporal changes in bed elevation. It is not independent from the flow module; rather, the two are coupled and operate together. The morphological evolution of the Danube riverbed is simulated through an iterative time-stepping process: at each time step, the flow module computes the cross-sectionally averaged water depth, flow velocity and bed shear stress under the given hydrological conditions, as described in the previous section. These outputs are then used by the morphodynamic module to estimate the vertical bed level change at each cross section. The model then proceeds to the next time step.

The theoretical foundations of the morphodynamic module are based on the following relationships. The bed shear stress b, which characterizes the capacity of the flow to initiate sediment motion, is estimated (Equation 5) using the flow velocity U and the bed resistance coefficient C_f:

$$\tau_b = \rho C_f U^2 \tag{5}$$

To determine sediment transport characteristics for the given section of the Danube, the Shields parameter, or dimensionless bed shear stress, τ^* is calculated based on Equation 6:

$$\tau^* = \frac{\tau_b}{\rho R g D} \tag{6}$$

where R is the submerged specific gravity of sediment, D is the mean grain diameter.

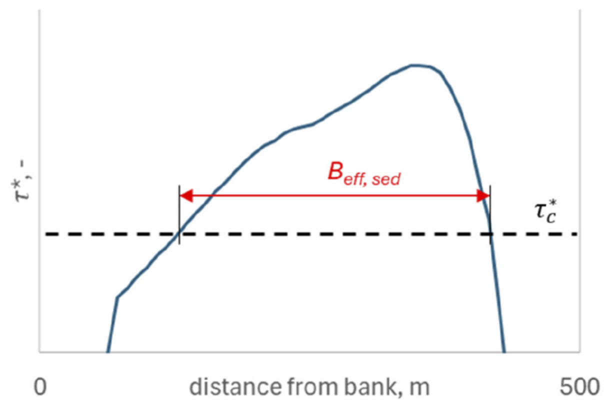

FIGURE 2
Determination of effective sediment transport width based on cross-sectional bed shear stress distribution.

For sediment density, we typically assume quartz with a density ρ_s = 2,650 kg/m^3. With water density ρ = 1,000 kg/m^3, this gives $R = \rho_s/\rho - 1$ = 1.65. The grain diameter D was determined from bed material sampling along the study reach, carried out by physical grab sampler. More details about the bed material data can be found in the related deliverable of the DanubeSediment project, implemented in the Interreg Danube Transnational Programme (DanubeSediment, 2019). Based on the DanubeSediment project the bed material along the study reach can be characterized by a constant value of 0.009 m.

Most sediment transport formulas in the literature are expressed in a dimensionless form, as introduced by Einstein (1950). The dimensionless bedload transport rate q* is given by Equation 7:

$$q^* = \frac{q_b}{D\sqrt{gRD}} \tag{7}$$

where q_b is the specific bedload transport rate (volume per unit width).

Since empirical transport formulas are typically developed under specific experimental conditions, their applicability depends heavily on sediment characteristics, especially grain size (e.g., Meyer-Peter and Müller 1948; van Rijn, 1984; Parker, 1990; Wilcock and Crowe, 2003). As the Meyer-Peter and Müller (1948) formula was originally developed for grain sizes ranging from 0.4 to 29 mm in bedload-dominated flows, the equation (Equation 8) was adapted here and applied using a representative grain size of 9 mm:

$$q^* = 8\,(\tau^* - \tau_c^*)^{3/2} \tag{8}$$

where q^* is the dimensionless bedload transport rate. The critical Shields parameter τ_c^* defines the threshold for sediment motion. While a value of 0.047 was suggested by Meyer-Peter and Müller (1948), some experiments indicated continuous motion already at 0.03 (Buffington and Montgomery, 1997). In this model, both the critical Shields parameter value and the exponent in the transport formula were calibrated.

The dimensionless transport rate can be converted to specific transport using Equation 7, which represents the sediment volume transported per meter width. Multiplying this by the relevant width of the flow section yields the total cross-sectional bedload transport rate. However, this step includes a correction based on the higher-resolution 2D hydrodynamic model. Previous studies have shown that bedload transport does not occur uniformly across the entire cross-section but is typically concentrated within an effective sediment transport width $B_{eff,sed}$ (see, e.g., Camenen et al., 2011; Rindler et al., 2023). The 2D model provides spatial distributions of bed shear stress, allowing us to identify the parts of each cross section where the shear exceeds the critical threshold under mean flow conditions. For the sediment transport calculation, only this part of the total cross-section width was considered (Figure 2). Accordingly, the cross-sectional bedload transport (given in mass/time) was calculated as $Q_b = q_b \times \rho_s \times B_{eff,sed}$.

Changes in bed elevation are driven by the longitudinal variability in sediment flux. Where incoming sediment transport ($Q_{b,IN}$) exceeds outgoing transport ($Q_{b,OUT}$), deposition and bed aggradation occur. Conversely, if outgoing transport is greater, bed degradation results. change is quantified using a volume continuity equation (Equation 9) for each model segment (Paola and Voller, 2005):

$$\Delta z = \frac{Q_{b,IN} - Q_{b,OUT}}{B\Delta x} \Delta t\,(1-\lambda) \tag{9}$$

where Δz is the bed elevation change, Δx = 500 m is the distance between cross sections, Δt = 86,400 s is the time step (1 day), λ = 0.25 is the porosity of the sediment, assumed for sand-gravel mixtures (Church, 2006).

The reach is dominated by relatively uniform coarse material, and field sampling showed limited longitudinal fining, justifying the use of a representative grain size. This simplification is reasonable for long-term incision-focused studies, though future extensions may include fractional transport as suggested by Török and Parker (2025). Because the reach is gravel-dominated and bedload controls long-term bed changes, suspended sediment processes were not included.

2.3 Field data for model parameterization, calibration and validation

For model calibration and validation, field measurements of water levels, bed elevations, and bedload transport rates were used. A detailed longitudinal water level survey was conducted in 2018 during a low-flow period, and these measurements could directly be compared to the water levels computed by the model. Additionally, for validating the flow model under mean flow conditions, we used water surface profiles simulated by the previously established 2D hydrodynamic model.

To validate the morphodynamic model, results from repeated bathymetric surveys were used. Bed surveys conducted in 2005, 2010, and 2018 along the study reach provided observed bed level changes for model validation. The bathymetric measurements were performed using a single-beam echo sounder with a longitudinal spacing of approximately 100 m, which is substantially finer than the model cross-section spacing of 500 m. This resolution allowed for a direct and robust comparison between simulated and observed bed level changes. As with the modeling approach, the cross-sectionally averaged bed levels were computed over the effective flow conveying parts of the channel, based on the previously described method.

To further validate the sediment transport model, we used the results of a bedload measurement campaign carried out in recent years at a selected cross section of the study reach. The multi-year dataset was used to establish a flow discharge-bedload transport relationship, i.e., a bedload rating curve, across a relatively wide range of discharges. These relationships were developed using a combination of direct and indirect measurement methods (Baranya, 2024).

3 Results

3.1 Flow model validation

As described previously, the model was developed based on the 2018 riverbed geometry measurements and the results of the 2D hydrodynamic model under mean-flow conditions. Based on the simulated specific discharge field, zones with values below 1 m^2/s were excluded, as preliminary analysis indicated that these areas do not contribute significantly to flow conveyance (Figure 3).

Based on the 2D map, cross-sectional width data were extracted at 500-m intervals. On average, the effective cross-sectional width relevant for discharge transport (B_{eff}) was reduced to about 70% of the original width (Figure 4). The model was run under low-flow (Q = 950 m^3/s) and mean-flow (Q = 2,200 m^3/s) conditions, assuming steady-state conditions. The calibration parameter of the flow model was the channel roughness factor C_f, which was uniformly set to 0.0033 along the entire reach.

The simulated water surface profiles (Figure 5) clearly show that the studied reach can be divided into an upper section with steeper slope and a lower section with lower slope, with the break point around rkm 1785, similarly to the results previously presented by, e.g., Nyiri and Török (2024). Over the entire study reach, the model satisfactorily reproduced the measured water levels (low-flow case) and the 2D-modelled water levels (mean-flow case). For the mean-flow condition, the difference between the two water surface profiles is negligible. In the low-flow condition, the overall agreement is good, although under- and overestimation can be observed over short sections. The largest deviation is found in the upper reach, where the model underestimates the measured levels by up to 20 cm. The mean absolute error (MAE) is 0.18 m for the low-flow case and 0.07 m for the mean-flow case, respectively.

3.2 Morphodynamic model validation

The morphodynamic model was run with the already calibrated hydrodynamic model. Unsteady simulations were run for the period 2005–2018, with the initial riverbed geometry defined based on the 2005 riverbed geometry survey and using the 2D model-based delineation introduced above.

As the model operates with a time-stepping approach, daily discharge time series and corresponding downstream water levels were defined as boundary conditions for the periods 2005–2018. The use of a daily time step ensures that the full range of hydrological conditions occurring during this period, from low-flow to high-flow events, is explicitly represented in the simulations. As for the sediment transport boundary condition at the upstream boundary zero transport was described, because the model

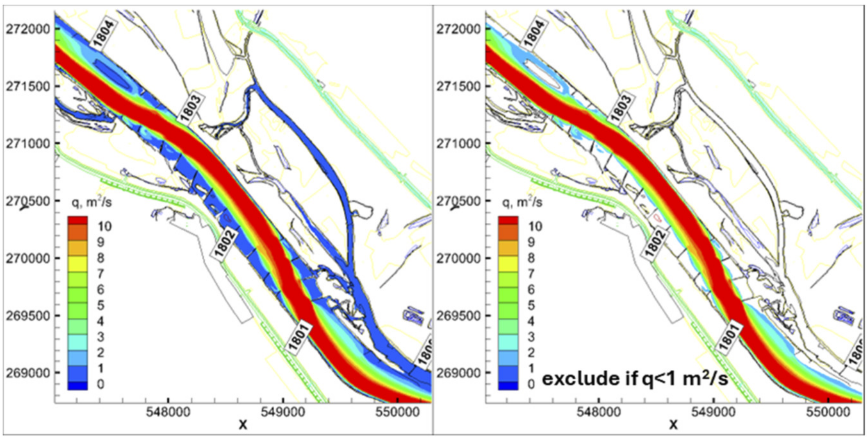

FIGURE 3
Determination of effective flow conveyance width based on 2D simulated specific flow discharge field.

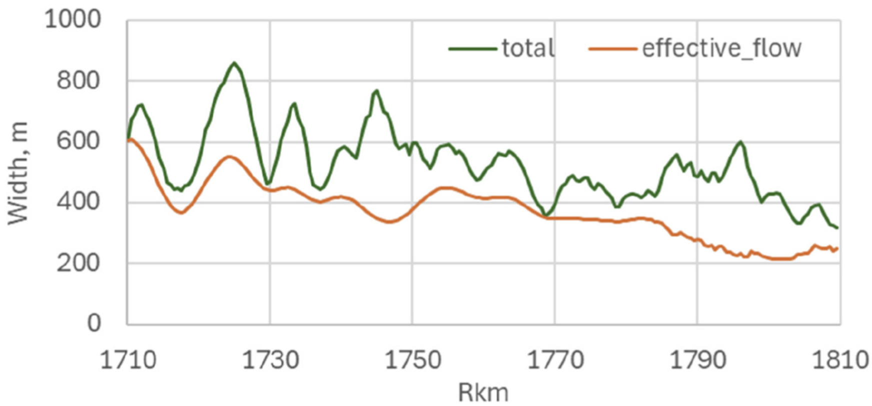

FIGURE 4
Longitudinal variation of actual (total) and effective channel width along the study reach.

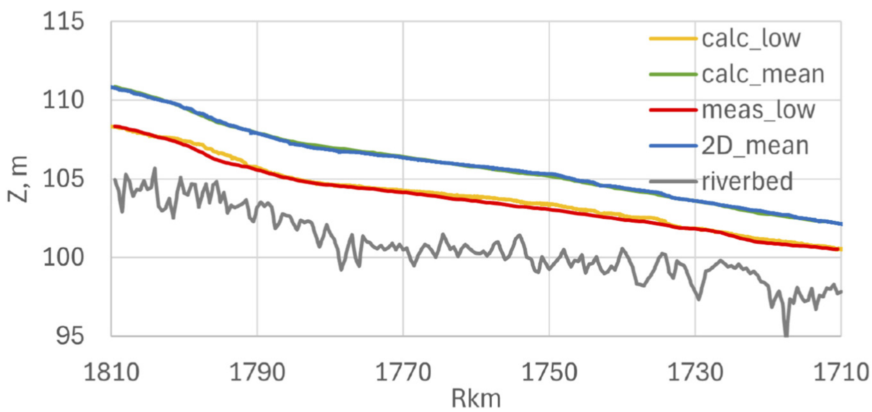

FIGURE 5
Longitudinal variation of riverbed elevations, simulated low and mean flow water levels (yellow and green lines, respectively), measured low (red line) and 2D simulated mean (blue line) water levels.

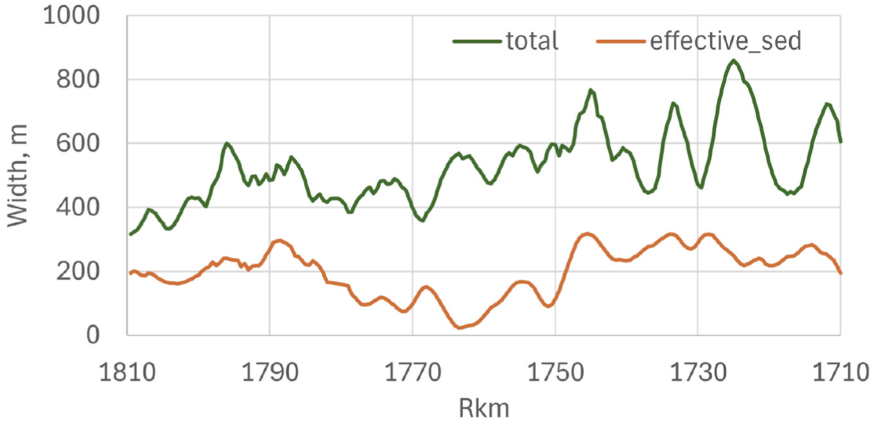

FIGURE 6
Longitudinal variation of actual (total) and effective sediment transport width along the study reach.

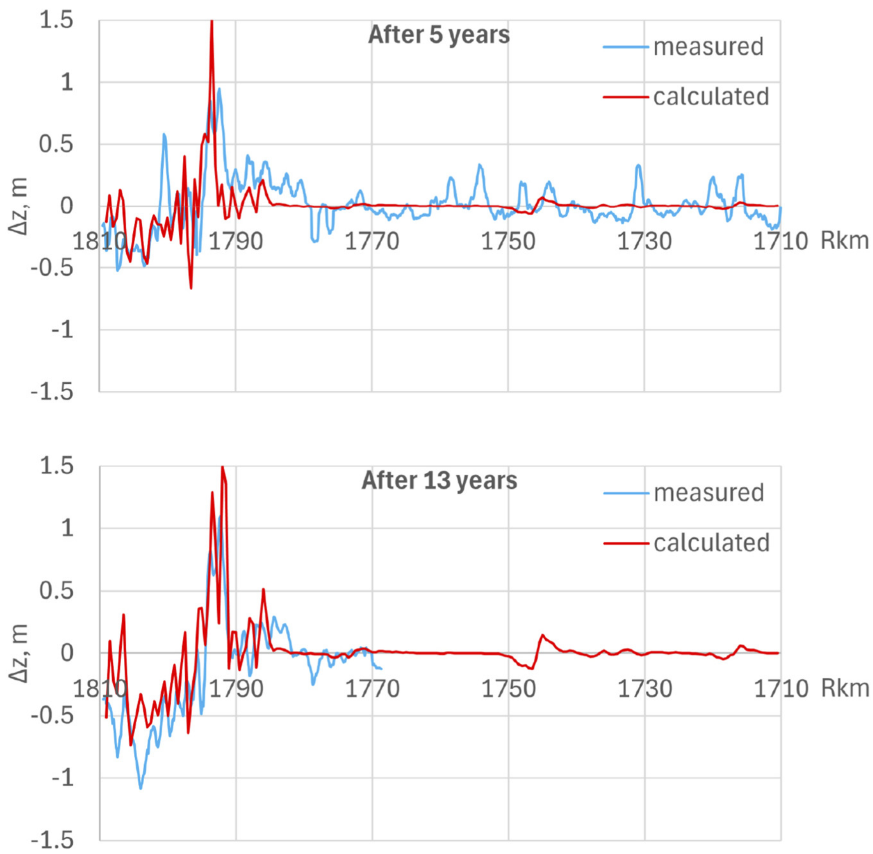

FIGURE 7
Measured (blue) and simulated (red) bed elevation changes after 5 (top, between 2005–2010) and 13 (bottom, between 2005–2018) years, respectively (note that measured bed levels are missing for 2018 between rkm 1710–1770).

domain starts immediately downstream of the artificial diversion channel of the Gabčíkovo HPP, where coarse sediment is effectively intercepted by the impoundment. In this configuration, the bedload continuity from the upper Danube is altered (Habersack et al., 2019), and the reach receives negligible upstream bedload supply under typical operations. Note that a test for close-to-zero bedload transport boundary values was also performed showing low sensitivity on the resulted morphodynamics.

For bed level change computations, the model incorporated the effective channel widths for sediment transport ($B_{eff,sed}$). In each cross-section, only those parts were considered where the bed shear stress computed by the 2D model exceeded the critical Shields

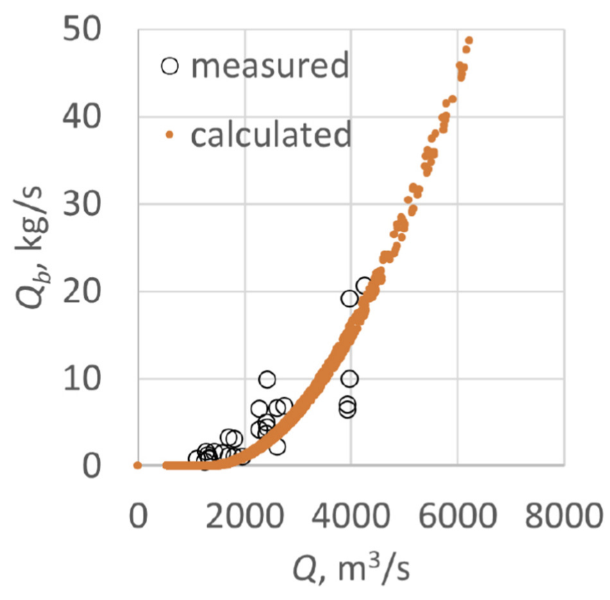

FIGURE 8
Bedload transport versus flow discharge at rkm 1790.6: measured data (Baranya, 2024) and simulated values from the calibrated model (2005–2018).

parameter at the mean flow case. For the entire reach, the effective channel width for sediment transport averaged about 40% of the total channel width (Figure 6).

The sediment transport model was calibrated using the critical Shields stress value and the exponent of the MPM formula, as described above. The best agreement, both in terms of bed level changes and bedload transport rates, was achieved with the $\tau_c^* = 0.03$ for the critical shear stress, and 2.1 for the exponent, respectively. These parameters should not be regarded as universally fixed, but rather as site-specific and subject to calibration, as also suggested by Habersack and Laronne (2002). The model adequately reproduces both the longitudinal and temporal behavior of the bed changes. Local deviations are within the order of 10 cm, but overall, the model captures the patterns of erosion and deposition well. The longitudinal bed level changes simulated by the model were compared to two sets of measured bed change data (Figure 7), collected in 2010 and 2018, respectively, corresponding to time spans of 5 and 13 years (for the latter, only the upper 40 km of the study reach was available). The bed change plots clearly indicate that dynamic bed changes take place in the steeper section of the Danube reach (up to around rkm 1785), while downstream of this point, the riverbed can rather be considered stable. Bed incision is evident between rkm 1810 and 1795, whereas downstream from this section, sediment deposition occurs due to erosion upstream. The maximum depth of incision after 5 years is approximately 0.5 m, increasing to 1 m after 13 years. The maximum deposition already reaches 1 m after 5 years, and later the magnitude remains similar, but the longitudinal extent increases. Moreover, similar to the measurements, the model only indicates dynamic morphological changes in the upper ~25 km of the reach, while the downstream sections are identified as morphologically stable. For the 5-year period, the MAE of simulated bed level changes was 0.14 m, with a slight negative bias (−0.04 m). For the 13-year period, MAE was 0.24 m, respectively, and the bias was small (+0.03 m). These values are within the accuracy range expected for large-river bathymetric surveys and confirm that the model reproduces both the magnitude and the spatial pattern of observed morphological change. Importantly, the model correctly captured the pattern of alternating incision and deposition, which is critical for the intended sediment-management applications.

As for the bedload transport values, the bedload rating curved established by Baranya (2024) for the monitoring section at rkm 1790.6 was used as model validation data. The model reproduces the observed non-linear increase in transport rate with discharge, spanning over two orders of magnitude (Figure 8). Although some scatter is present in the measurements, reflecting natural variability and measurement uncertainty, the agreement between measured and simulated values is satisfactory, particularly in the mid-to high-flow range (>2000 m^3/s), where morphodynamic processes take place.

While validation at a single cross-section is a limitation, it reflects the reality of gravel-bed monitoring in the Danube and similar large rivers, where bedload measurements are difficult and spatially sparse (Habersack et al., 2019). In the context of the present large-scale, long-term application, the combination of longitudinal bathymetric validation and bedload rating curve validation is unique and provides a robust basis for confidence in model behaviour.

3.3 Model sensitivity to channel-width parameterization

To assess the role of the 2D-derived effective width approach in the morphodynamic model, four long-term simulations (2005–2018) were compared (Figure 9):

1. v1: Validated version–spatially varying effective flow conveyance widths (B_{eff}) derived from 2D hydrodynamics, as well as the spatially varying effective sediment transport width ($B_{eff,sed}$).
2. v2: Total width–replacing effective flow conveyance width with the full cross-section width.
3. v3: Constant width–same width for all cross-sections (=370 m, the mean effective width).
4. v4: No τ-based correction–same as validated, but without adjusting effective sediment transport width, i.e., $B_{eff,sed} = B_{eff}$.

The results show that the 2D-derived effective-width parameterization is critical for reproducing observed morphodynamic patterns and magnitudes. In the most active reach (rkm 1795–1810), the validated model predicts persistent, substantial erosion, consistent with observations. When the total channel width is used (v2), the morphodynamic signal is severely distorted: erosion amplitudes are damped and, critically, local deposition appears where only erosion is expected. This inversion arises mainly because the total width counts groyne-field dead zones in the conveyance, reducing unit discharge and shear and thus altering transport gradients. Groyne fields commonly behave as recirculating areas with limited downstream conveyance and intermittent exchange with the main flow, as shown by Uijttewaal (2001) and later laboratory studies on groyne-layout

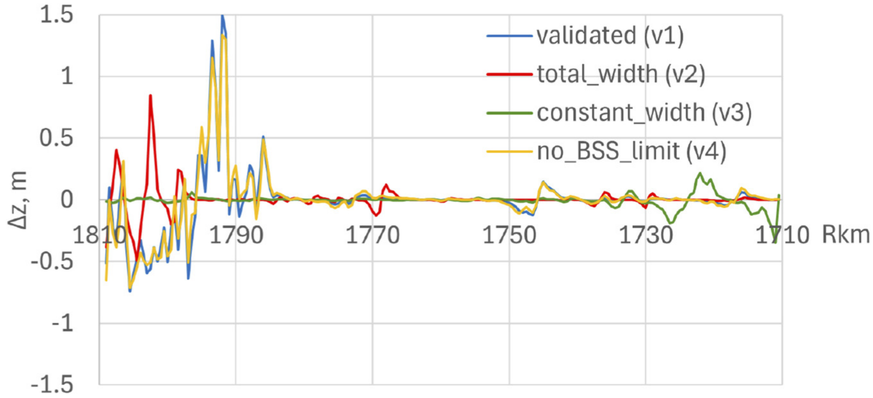

FIGURE 9
Simulated riverbed elevation changes after 13 years for the model scenarios (blue: reference model; red: applying the actual channel width at each cross-section; green: applying constant channel width, equivalent to the mean effective width, along the entire reach; yellow: neglecting the bed shear stress based correction for the effective sediment transport width).

effects and exchange processes (Uijttewaal, 2005; Weitbrecht et al., 2008; Yossef and de Vriend, 2010).

The constant-width case (v3) performs even worse, essentially suppressing the morphodynamic response along the entire study reach. In fact, by homogenizing the specific discharge, it removes local transport capacity gradients, leading to Δz values close to zero and a complete loss of realistic bed change patterns.

In contrast, omitting the effective sediment transport width approach (v4) has only a minor effect. The spatial patterns remain nearly identical to the validated run, with only small amplitude differences in high-erosion zones. This suggests that the τ-based correction fine-tunes the results, whereas the main added value comes from using spatially variable effective flow conveyance widths that reflect the actual hydraulics. Notably, Camenen et al. (2011), also in a Danube case study, demonstrated that computing bed-load from a mean cross-sectional shear stress is generally unsatisfactory, and that introducing cross-sectional variability of τ, with an analytical approach in their case, substantially improves 1D bed-load predictions. The weaker sensitivity to the τ-correction in this study likely stems from the fact that the 2D-derived effective widths already consider much of the lateral conveyance and dead-zone effects, such as groyne fields, so the additional correction acts as a second-order refinement rather than a first-order control.

Overall, the analysis demonstrates that 2D-based effective width parameterization is crucial for realistic morphodynamic modelling. It preserves the spatial variability in flow conveyance that controls sediment transport gradients, ensures correct prediction of erosion/deposition locations, and prevents the large-scale qualitative and quantitative errors that arise when cross-sectional variability is neglected.

3.4 Modeling of sediment management measures

Using the field-validated model, 30 years of morphodynamics was simulated, as the observed 13-year period followed by a 17-year forecast. For the sake of simplicity, the inflow boundary conditions for the future simulations, the 13-year inflow hydrograph was repeated and, consistent with the validation setup, the upstream bedload boundary was set to zero. While climate change is expected to influence future flow regimes, including the occurrence of hydrological extremes, the large uncertainties associated with regional discharge projections currently limit their direct application in long-term morphodynamic simulations. Consequently, climate change impacts were not explicitly addressed in this study. To assess long-term management effects, three variants were evaluated: (R) do-nothing reference; (W) channel widening, effective flow conveyance width increased by a factor of 1.5 along the study reach as a proxy for groyne-field removal; and (F) targeted sediment feeding of 10,000 m^3/yr at rkm 1804, the local incision hotspot. Measures (W, F) were implemented after year 13, and their effects were evaluated over the subsequent 17 years.

Focusing only on the dynamic section of the river, the longitudinal profiles for the reference model variant (R) show that the most dynamic reach 1790–1810 remains dominated by erosion (Figure 10 top). To assess the temporal behavior of the bed changes, time series of Δz at rkm 1802 was investigated. Similarly to the model validation runs, this section exhibits a persistent incisional trend that decelerates over time, approaching a quasi-equilibrium after ~20–25 years. By year 30, incision is about 0.8 m, suggesting a mean bed incision of 2.7 cm/yr.

As for the increased river width model variant (W), the analyzed measure indeed reduces specific flow discharge and bed shear stress, thereby lowering transport capacity that drives bed incision processes. This is evident in the longitudinal profile that indicates smaller amplitudes of the erosional peaks around rkm 1795–1810 (Figure 10 middle). At rkm 1802, widening roughly halves the long-term incision to about 0.4 m by year 30 (equal to 1.3 cm/yr). Longitudinal extension of sediment deposition patterns downstream of rkm 1795 also decreases compared to the reference version, suggesting more sustainable navigational channel.

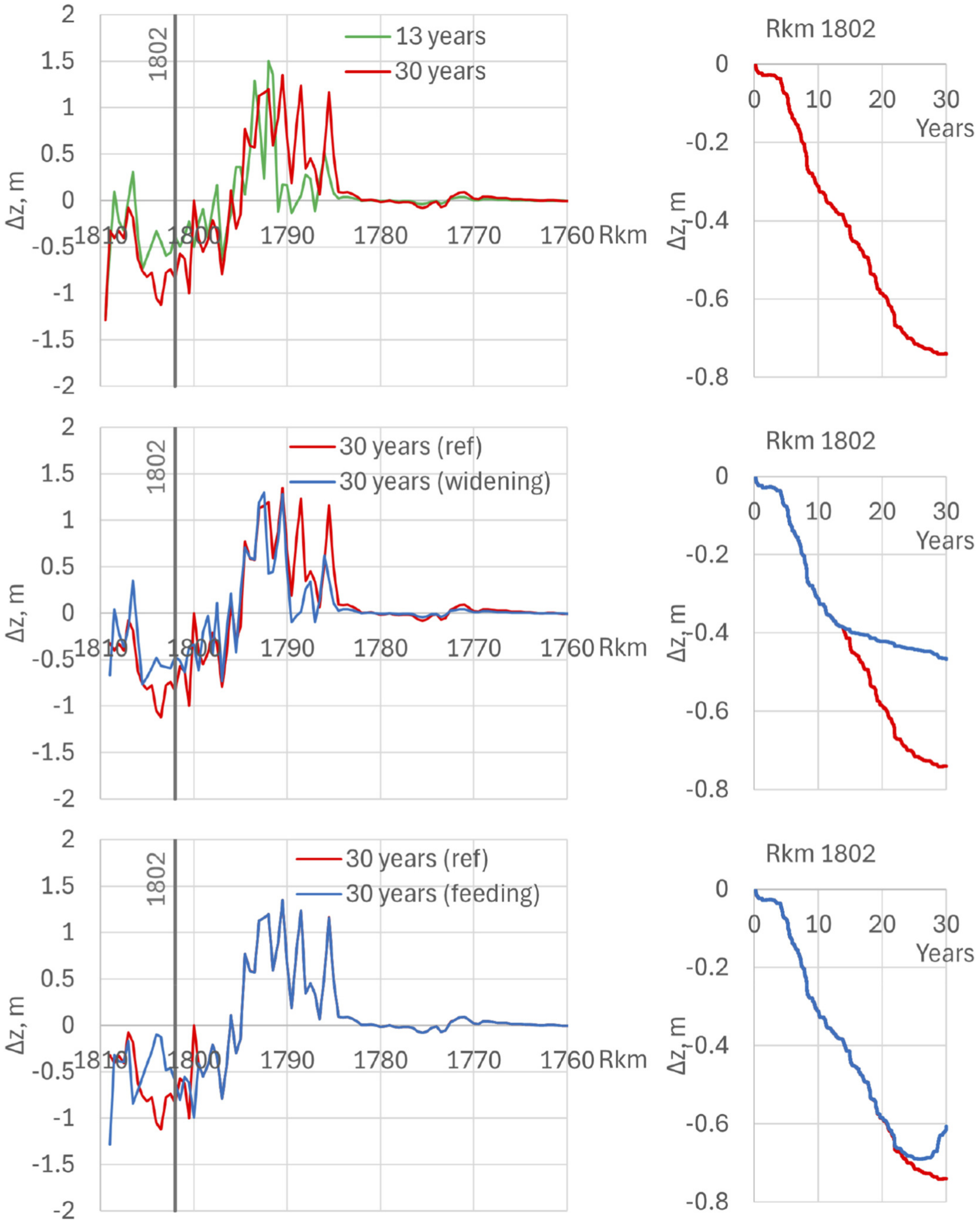

FIGURE 10
Simulated riverbed elevation changes after 30 years for the section between rkm 1760–1810 (left) and temporal variation of bed changes at section rkm 1802 (right) for the three model variants: top: reference case with no interventions; middle: widening of the effective channel width to 1.5x; bottom: local sediment feeding at rkm 1804 of 10,000 m^3/yr.

Artificial feeding, or nourishment, of sediments (model variant F) produces a locally significantly reduced erosion, centered on rkm 1804, resulting in almost zero bed level change there (Figure 10 bottom). Also, sediment feeding reduces downstream incision, but the effect is weaker than the channel widening at the same site. By year 30, rkm 1802 shows ~0.55–0.60 m of erosion, i.e., ~2.0 cm/yr, showing an improvement of ~0.2–0.25 m relative to the reference variant. The measure was implemented after year 13 at rkm 1804, and the first clear impact at rkm 1802 appears only around year ~20, implying a propagation time of roughly 7 years between the sites. Time series of bed changes suggests partial stabilization after ~20–25 years, with modest recovery toward the end, indicating that the annual 10,000 m^3 input seems to be insufficient to fully offset the local transport capacity under the recurring hydrograph.

4 Discussion

4.1 Hydromorphological stress and sediment imbalance in a large, regulated river

The model results confirm that the upper section of the Hungarian Danube continues to experience a persistent sediment deficit and associated hydromorphological stress, manifested by pronounced bed incision between rkm 1810–1795 and relative downstream stabilization. This spatial pattern is consistent with decades of prior assessments and reflects the combined effects of upstream hydropower impoundment, historical sediment extraction, and channelization through groyne fields, which constrain lateral channel mobility and reduce sediment supply, leading to "hungry water" conditions and channel deepening (Kondolf, 1997). Such downstream attenuation of incision is characteristic of river reaches below hydropower reservoirs, where rapid post-impoundment degradation progressively adjusts toward a new dynamic equilibrium in slope and transport capacity (Kondolf, 1997; Brandt, 2000). Comparable long-term observations from the Danube east of Vienna similarly report persistent but decreasing degradation rates, accompanied by management interventions such as sediment feeding, bed coarsening, and channel widening aimed at stabilizing bed levels (Klasz et al., 2016; Habersack et al., 2019).

These morphological changes extend beyond geomorphology, as progressive channel incision lowers water levels and groundwater tables and reduces the frequency and duration of side-channel as well as floodplain inundation, thereby influencing key ecological processes, including (i) hydrological and lateral connectivity between the main channel, side channels, and floodplains; (ii) groundwater–surface water interactions; (iii) habitat availability and quality for fish, particularly spawning and nursery habitats; (iv) substrate composition and stability for benthic communities; and (v) organic matter and nutrient exchange within the river corridor (Shields et al., 1994; Loheide and Booth, 2011; Habersack et al., 2016). In this sense, incision is not solely a geomorphic phenomenon but a driver of freshwater ecosystem stress. The validated model's ability to reproduce these patterns provides a quantitative basis for diagnosing the degree and extent of hydromorphological pressure in large, regulated rivers.

The clear difference between the active, erosion-prone upper reach and the more stable downstream section is particularly relevant for restoration planning. It indicates where interventions such as sediment feeding or morphological reactivation will have the greatest restorative leverage and where they may have limited effect. Identifying and prioritizing such "pressure hotspots" is fundamental for the cost-effective implementation of large-river restoration measures under European policies such as the Water Framework Directive and the EU Biodiversity Strategy.

4.2 Interpretation of the width-parameterization results and implications for modelling

The comparison of model variants (introduced in Section 3.3) highlights the central role of spatially variable effective width in realistically reproducing the reach-scale morphodynamic signal. The use of total geometric width systematically underestimates incision and produces deposition where none is observed. The constant-width variant suppresses nearly all morphodynamic activity. Only the 2D-informed effective-width approach captures the observed magnitude and spatial distribution of erosion and deposition.

These differences illustrate an important conceptual point: the morphodynamically active river width is not the geometric width, especially in highly regulated rivers. Groynes, low-flow sections, and recirculation zones are hydraulically and morphologically inactive for much of the flow regime. Treating them as active artificially dilutes shear stress and sediment transport capacity across the full cross-section, leading to quantitatively and sometimes qualitatively incorrect results.

In restoration science, distinguishing between structural characteristics (the constructed corridor) and functional characteristics (the hydraulically active corridor) is crucial (Ward, 1989; Jungwirth et al., 2002). Effective width therefore represents a bridge between process-based hydraulics and practical large-scale modelling: it preserves the lateral variability of hydraulic conditions without requiring computationally intensive multidimensional simulations for long time horizons.

The proposed hybrid 1D–2D approach thus offers an important methodological advance for rivers where (i) decadal predictions are needed, (ii) hydromorphological pressures are strong, and (iii) scenario testing must be efficient yet realistic. This is particularly relevant for European rivers with long histories of channel training, where restoration strategies often aim to reactivate or reconnect portions of the lateral corridor (Schmutz and Sendzimir, 2018).

4.3 Implications for restoration: widening and sediment feeding as complementary measures

The modelling results highlight two complementary process-based pathways for mitigating long-term bed degradation in large, trained rivers: reducing sediment transport capacity through channel widening and increasing sediment supply through sediment feeding. Channel widening increases the hydraulically active corridor, thereby lowering unit stream power and sediment transport capacity (Surian and Rinaldi, 2003). This mechanism is consistent with experiences from European rivers, where providing additional space has promoted gravel-bar formation, enhanced hydraulic and substrate heterogeneity, and improved lateral connectivity—key attributes associated with ecological resilience and the recovery of side-channel habitats (Surian and Rinaldi, 2003; Wohl et al., 2015). These findings align with the recently published Danube Sediment Management Guidance, which explicitly recommends moderate channel widening to alleviate bed degradation (Habersack et al., 2019), as well as post-project monitoring from rivers such as the Thur (Switzerland) and the alpine Ahr, where widening resulted in gravel-bar development and increased bed elevations (Campana et al., 2014; Martín et al., 2018).

Sediment feeding directly addresses sediment discontinuity, a pervasive pressure in regulated rivers where upstream trapping and channel confinement limit the downstream supply of coarse material. International case studies demonstrate that appropriately designed replenishment measures can locally raise bed levels, stabilize incision hotspots, and improve substrate conditions, particularly where spawning or benthic habitats have been degraded (Ock et al., 2013; Mörtl and De Cesare, 2021; Chardon et al., 2021). Long-term experiences from the Rhine river highlight the importance of sufficient volumes and appropriate grain-size selection (Chardon et al., 2021; Czapiga et al., 2022), while recent sediment management activities on the Danube similarly emphasize targeted bedload additions as a key measure to counter persistent bed incision (Klasz et al., 2016; Habersack et al., 2019).

Together, these insights highlight the value of combining measures that reduce capacity with those that increase supply as was shown by, e.g., Chardon et al. (2018). Widening creates a geomorphic template capable of retaining added sediment, while feeding accelerates morphological and ecological recovery where sediment deficits are most acute. In European rivers shaped by decades of channel training and confinement, such integrated, process-based strategies are increasingly central to restoring lateral dynamics, reactivating floodplain interactions, and meeting hydromorphological objectives under the Water Framework Directive. The hybrid 1D–2D modelling framework provides a practical tool for exploring these interactions over decadal scales and for informing the strategic design of restoration interventions.

4.4 Applicability, limitations and future directions

Beyond the specific Danube case, the study demonstrates how hybrid modelling can support freshwater restoration across Europe. The approach: i) enables screening of multiple restoration measures over multi-decadal horizons, ii) identifies geomorphic pressure points, iii) provides quantitative expectations of long-term bed evolution, iv) can be applied to other regulated rivers where computational constraints limit 2D/3D modelling.

This aligns with continental-scale initiatives such as the Danube River Basin Management Plan and the EU Nature Restoration Law, both of which emphasize restoring sediment continuity and hydromorphological processes.

Although effective for long-term assessment, the model simplifies some processes important for ecological interpretation, such as unsteady hydrodynamics, mixed-size sediment sorting, bank erosion, and fine-sediment transport. Future developments could incorporate: i) fractional transport and active-layer dynamics, ii) event-scale unsteady hydraulics for disturbance-driven habitat processes, iii) evolving width or bank-erosion modules for systems with mobile banks, iv) dynamic updating of effective widths as morphology changes, v) linking morphodynamic outputs with habitat or ecological models. Such extensions would enhance the value of the modelling framework for integrated river restoration and freshwater ecosystem assessments.

5 Conclusion

Applied to a 100-km gravel-bed reach of the Hungarian Danube, the framework successfully reproduced observed patterns of incision, deposition, and morphological stability, supported by validation against water levels, multi-year bathymetric surveys, and bedload measurements. The comparison of model variants confirmed that spatially variable effective widths are essential for producing realistic morphodynamic behaviour in heavily trained rivers.

Scenario simulations highlighted the continued adjustment of the system under sediment deficit and demonstrated the contrasting but complementary effects of channel widening and sediment feeding as restoration measures. These results underscore the value of the hybrid approach for evaluating sediment-management strategies, identifying pressure hotspots, and supporting river-restoration planning.

Although simplified in several respects, the model is strongly constrained by field data and provides a transparent, scalable decision-support tool for freshwater managers. Its applicability to other sections of the Danube, or other regulated European rivers makes it a useful framework for addressing hydromorphological stress and restoring sediment continuity in support of ecological resilience.

Data availability statement

The datasets presented in this article are not readily available because certain input datasets (bathymetry, discharge time series, training structures) are licensed and not publicly distributable. Derived results generated by the author are available on request. Requests to access the datasets should be directed to baranya.sandor@emk.bme.hu.

Author contributions

SB: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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