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Balancing Sediment Connectivity and Energy Production via Optimized Reservoir Sediment Management Strategies

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Key Points:

- The D-CASCADE model can reproduce robust, basin-wide patterns of river sediment connectivity in the Se Kong-Se San-Sre Pok (3S) river basin
- We quantify the impact on sediment transport for different grain sizes of three dam development scenarios on the lower 3S system
- We optimize the design of drawdown sediment flushing operations considering both sediment connectivity and hydropower generation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Sediment connectivity plays a fundamental role in sustaining ecosystem goods and services in fluvial systems, including hydropower production. Dams alter the natural processes of sediment transport by trapping sediment and reshaping downstream hydrology and geomorphology. Due to these processes' interconnected nature, dams' impacts extend in time and space beyond the dam site to the entire river system. System-scale approaches to reduce dam impacts commonly only consider dam siting, overlooking the potential of sediment management strategies integrated into the dam operations to offer more flexible solutions for mitigation. Herein, we contribute a sediment routing model (D-CASCADE) to assess the impacts of reservoirs and their management strategies on river sediment connectivity. D-CASCADE is applied to the 3S river system, a tributary of the Mekong River, a hotspot of potential dams in the Lower Mekong. We analyze three dam development portfolios. The effect of reservoir management is examined by assessing daily sediment delivery with specific dam release strategies. Model results predict sediment yield to the Mekong to reduce by 31%–60%. Finally, we explore trade-offs between hydropower generation and sediment connectivity across cascades of multiple reservoirs. Results show that repeated flushing operations during the early wet season could significantly increase sediment delivery with minimal (max 6%) hydropower losses. While poor trade-offs between sediment and hydropower have been locked-in in the Mekong, our results highlight the potential of including sediment connectivity models in multi-objective decision-making frameworks to devise integrated water and sediment management strategies that mitigate connectivity disruptions while minimizing losses in other sectors.

1. Introduction

While hydropower can be a reliable and low-carbon energy source, the construction and operation of hydropower dams cause severe environmental impacts. Reservoirs disrupt natural river connectivity patterns that characterize the movement of water, sediments, and organisms (Kondolf, 2000; Ligon et al., 1995; Wohl et al., 2015). In particular, sediment movement is halted by the low hydraulic forces inside the reservoirs, resulting in reservoir siltation (Graf et al., 2010; Vörösmarty et al., 2003) and sediment starvation downstream (Kondolf, 1997). The first process reduces reservoir storage capacity (Palmieri et al., 2001; Wisser et al., 2013), damages hydroelectric equipment, and poses safety hazards (Wisser et al., 2013). Worldwide, an average of 0.5%–1% of total reservoir storage is lost yearly due to sedimentation (White, 2001). The second impact is more insidious since it is not limited to the reservoir's boundaries. Still, it has the potential to affect the river system as a whole, with long-term impacts on fluvial hydromorphological processes (Bizzi et al., 2015; Ma et al., 2022; Sholtes & Doyle, 2011; Wyżga et al., 2016), riverine ecosystems (Gilvear et al., 2013; Wild & Loucks, 2012), river deltas (Kondolf et al., 2022; Syvitski et al., 2009), infrastructures and livelihoods (Kondolf, 1997) far downstream of the reservoir. Additionally, cumulative downstream effects of dams might occur and far surpass the impacts of individual dams if multiple dams are built on a river (Kondolf, Gao, et al., 2014; World Commission on Dams, 2000; Ziv et al., 2012).

A variety of sediment management strategies can be implemented in reservoirs to preserve reservoir capacity or combat sediment depletion downstream, which have been proven effective in several case studies around the world (Jansson & Erlingsson, 2000; Kokubo, 1997; Stevens, 2000; Sumi, 2008; Vischer, 1997; Wang et al., 2018). These techniques aim to reduce or prevent the inflow and sedimentation of material into the impoundment (e.g., soil erosion control via reforestation or changes in agricultural practices, installation of sediment bypasses, sediment sluicing in reservoirs) or to remove settled sediment (e.g., mechanical or suction dredging).

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Drawdown flushing belongs to the latter category and involves the total emptying of the reservoir through low-level gates and the re-establishment of river-like flow conditions in the reservoir for a limited time. If the water discharge is sufficient to induce movement in the deposited sediment, flushing results in the scouring of the sediment deposited in the reservoir (Kondolf, Gao, et al., 2014; Stevens, 2000). Flushing is most effective when performed in small and narrow reservoirs, or on rivers with strong seasonal flows (G. L. Morris & Fan, 1998). The operation is typically too costly and time-consuming to be performed on a regular basis for large dams, or the scouring effect of flushing may be too narrow to effectively remove sediment from wide reservoirs. Older reservoirs are also not ordinarily designed with low-level gates, and retrofitting is often not possible. However, when executed correctly, flushing is considered one of the most effective sediment management techniques and has been performed successfully in numerous reservoirs around the globe (Atkinson, 1996; Palmieri et al., 2003; Stroffek et al., 1996; White, 2001).

Even when technically viable, drawdown flushing presents interesting trade-offs between sediment removal and a dam's operational objectives. For example, draining the reservoir and interrupting standard operations during flushing will result in losses in hydropower generation, which can be substantial. The presence of multiple dams on the same river network introduces a new layer of complexity, as flushing must be coordinated to avoid unplanned consequences. For example, in the case of two dams in series on a river, sediment flushing should be synchronized to avoid the deposition in the downstream reservoirs of material mobilized from the flushing of the upstream dam (Thareau et al., 2006).

Few attempts have been made to assess basin-wide negative externalities on sediment connectivity of multi-dam systems, and even less to assess how strategic reservoir planning can mitigate said impacts. Many studies have tackled the problem of quantifying the effect of dam operations on sediment delivery, including both standard operations and sediment flushing, and considering single or multiple reservoirs (Bernardi et al., 2013; Lepage et al., 2020). These case studies are limited in their scope to already existing infrastructures and mostly focus on dam filling prevention, or local impacts on sediment transport and biotic processes. Other papers explore the trade-offs between sediment trapping and energy production for large-scale dam development projects, including only steady-state modeling of reservoirs (Schmitt et al., 2018a, 2019), or considering simple operations alternatives (Wild & Loucks, 2014). Wild et al. (2016) present an application of a sediment connectivity model to evaluate the effect of drawdown sediment flushing on dam trapping and energy production on a multi-dam scheme on the Mekong river. The paper explores different alternative scenarios of dam development, sediment delivery and flushing design.

While these studies demonstrate the potential of large-scale sediment models to support sediment management for multi-dam schemes, they either do not consider dynamic processes like channel morphological evolution and reservoir water and sediment management (Schmitt et al., 2019), or choose to focus mostly on local impacts on dam storage, and not large-scale sediment starvation; with sediment management options designed using standard configurations (Wild et al., 2016). Moreover, sediment volumes are often analyzed as a uniform mass, ignoring how the presence of reservoirs may also alter sediment granulometric composition, which has complex consequences both on sediment trapping and network morphology and biology (Ma et al., 2022).

In this study, we present a novel application of a sediment transport model for the quantification of cumulative impacts on sediment connectivity brought not only by the inclusion of dams on the network but time-varying water and sediment management strategies of multiple reservoirs. This study used the dynamic sediment connectivity model D-CASCADE (Tangi et al., 2019), a large-scale, distributed sediment connectivity model which provides both a basin-scale perspective of sediment routing and a reservoir-level analysis of water and sediment management strategies. Sediment heterogeneity is explicitly accounted for by employing a grain class partitioning of sediment delivery.

D-CASCADE is an exploratory tool that belongs to a group of recently developed numerical models of network-scale sediment (dis)connectivity (Czuba et al., 2017; Czuba & Foufoula-Georgiou, 2014; Gilbert & Wilcox, 2020; Gran & Czuba, 2017; Pfeiffer et al., 2020; Schmitt, 2016; Wild et al., 2021), which trades part of the accuracy of traditional physics-based models for increased flexibility and lower data requirement, to be run over longer timeframes and larger areas and characterize (dis)connectivity patterns among different parts of the river system.

This study includes the first use of a dynamic sediment connectivity model within a multi-objective decision-making framework that aims to optimize both dam siting and operation for multiple reservoirs on the same river system. We employ D-CASCADE to explore the trade-offs between hydropower generation and sediment connectivity conservation by considering both the siting and operation of multiple hydropower dams and reservoirs in the Se Kong—Se San—Sre Pok (3S) river basin, a large tributary of the Lower Mekong River.

First, we present an analysis of the impact of different dam development portfolios on sediment delivery to the Mekong, focusing on the lower part of the river network. This analysis is repeated for multiple realizations of natural sediment transport in the rivers and thus sediment delivery to the dam sites. These realizations help us account for the uncertainty in sediment transport in the poorly monitored 3S basin. Then, we couple the D-CASCADE model with a multi-objective evolutionary algorithm (MOEA) (Hadka & Reed, 2013), to derive Pareto-Optimal (PO) configurations of coordinated drawdown sediment flushing operations for multiple reservoirs minimizing trade-offs between energy generation and outlet sediment delivery. The design of the sediment management operations is optimized for multiple parameters: flushing frequency, timing, and duration, and the synchronization between dams in cascade.

The input data and scenarios utilized in this work, in particular regarding the type of processes and dam portfolios analyzed, are partially based on Schmitt et al. (2018a) and Wild et al. (2016). Compared to the work of Schmitt et al. (2018a), we use a dynamic approach to model dam operational rules and simulate sediment connectivity and transport through the network. Moreover, the approach from Wild et al. (2016), presents fixed operational rules and a simplified and conceptual representation of sediment transport via a simple rating curve linking discharge and sediment transport. This paper is the first to implement sediment routing through the river network for a specific discharge series (Tangi et al., 2022) and to model sediment connectivity within the objective function in an approach to minimize impacts of dams on sediment (and by extension on geomorphology).

2. Case Study

The Mekong river is a transboundary river in South-East Asia, which ranks among the largest river systems in the world (Winemiller et al., 2016). Its high sediment load and flood-pulse hydrology support one of the most productive freshwater fisheries on earth and a large variety of ecological hotspots across its around 5,000 km course (Campbell, 2009; Hortle, 2009). Sediment delivery also helps offset land subsidence and sea level rise in the highly inhabited and productive Mekong delta (Kondolf et al., 2018; Schmitt et al., 2021).

The river network composed of the Se Kong, Se San, and Sre Pok rivers, often referred to as 3S, is one of the major tributaries of the Lower Mekong River. The three rivers converge together just before joining the main river, roughly 500 Km upstream of the delta (Figure 1a). The 3S river system drains 82,500 km^2 across Vietnam, Laos, and Cambodia (Se Kong: 30,400 km^2; Se San: 20,000 km^2; and Sre Pok: 32,000 km^2) and contributes to 17%–20% of the annual discharge of the Mekong River (Sarkkula et al., 2010a) and 25% of its annual sediment load (Kondolf et al., 2018). The annual hydrological regime is controlled by monsoon-induced floods, which carry up to 75% of the total annual flow (Piman et al., 2016).

Dam construction is progressing fast through the Mekong basin, driven by energy demand (International Energy Agency, 2015). The 3S river system is also included in this large-scale dam development effort, with 20 instream dams already built or under construction, and around 20 dams planned. Currently, most of the dams are in the upper Se San and Sre Pok, except for the Lower Se San 2 (LSS2) dam, a large downstream dam operating since 2018. Schmitt et al. (2018a) identified the impacts of sediment delivery of the Lower Se Kong, Lower Se San 3 (LSS3), Lower Sre Pok 3 (LSP3), and LSS2 dams (shown in Figure 1) to be especially critical due to their downstream location and high trapping potential. In particular, the LSS2 dam is shown to have a disproportionate impact on suspended sediment transport to the Mekong compared to its hydropower potential.

Direct measurements of sediment supply and Grain Size Distribution (GSD) before dam construction are not available in the 3S basin. Empiric evidence based on field data on the Lower Mekong characterizes the 3S basin as one of the principal contributors of sediment to the main river, especially sand, which plays a vital role in the morphodynamic stability of the river and its delta (Bravard et al., 2014; Kondolf et al., 2014; Piman et al., 2016). Kondolf et al. (2014) and Wild and Loucks (2014) estimate total sediment yield leaving the 3S basin to be around 24–25 Mt/yr, based on the residuals of the sediment budgets of the Mekong before and after the 3S basin confluence (Koehnken, 2012a). However, by their designs, these sediment yield prediction methods ignore conveyance losses due to sink areas and choke points, meaning the original sediment supply is potentially higher. Other models (Carling, 2009; Sarkkula et al., 2010b) used as a baseline by the Mekong River Commission (Koehnken, 2014) lower the estimated sediment yield to 17–18 Mt/yr, based on 1990–2000 modeling results.

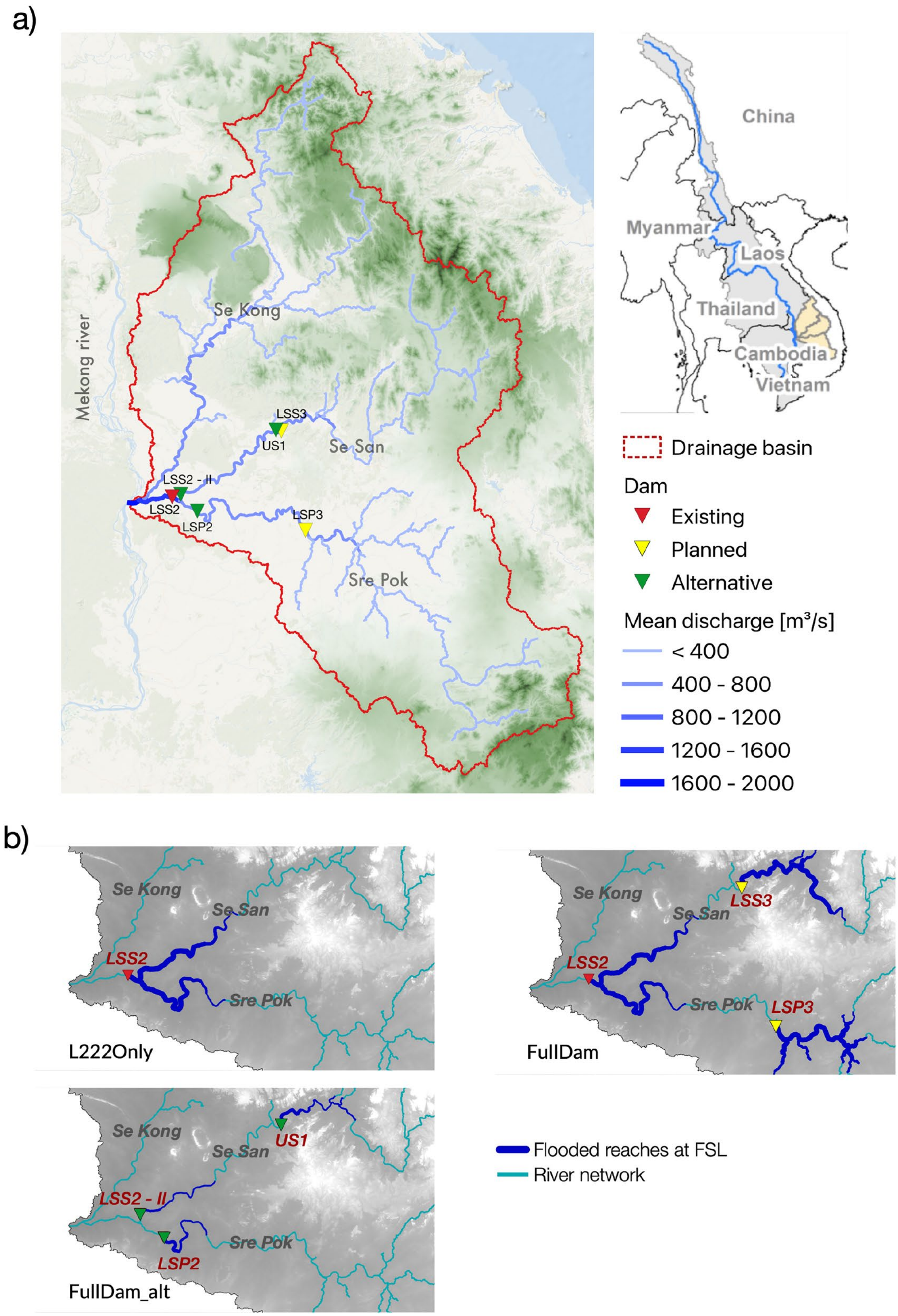

Figure 1. The 3S river network as represented in the D-CASCADE modeling framework, including reservoir location and average, reach water discharge. The study focuses on the six reservoirs shown in the picture: the Lower Se San dam (LSS2) already constructed, the planned LSS3, and LSP3 dams, and an alternative configuration proposed by Annandale (2013) consisting of the three dams with instream reservoirs LSS2-II, LSP2, and US1. Figure (a) shows the broad 3S basin river system, whereas Figure (b) details the dam's location and flooded reaches at full supply level for the three dam development portfolios considered in the analysis.

The impact of dam construction on the total sediment yield delivered to the Mekong is debated. Koehnken (2014) estimated sediment delivery to be around 8–11 Mt/yr based on 2009–2013 measurements with 16 active hydropower impoundments, primarily located in upstream reaches of the Se San and Sre Pok. However, the completion of the LSS2 dam, operating since 2018, is bound to reduce the sediment yield further. Schmitt et al. (2018a) estimated a 97% reduction in the 3S sand sediment budget if all planned dams are constructed.

The reduction in sediment delivery from the 3S system, especially sand, is significant in our case study, as it contributes to the cumulative sand starvation which currently threatens the Mekong Delta (Schmitt et al., 2018a). Thus we focus primarily on changes in the quantity and type of material delivered to the network outlet as indicators of sediment connectivity alteration brought by competing dam development scenarios.

Only some of dams, notably mainstem run-of-river dams on the lower Mekong, have been designed with outlets for sediment passage (e.g., the Xayaburi and Don Sahong dams) (MRC (Mekong River Commission), 2019). Available information indicates that most other dams have been constructed without any kind of sediment bypass or bottom outlet (Kondolf et al., 2014).

3. Methods

To derive estimates of daily network sediment load for the 3S river system under different dam development scenarios, and to evaluate the effects of drawdown sediment flushing operations on sediment trapping and delivery, we adopt a 3-step methodology, visualized in the workflow in Figure 2:

1. Baseline sediment budget definition: we apply the basin-scale sediment connectivity model D-CASCADE on the entire 3S river network without reservoirs, to quantify reach sediment budgets and transport rates for the unimpeded river system and compensate for the lack of distributed field data. Multiple scenarios with different input catchment sediment supplies are analyzed to account for the uncertainty in the model initialization. Using quantitative field observations and literature estimations regarding annual sediment transport at the 3S river confluence, we select several scenarios to serve as a baseline for the simulations with reservoirs.
2. Reservoir siting assessment: D-CASCADE is applied on the 3S basin for three different portfolios of dam siting, with a special focus on downstream dams (which would trap most of the basin's sediment). These portfolios represent alternative dam development configurations for the lower 3S basin.
3. Reservoir sediment management: Coordinated sediment flushing operations are designed using a MOEA to explore interesting trade-offs between the two conflicting objectives of energy generation and outlet sediment delivery; under uncertainties on the estimations of the network sediment supply.

3.1. The D-CASCADE Model

D-CASCADE is a basin-scale, dynamic, exploratory sediment transport and delivery model representing sediment connectivity as a combination of "cascades," individual sediment transport processes identified by their provenance, and the volume and GSD of the material they transport. The cascades are routed through a river network modeled as a direct graph partitioned into reaches. Each reach represents a section of the river network with homogeneous geomorphic and hydraulic features. Channel features (e.g., width, gradient, water depth, and velocity, and roughness coefficient) are defined for each reach. Sediment transport capacity equations are used to assess sediment budgets for each reach and determine if any sediment deposition or mobilization occurs. The model's outputs consist of distributed, disaggregated spatial and temporal sediment transport information, and statistical connectivity properties between different sediment sources and sinks. Thus, D-CASCADE can quantify the effects of multiple heterogeneous drivers of change and determine and characterize each driver's contribution to the cumulative change.

In Tangi et al. (2022), the D-CASCADE modeling framework was used to reconstruct the long-term effects of anthropic-driven land use change on sediment connectivity of a small fluvial system in NSW, Australia. In this paper, the model is modified for a significantly larger case study and a higher temporal resolution. Thus, we do not make use of the more advanced functions to model downstream morphologic evolution of river channels and sedimentary deposits seen in Tangi et al. (2022). This is first and foremost because of the shorter time-horizon considered, and secondly, because of the absence of stratigraphic data available for validation. However, new specific add-on components are developed to account for the inclusion of dams and the dynamic management of the reservoirs' water and sediment storages.

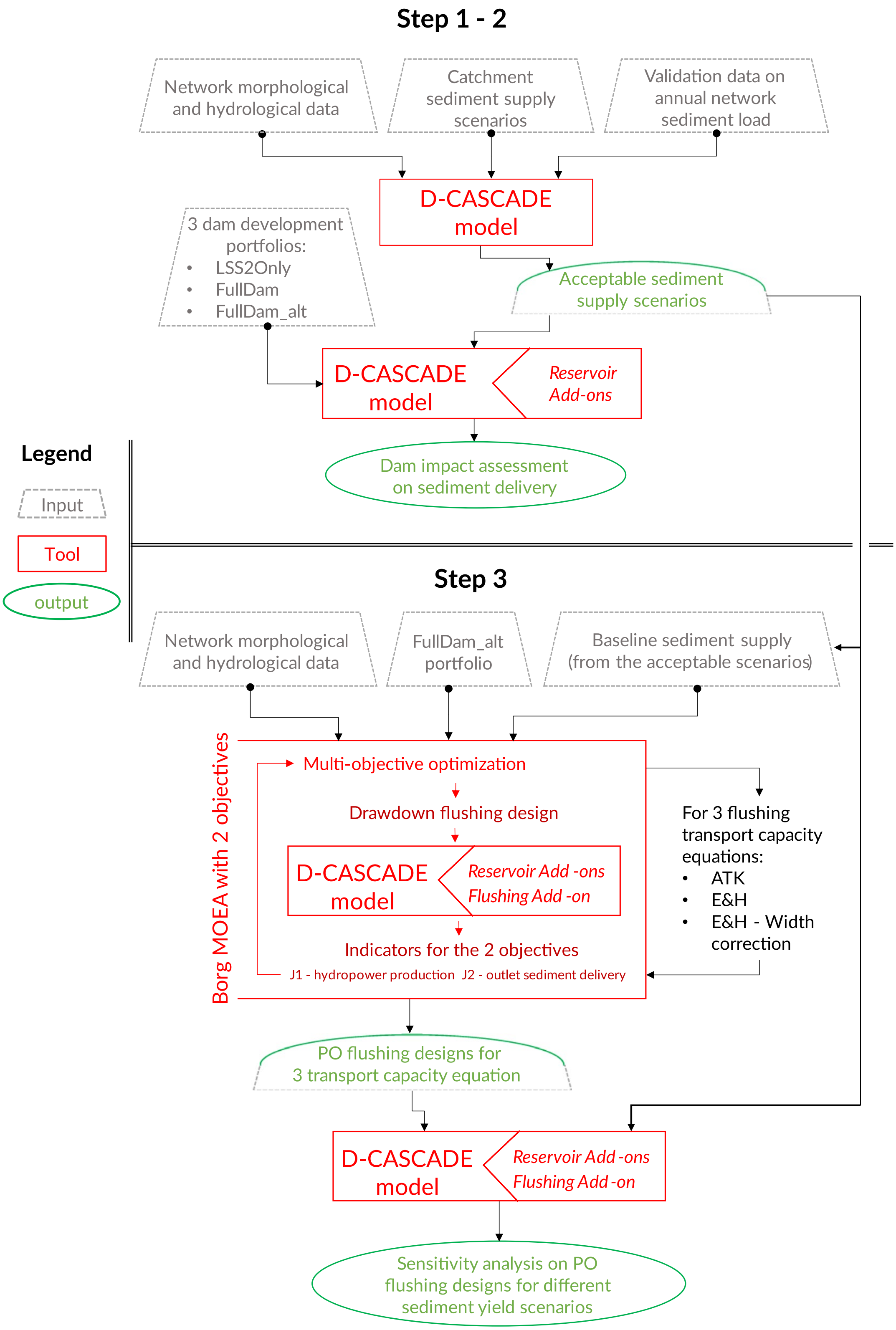

Figure 2. The workflow illustrates the methods used in the paper to quantify reservoir impacts and extract Pareto-optimal designs of synchronized drawdown sediment flushing. In steps 1 and 2, we extract credible estimations of network sediment connectivity from different scenarios of catchment sediment supply, validated via field data of average annual network sediment load. In step 3, we optimize the design of coordinated sediment flushing operations under two objectives: sediment delivery, and hydropower production. We then test how these designs are affected by uncertainties in catchment sediment supply.

In this section, we highlight the new features and components of the D-CASCADE model included in this research. More information on the basic structure and working of the D-CASCADE modeling framework is detailed in Tangi et al. (2022).

3.2. Defining Baseline Sediment Budgets

To assess the spatiotemporal impacts of dam inclusion and management on the 3S basin, we need to reconstruct reach sediment budgets and sediment delivery for the undammed river network.

We thus delineate the river network for the 3S basin and characterized each reach morphological features using available information on channel morphology. The 3S river network was extracted from a 90 m void-filled, Digital Elevation Model (DEM) (Consultative Group on International Agricultural Research, 2008), via the standard network delineation algorithm implemented in Topotoolbox (Schwanghart & Kuhn, 2010). The area threshold for channel initiation was set to 500 km^2. In total, a network of 3,225 km was extracted, consisting of 463 reaches with an average length of 7 km. The gradient for each reach was derived from the DEM from the elevation difference between a reach's start and end points, and the length of the reach. Outliers given by grid elevation errors in the DEM were corrected via interpolation. Channel width and roughness coefficient are obtained from the data set used in Schmitt et al. (2018a); Schmitt et al. (2018b) via satellite imagery and literature estimates. The hydrological record used consists of daily data from 1995 to 2005 obtained via the grid-based Variable Infiltration Capacity (VIC) hydrological model (Chowdhury et al., 2021; Dang et al., 2020; Galelli et al., 2022) with a 6.7 km resolution. Reaches are assigned to a single cell in the VIC grid, and thus a single hydrological series, chosen as the cell which overlaps the most with its course.

The D-CASCADE model considers five different sediment classes: fine gravel, coarse sand, fine sand, coarse silt, and fine silt, or 2.8, 0.71, 0.16, 0.044, and 0.011 mm classes.

The reach transport capacity is calculated via Engelund and Hansen (1967) equation for the total load (i.e., both suspended and bed load), which has already been employed previously for large sediment connectivity models on the Mekong and 3S (Schmitt et al., 2018a, 2018b) and other rivers (An et al., 2021; Naito et al., 2019). As this formula returns the total transport capacity, we obtain fractional transport rates for the five classes considered via the Bed Material Fraction (BMF) approach described in Molinas and Wu (2000). To measure how far downstream mobilized sediment volume travels in a year, we use an empirical equation (Czuba & Foufoula-Georgiou, 2014; Hassan et al., 1991; Pfeiffer et al., 2020) which discriminates between different sediment classes to simulate differential travel rates.

While there are rough estimates of sediment loads at the outlet of the 3S basin, there is no field data available on how much sediment is supplied from hillslope processes to the 3S network, and which grain sizes it has. This is a limitation because sediment supply from hillslopes to a reach will determine the initial sediment transport in the sediment cascade originating in that reach, and thus the boundary conditions required to set up a network-scale sediment model. Kondolf et al. (2014) estimated sediment yields on the 3S river to range from 280 to 290 $t * km^{-2}yr^{-1}$, corresponding to a total annual sediment supply of around 24 Mt/yr to the network. However, these estimates are extracted based on downstream sediment load data, which ignores deposition in the network (Walling, 1983). Thus, the catchment sediment supply could be potentially much higher than what can be observed from downstream loads (Schmitt et al., 2018b).

Similar to Schmitt et al. (2018b), we define multiple sediment supply scenarios, different in both the total annual supply to the network and the statistical distribution of grain sizes in the supplied sediment, and then select those scenarios for which modeled loads at the outlet coincide with observations. We use 10 input yield scenarios (15, 20, 25, 30, 35, 40, 45, 50, 55, 60 Mt/yr) and 8 grain size scenarios (with median diameters, D50, of: 1, 0.75, 0.5, 0.25, 0.1, 0.075, 0.05, 0.025 mm), resulting in a total of 80 scenarios. The spread of the GSD around the D50 is derived by fitting a Rosin distribution (Ferguson et al., 2015) to field data from the lower Mekong (Koehnken, 2014). Finally, we derive daily sediment loads by partitioning the annual values proportionally to the water discharge so that higher sediment supplies will occur during the monsoon season when precipitation and soil erosion is most abundant (Darby et al., 2016; Koehnken, 2012a).

Of all sediment supply scenarios, we only kept scenarios for which modeled sediment load at the outlet coincided with available field observations. We use those scenarios to represent annual sediment supply.

Table 1
Reservoir and Dam Features at Currently Built or Planned LSS2, LSS3, and LSP3 Dams (MRC (Mekong River Commission), 2014), as Well as the Three Alternative Dams: LSS2-II, LSP2, and US1 (Annandale, 2013; Wild & Loucks, 2014)

Reservoir and dam features	LSS2	LSS3	LSP3	LSS2-II	LSP2	US1
Name	Lower Se San 2	Lower Se San 3	Lower Sre Pok 3	Lower Se San 2—II	Lower Sre Pok 2	Upstream Se San 1
Rated head (m)	26	28	28	16	13	12
Reservoir storage capacity at Full Supply Level (FSL) (Mm^3)	1,793	5,640	5,863	136	258	231
Mean annual unregulated inflow rate (m^3/s)	1,382	452	646	527	788	452
CAP/MAR	0.043	0.401	0.267	0.008	0.010	0.016

Note. CAP/MAR indicates the total reservoir capacity (CAP) to mean annual runoff (MAR) ratio, which according to Kondolf et al. (2014) should not exceed 0.04 for drawdown flushing to be successful.

3.3. Reservoir Impact Assessment

After deriving plausible scenarios of sediment supply, we employ D-CASCADE to predict the impacts on network sediment transport and delivery of a series of reservoirs on the main tributaries. The analysis in this chapter focuses on six dams on the lower 3S system, whose design features are reported in Table 1. The LSP3 and LSS3 dams are defined using data from the Open Development Mekong database (MRC (Mekong River Commission), 2014). These dams are currently planned without bottom outlets, and thus without the ability to implement drawdown flushing. According to the previous assessments by Schmitt et al. (2018a), these dams would trap most of the basin's sediment, due to their downstream position on the main channels and their large impoundment volume and trapping efficiency. The other three reservoirs (LSS2-II, LSP2, and US1) were proposed by Annandale (2013) as an alternative to LSS2 to reduce sediment trapping and allow for feasible drawdown. These dams present a reduced reservoir volume to enable the complete emptying of the basin via low-level and mid-level outlets, to permit drawdown sediment flushing (Wild et al., 2016).

In Tangi et al. (2022), we introduced the concept of add-ons components in D-CASCADE, defined as tools included in the modeling framework and designed to simulate hydro-morphological processes at the reach level that the graph-based structure of D-CASCADE cannot capture. Interactions between add-ons components and D-CASCADE are typically dynamic and two-directional, as changes in reach hydro-morphological features modeled by the add-ons may affect basin-wide connectivity patterns, and vice versa.

To integrate the dynamic representation of reservoir features and dam operational strategies, we developed four novel add-on components in the D-CASCADE modeling framework (See Supporting Information S1 for more detail):

- *The dynamic reservoir storage modeling add-on* calculates the hydromorphological features, that is, channel gradient, width, water velocity, and depth, of the flooded or partially flooded reaches falling inside the reservoir impoundment and traces their evolution through time as the reservoir storage volume varies.
- *The reservoir management add-on* simulates reservoir release strategy which determines the reservoir release in each timestep and the daily hydropower generation. In this work, we utilize a four-parameter rule curve that has been implemented by Dang et al. (2020) on the VIC model for the reservoirs on the Mekong River, and represents a reasonable simplification of the typical management strategy employed by hydropower dams in monsoonal river basins. The basin is kept at low levels at the start of the monsoon season in order to store the increased inflow during the wet season, and is at its highest at the end of the season (Piman et al., 2013; Wild et al., 2016; Wild & Loucks, 2014).
- *The reservoir sediment trapping add-on* estimates the sediment deposit inside each reservoir at each timestep and the loss in reservoir storage capacity due to continuous sedimentation. In turn, this loss will decrease the maximum reservoir volume at full supply level and affect the dam release determined by the reservoir management add-on.
- *The downstream water discharge add-on* updates the daily discharge for all reaches downstream of the reservoir according to the water released from the dam. For reservoirs in series, the release of the upstream dam influences the discharge of all reaches until the downstream dam location. Thus, water input to the downstream dam is directly affected by the release of the upstream dam at the same timestep.

In this work, we analyze three dam development portfolios for the 3S river system (Figure 1b), focusing only on the downstream dams listed in Table 1:

- **LSS2Only**: this portfolio only includes the LSS2 reservoir, the largest and most downstream dam, already operational;
- **FullDam**: this portfolio features all reservoirs currently planned or existing on the lower 3S system, that is, the LSS2, LSS3, and LSP3 dams;
- **FullDam_Alt**: this portfolio consider the alternative configuration for the LSS2 dam proposed by Annandale (2013) (LSS2_II, LSP2 and US1 reservoirs). The reservoirs in the FullDam_Alt portfolio are designed to be suitable for drawdown sediment flushing and thus assumed to be fitted with bottom outlets for this purpose.

The simulations with reservoirs are repeated for all plausible sediment supply scenarios defined in the first step. For each combination of a dam portfolio and a sediment supply scenario, we collect distributed, time-varying data on catchment sediment yields and GSDs, as well as reservoirs' water and sediment volumes.

3.4. Strategic Reservoir Sediment Management

Given its proven effectiveness in reducing in-reservoir sediment storage compared to other sediment management strategies (Atkinson, 1996; Kondolf, Gao, et al., 2014; White, 2001), this study focuses only on drawdown sediment flushing, evaluating its effects on hydropower production, reservoir sediment storage, and downstream sediment delivery. We identify PO designs for the reservoirs in the FullDam_alt scenarios, which are specifically devised for effective drawdown sediment flushing.

A specific add-on has been designed to include sediment flushing in the modeling framework. When activated, the component alters the reservoir's release strategy to achieve a complete cycle of drawdown flushing (Drawdown, flushing, and refill). In the add-on, the design, timing, and frequency of the flushing operations are controlled by five parameters, which are shared between reservoirs:

1. *Frequency* (year): frequency of flushing operations. In the simulation, we test flushing operations repeated every one, two, or 3 years.
2. *Starting month of operation* (month): starting date of the 120 days window during which flushing is allowed.
3. *Inflow rate triggering flushing drawdown* (m^3/s): Minimum inflow rate to trigger the flushing add-on, calculated as a percentile of the daily discharge data series attributed to the reach where the dam is located.
4. *Duration* (days): number of days of flushing, counted after the drawdown phase is over.
5. *US1/LSS2-II Synchronization* (days): number of days between the beginning of the flushing operation in the upstream US1 dam and the downstream LSS2-II.

The second and third parameters determine the timing of flushing operations for the two upstream dams (US1 and LSP2). When both conditions are satisfied, and the inflow does not exceed the physical capacity of the bottom outlets, the flushing add-on is triggered. These parameters increase flushing efficiency by avoiding operations during low-flow periods.

Flushing for the LSS2-II is triggered after a fixed number of days have passed from the beginning of the flushing in the US1 dam (defined by the fifth parameter). Synchronization between flushing operations in dams in series, taking into account the lag time for sediment delivery from one reservoir to the other, is paramount to avoid sediment becoming trapped in downstream reservoirs after being released from upstream reservoirs.

During the entirety of the flushing operations, hydropower production is halted. The duration of sediment flushing depends not only on the fourth parameter, but also on drawdown and refill duration. This varies according to both the reservoir storage at the start of the operation, which must be evacuated completely during drawdown, and the target reservoir storage at the end of the flushing phase, which the storage must match during refill before returning to standard operations.

During flushing, river-like conditions are re-established in reaches inside the impoundment. The abundance of fine sediment and the lack of a previously established channel lead the inflow to carve its path through the sediment, forming deeply incised channels (Atkinson, 1996; Lai & Shen, 1996). D-CASCADE cannot capture such complex 3D morphodynamic processes which would, in reality, control sediment mobilization during flushing. Instead, we rely on three empirical relations to determine flushing efficiency.

1. an empirical transport capacity for flushing flows reported in Atkinson (1996), based on observations of frequent flushing in dams in China. This equation also employs an empirical formula to correct the value of channel width during flushing based on inflow, which is used instead of the original reach width [ATK];
2. the standard Engelund and Hansen (1967) equation, used in the model for non-flushing transport capacity computation, where we reset the morphological features of affected reaches to pre-reservoir values [E&H];
3. the Engelund and Hansen (1967) equation, but with channel width during flushing altered via the width correction equation in Atkinson (1996) [E&H—Width correction].

To derive PO designs of drawdown sediment flushing, we apply the Borg MOEA (Hadka & Reed, 2013) to the following problem:

$$\max_{u}\,(J_1(u), J_2(u)) \tag{1}$$

$J_1(u)$ and $J_2(u)$ are, respectively, the indicators for hydropower generation and sediment delivery. u is a decision vector containing a combination of the five parameters defining the design of the flushing operations. Indicator $J_1(u)$ is defined as the average annual energy production (GWh/yr) for the 11 years of simulation, measured as the average of the cumulative daily energy production of all the dams in the portfolio for every year of the simulation. The reservoir management add-on measures daily hydropower generation (GWh/day). More details on the calculation of objectives are available in the Supporting Information S1 materials. Indicator $J_2(u)$ measures the average annual sediment delivery to the Mekong (Mt/yr). Annual sediment delivery is determined as the sum of all the sediment cascades delivered to the network outlet in each simulation year. Given the lag between catchment sediment inflow and sediment transport to the outlet, we spin up the model for a year, thus discarding the results for the first year.

The optimization returns the PO designs of the flushing operations, representing optimal trade-offs between the two considered objectives. We ran three separate optimizations, one for each sediment flushing equation, using a single scenario of sediment supply as a baseline. To test the robustness of the thus-derived PO solutions, we rerun them for all the accepted sediment supply scenarios and evaluate how the position of the PO solutions and the shape of the Pareto front change with these variations.

4. Results

4.1. 3S System Sediment Budgets Estimation

Figure 3 shows the average annual sediment yield and the average coarse fraction (sand and gravel) at the outlet for the 80 scenarios of sediment supply. Sediment load at the outlet correlates directly to sediment supply and input grain sizes. A finer sediment input is correlated with higher sediment loads at the output as finer sediment sizes are transported at higher rates than coarser grain sizes under the same hydraulic conditions. Thus, coarser sediment classes are more likely to be trapped in zones of low transport capacities, or “bottlenecks” (Schmitt et al., 2018b)) and scenarios with coarse grain sizes but high supply do not result in more sediment delivery to the basin outlet.

All simulations show distinct sediment fining patterns along the network as fine grain sizes are transported preferentially, as evident by the by the decreasing D50, for the same scenario, from input sediment supply to output sediment load in Figure 3. For the simulation with coarse input D50, the difference between input and output GSD is most evident, as most of the coarse material will encounter bottlenecks of low transport capacity. At the same time, the finer classes, initialized in lesser quantities, are transported more rapidly through the network. As scenarios with finer sediment input present a higher connectivity rate, the input material can be more efficiently conveyed to the outlet. As a result, finer scenarios are more distant from each other.

We select 16 scenarios resulting in sediment loads at the 3S-Mekong confluence in the range 17–25 Mt/yr reported in previous studies Koehnken (2014), Kondolf et al. (2014), and Wild and Loucks (2014). Those 16 scenarios were the basis for our simulation of dam siting and operation. Grain size composition for those scenarios at the basin outlet consisted of around 20%–40% of coarser material (sand and gravel) and 80%–60% of finer material (silt, clay).

4.2. Cumulative Impact Assessment of Multiple Reservoir Operations

We run D-CASCADE on the 3S network for 11 years of simulation for the three dam development portfolios under the 16 acceptable sediment delivery scenarios. Figure 4a illustrates the average modeled catchment

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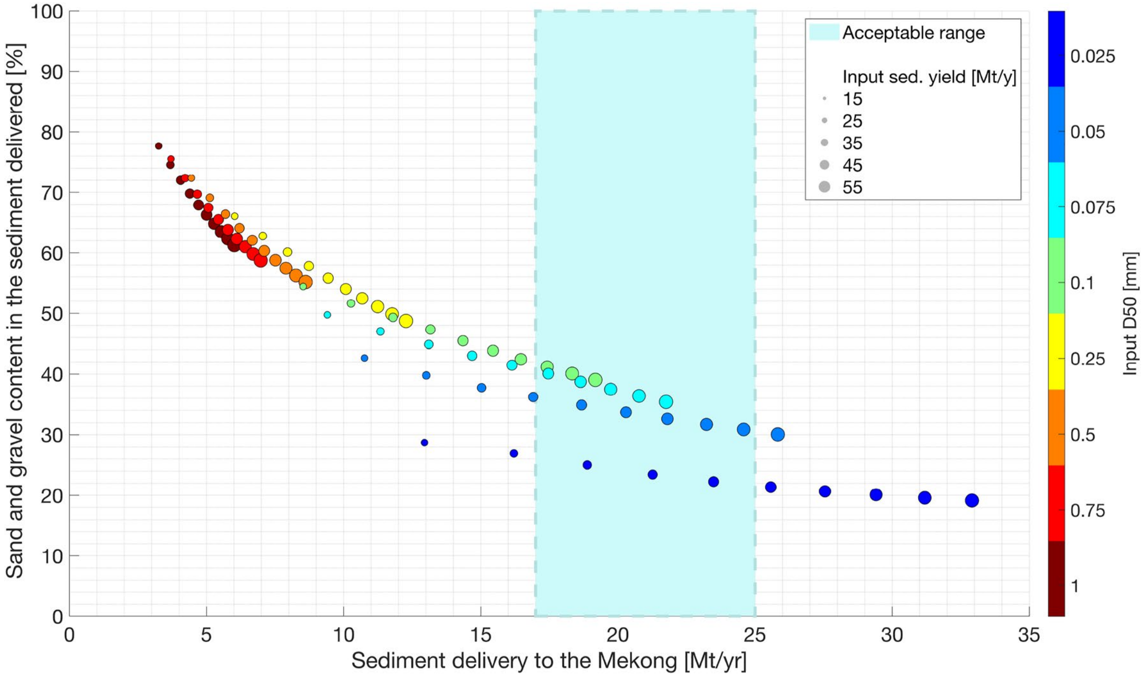

Figure 3. The figure shows the average annual sediment delivery (Θ(3S) [Mt/yr]) and the percentage of coarse sediment (sand and gravel) at the outlet, for the 80 D-CASCADE simulations with different scenarios of input annual sediment supply and sediment median grain size. Marker size defines the total annual sediment delivery to the network, while marker color indicates the D50 of the input material. The light blue area represents the acceptable range of solutions given the estimates of sediment yield from the 3S basin to the Mekong from literature.

sediment yield to the output, partitioned by tributaries and grain classes. As expected, all dam development scenarios lead to a decrease in sediment yield at the outlet. In the LSS2Only and FullDam scenarios, the total sediment yield decreases around 52% (min-max 51%–56%) and 56% (55%–60%) respectively, and the combined delivery from the Se San and Sre Pok drops by 88% and 94%, averaging around 0.6–1.4 Mt/yr instead of the 11.8 Mt/yr in the undammed case. The sediment starvation is predominantly caused by the LSS2 dam, because of its massive impounded volume and high water residence time. The inclusion of the two large upstream reservoirs causes a further reduction of the sediment delivery by another 50% in comparison to the LSS2Only scenario. An animation of the dynamic evolution of total daily sediment transport in the 3S network in the undammed and FullDam scenario, simulated by D-CASCADE, is available in the Supporting Information S1.

Alternative dam portfolios without LSS2 show a significantly lower impact on sediment delivery. In this scenario, cumulative sediment yield from the Se San-Sre Pok system decreases by 54% (5.3 Mt/yr). Total sediment yield is reduced by 32% (31%–34%). The impact of those alternative scenarios on sediment is lower due to the smaller impounded volume and water residence time in the alternative reservoirs, which raises hydraulic forces inside the impoundment, transport capacity, and ultimately sediment release.

Another significant effect of reservoir placement in the network is the preferential trapping of finer grain sizes. In all scenarios, the sediment mixture delivered to the outlet is significantly more dominated by silt than for the undammed scenario, as sand fractions are more easily detained inside the reservoir by low transport capacity in the flooded reaches. This reduction is particularly severe for the two LSS2 scenarios, where virtually no sand is delivered to the lower Mekong from the Se San and Sre Pok rivers (99% reduction), but is also present in the FullDam_alt scenario (80% reduction).

The effects of sediment trapping under different dam development scenarios on reservoir water storage are described in Figure 4b. Smaller reservoirs, as expected, are filled with sediment at a much higher rate, losing up to 16% of their total storage in 10 years. However, even larger reservoirs are affected by a non-negligible rate of sedimentation. In the LSS2Only scenario, the LSS2 reservoir loses 4.4% of its storage capacity on average

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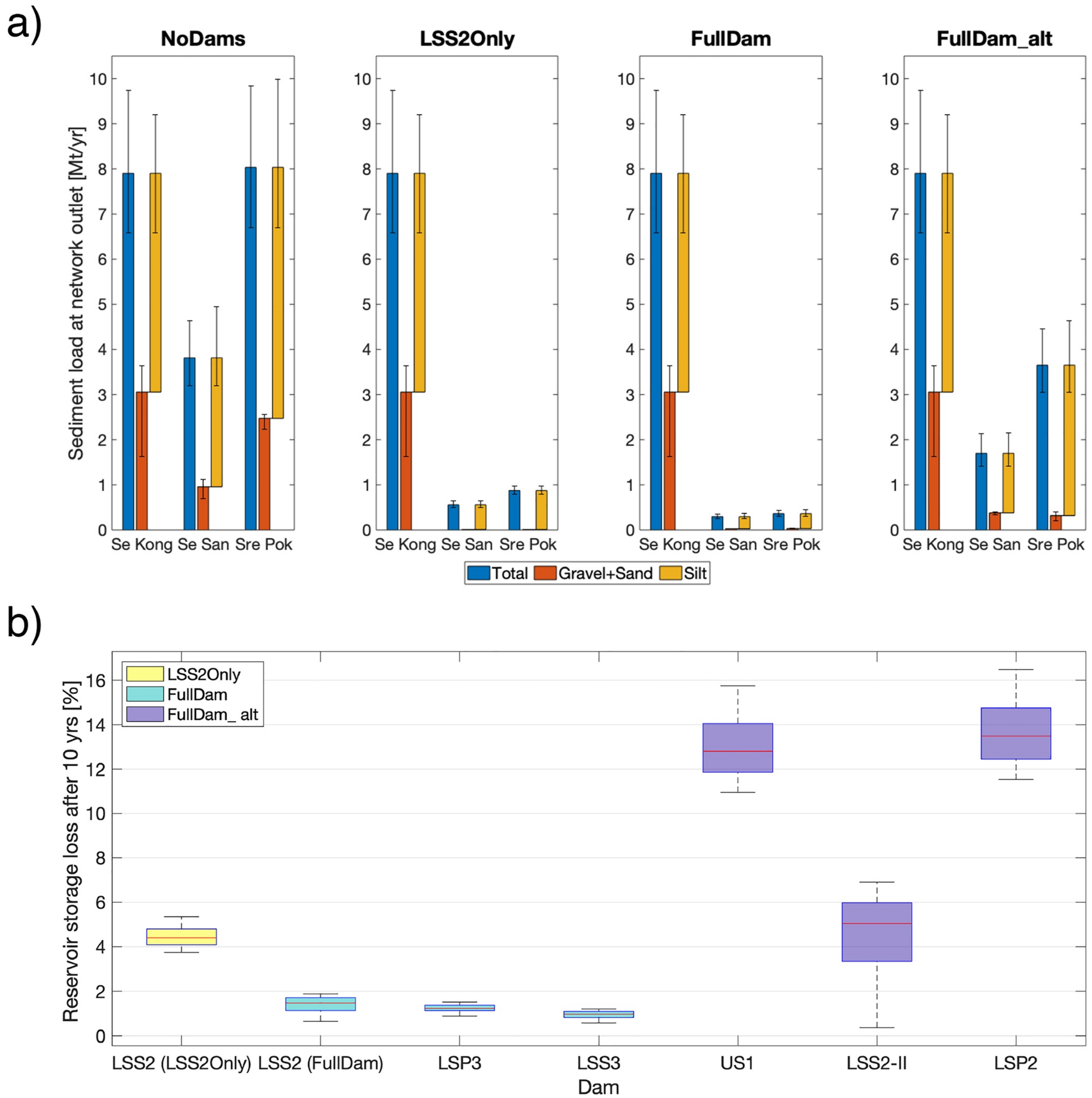

Figure 4. D-CASCADE outputs for the network connectivity simulation with different dam development scenarios. Figure (a) shows the average annual catchment sediment yield to the Lower Mekong River under different dam development scenarios, partitioned by 3S main river systems and grain size classes. Bars show the average results for the 16 sediment delivery scenarios; uncertainty bars show the range of values taken by the simulations. In all scenarios, the Se Kong river is not influenced by dam development and thus delivers the same sediment volumes. The boxplots in figure (b) show the range of reservoir water storage capacity loss after 10 years of simulations for each reservoir in the scenarios.

in 10 years. In the case of multiple reservoirs in series, as in the two FullDam scenarios, sediment trapping and consequent storage capacity losses affect the upstream reservoir considerably more. On the other hand, dams situated downstream of other barriers benefit from the lack of material in the input discharge due to the upstream sediment starvation. Due to their limited storage capacity relative to the upstream sediment delivery, the smaller reservoirs in scenario FullDam_alt appear more sensitive to changes in input sediment supply.

4.3. Strategic Reservoir Sediment Management

The simulations of D-CASCADE in the Borg MOEA for the optimization of sediment flushing design were run using the sediment supply scenario with D50 = 0.05 mm and total annual sediment input of 40 Mt/yr, which represents a midpoint among the acceptable scenarios both in terms of supply and GSD. Once the Borg MOEA algorithm has identified PO flushing strategies, we quantify the sediment delivery and energy production of said strategies for the ensemble of 16 sediment supply scenarios. We repeat these analyses for all three different equations for flushing sediment transport capacity. Thus, we reoptimize the system for each flushing formula, and tested the derived optimal operation rules for 16 different sediment supply scenarios.

Figure 5 shows the performances of PO designs of coordinated drawdown sediment flushing for the reservoirs in the FullDam_Alt configuration for the two objectives of sediment delivery to the outlet and energy production. Figure 5a presents the resulting Pareto front for the three flushing equations defined before. All scenarios show that a moderate to substantial increase in sediment delivery is possible with a limited reduction in energy production (maximum loss in generation is only 6,1%). The variability of sediment delivery for the same dam configuration (error bars in Figure 5a) reflects the wide variety in sediment supplies. Sediment inputs exert an influence on energy production too, as sediment trapping reduces the maximum storage capacity of the reservoirs. This effect is minor, as is clearly shown by the fact that the horizontal uncertainty bars in Figure 5a are barely visible.

Simulation results are very sensitive to different flushing transport equations. Particularly, the use of the Atkinson (1996) equation results in much higher predictions of flushing efficiency than Engelund & Hansen's (E & H) equation. Combining Engelund and Hansen (1967) with the channel width correction equation from Atkinson (1996)'s method does not yield significant differences compared to the original E&H equation, as PO scenarios are just slightly less effective in the sediment delivery objective. Flushing designs favoring sediment delivery restoration can basically restore pre-reservoir sediment delivery to the Mekong (maximum increase of 54%) using the ATK equations. In contrast, similar sediment-focused designs with the other equations can only increase delivery up to 21%.

Figure 5c shows more information on the overall design of the PO flushing strategies using the ATK formula. As expected, more frequent flushing (e.g., yearly flushing indicated by diamond markers in the figure, located in groups II and III in the figure, results in more sediment delivery but comes at the cost of energy production. Designs with less frequent flushing (e.g., bi-yearly, square markers, in group I) perform similarly to one with yearly flushing, with slightly more energy production at the cost of a starker decrease in sediment delivery. In accordance with real-world best practices, all PO solutions schedule flushing during the wet period (May-Oct) (Kondolf, Gao, et al., 2014). Sediment-focused designs, like the one in group III, begin flushing only until September-October, while more balanced configurations seem to prefer the early monsoonal season (Apr-Jul). Flushing duration average around 8 days total (min-max: 6–11 days).

The FullDam_alt dam portfolio was conceived as an alternative to the construction of the LSS2 dam. Figure 5b compares the performances of the PO flushing designs for the FullDam_alt dam portfolio shown in Figure 5a and of the LSS2 dam. The alternative configurations would have generated substantially less hydropower than the LSS2 dam (31%–40% decrease) but would have guaranteed more sediment delivery to the Mekong (27%–151% increase).

5. Discussion

Our findings demonstrate the potential of the dynamic sediment connectivity model D-CASCADE for developing strategic sediment management plans that consider dam siting and design. Each step of the 3-step approach used in this work showcases methodological advances in river connectivity modeling, reservoir impact assessment, and integration of sediment transport models in multi-objective analyses.

By employing simple estimations of annual sediment supply as input to the system, D-CASCADE can generate complex spatial-temporarily distributed scenarios of delivery and transport in a river system. Its numerical efficiency allows for screening many basin-scale sediment connectivity patterns, while maintaining a dynamic and basin-scale perspective. In a data-scarce case study like the 3S system, this property allows quantifying credible patterns of sediment delivery by initializing the model boundary conditions with multiple parameter configurations. We can then identify an ensemble of model realizations whose outputs are consistent with the limited field

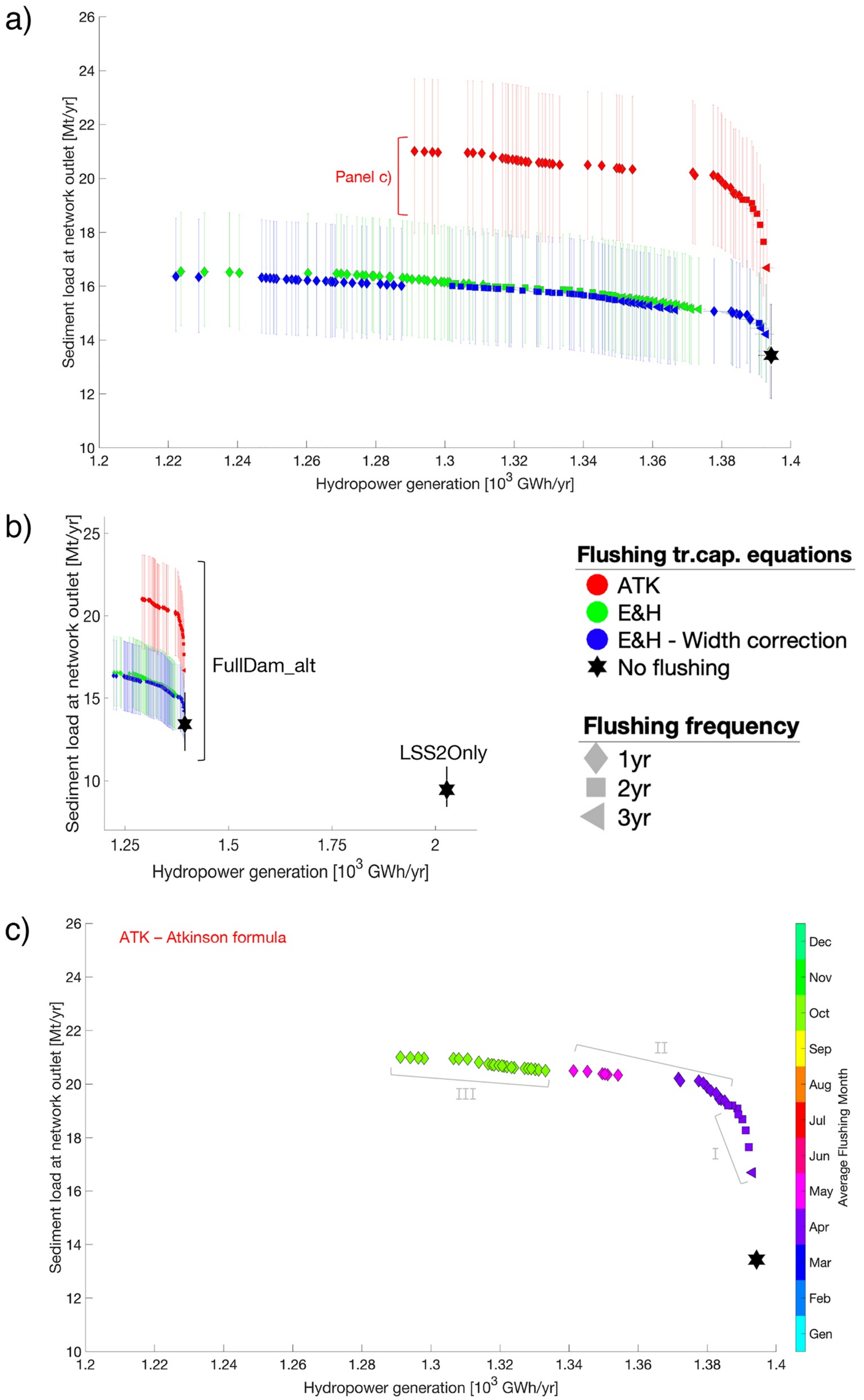
a)
Sediment load at network outlet [Mt/yr]
Panel c)
Hydropower generation [10^3 GWh/yr]
b)
Sediment load at network outlet [Mt/yr]
FullDam_alt
LSS2Only
Hydropower generation [10^3 GWh/yr]
Flushing tr.cap. equations
ATK
E&H
E&H - Width correction
No flushing
Flushing frequency
1yr
2yr
3yr
c)
ATK – Atkinson formula
Sediment load at network outlet [Mt/yr]
I
II
III
Hydropower generation [10^3 GWh/yr]
Average Flushing Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Gen

Figure 5.

and literature data available at the mouth of the system. These realizations also provide insights into the overall configuration and composition of the sediment connectivity patterns of the network. In contrast to previous, steady-state implementations of CASCADE (Bizzi et al., 2021; Schmitt et al., 2018b), D-CASCADE provides insights on how dynamic, time-varying hydro-morphological or anthropic processes affect sediment connectivity over time and space.

The fraction of coarse material in the sediment delivery to the outlet (20%–40%) in the acceptable scenarios is higher than the one of the Mekong River in the same geographical area (15%–35% based on data by Koehnken (2014)). This is coherent with field data by Koehnken (2012a), Koehnken (2012b), which shows that sediment influx from the 3S basin causes an increase in the coarseness of the sediment load in the Mekong.

Results for the sediment supply scenarios suggest that the system's overall efficiency for sediment delivery is highly dependent on the type of material initialized as input, as well as the quantity of material from the catchment. All simulations also resulted in coherent basin-scale sediment fining, as is evident by comparing the GSD of the sediment supplied to the network compared to the one of the output sediment load, which is frequently observed in large sand-bed river systems (P. Morris & Williams, 1999; Frings, 2008). It must be noted, however, that the effects of already existing upstream dams on the sediment delivery downstream are not considered, as estimating network sediment delivery post-dam construction would add additional uncertainty in the absence of recent sediment data from the basin.

In all the considered scenarios, dams bring a remarkable decrease in sediment delivery to the outlet. Dam trapping efficiency varies according to their flooded area, the impounded volume, and their location. Furthermore, reservoir sediment trapping affects different sediment classes at varying degrees, with fine sediments carried in suspension escaping the impounded area at higher frequencies due to preferential transport and higher settling velocity.

The LSS2 reservoir, with its massive flooded area and volume, has the most significant impact on river sediment delivery. Its position on the Se San—Sre Pok's confluence means that sediment from the two major tributaries would need to be transported through a major reservoir. The current planned configuration of dams (LSS2, LSS3, and LSP3) would significantly reduce the sand delivery to the Lower Mekong. As sand plays a crucial role in conserving the morphological stability of the Mekong delta, the decrease in sand yield would contribute to the risk of coastal land loss and delta subsidence below sea level (Kondolf et al., 2022). While not considered in our analysis, sediment retention could be even higher given the many other reservoirs located or planned upstream of the barriers being considered. However, the yields from the "LSS2Only" and "FullDam" scenarios seem to be similar despite the additional presence of upstream reservoirs in the second scenario (Figure 4a). Thus, the D-CASCADE model indicates that building reservoirs above the LSS2 dam may have little effect on the overall sediment yield to the outlet, as the reservoir almost completely disconnects the two tributaries from the outlet, as also seen in Schmitt et al. (2018a).

On the other hand, the alternative dams LSS2-II, LSP2 and US1 would have trapped considerably less material due to their small impoundment and subsequent low average residence time of the water in the reservoir. Hydraulic forces in the smaller reservoirs are in fact enough to entrain and transport part of the incoming material out of the impoundment.

However, results suggest that these small reservoirs may have not been suited in locations such as the lower 3S system, as their limited capacity would have meant a large fraction of the inflow during the wet season couldn't be stored and used during the dry season (as denoted by their CAP/MAR value in Table 1). Model simulations show that all alternative reservoirs should employ spillways for extended periods during the wet season to cope with high inflow rates. Finally, considering the large sediment yield of the 3S system, reservoirs with relatively contained water storage capacity would have been especially susceptible to impoundment filling from sediment trapping (Figure 4b).

Figure 5. Trade-offs between sediment supply to the Mekong and hydropower generation for different Pareto-Optimal (PO) coordinated drawdown sediment flushing strategies. Figure (a) shows the performance of PO strategies for three transport capacity equations (ATK—Atkinson (1996); E&H—Engelund and Hansen (1967); E&H—Width correction—Engelund and Hansen (1967) with Atkinson (1996) width correction equation). Uncertainty bars indicate the variability in modeled total sand flux and energy production over 16 different sediment supply scenarios. Figure (b) shows a comparison of the performances of the different flushing designs vs. the LSS2Only portfolio. Figure (c) presents more details on the PO strategies for the ATK scenario: marker color indicates the average flushing month. Different regions on the Pareto front are identified with roman numbers to facilitate discussion. In both figures, marker type indicates flushing frequency.

Regarding the optimization of the designs of coordinated drawdown flushing operation on the 3S system, our results suggest that optimal configurations should have attempted to schedule the operations during April-May, that is, the beginning of the monsoon season. By doing so, it would have guaranteed a sufficient inflow to scour sediment in the impoundment during flushing and assured a rapid and complete refilling afterward. These results are consistent even considering the high variability introduced by the different sediment input scenarios, and confirm the one found in Wild et al. (2016) and other literature regarding flushing in monsoonal regions, which suggests that the preferred timing for drawdown flushing should be at the beginning of the wet season. Here, high inflows provide enough hydraulic forces to erode part of the sediment storage without exceeding the discharge capacity of the bottom outlets. Moreover, drawdown is also facilitated in this period, as reservoirs' levels tend to be lower at the end of the dry season due to limited inflow and to guarantee storage capacity for the wet season inflows (Annandale, 2013; White, 2001; Wild et al., 2016). Finally, dry-season flushing is not advised as it may lead to an inflow of sediment to the downstream fluvial environments in months when low-magnitude sediment loads are expected (Baran & Nasielski, 2011).

Regarding the trade-offs between hydropower generation and sediment delivery, the results suggest that sediment management operations would have been performed without noticeable losses. As expected, more frequent flushing would have benefited sediment delivery to the Mekong. As an alternative, delaying flushing toward September-October, later in the wet season, would have led to higher inflows, more scouring potential, and less hydropower production, as drawdown takes longer and more of the inflow is lost during flushing (Figure 5c). It must be noted that the reservoirs in the FullDam_alt scenario have very limited storage capacity in comparison to the inflow (CAP/MAR rate in Table 1). Therefore, both drawdown and refill would have occurred rapidly (in the order of 2–3 days), reducing the overall losses in energy production. Faster drawdown and refill would also have meant that more time can be allocated to flushing, which may justify why flushing durations obtained via optimization are longer compared to what the literature typically suggests (around 3–5 days) (Kondolf, Gao, et al., 2014; Wild et al., 2016).

While the design of the PO flushing operations does not show noticeable changes using different flushing sediment transport capacity equations, the effectiveness of these sediment management operations is highly affected by this choice. Employing the Atkinson (1996) equation leads to substantially more sediment scouring in the flushed reservoir. In general, PO designs associated with this equation can remove most of the trapped sediment in the reservoirs, especially for more sediment-focused solutions. On the other hand, the PO solutions using both configurations of the Engelund and Hansen (1967) equation are remarkably less effective for sediment removal. Even the more sediment-focused designs can increase delivery by just 2.5 Mt/yr on average. Between the two, the solutions found using the E&H equation with the original channel width are marginally more effective in flushing sediment, as the channel width equation used in Atkinson (1996) leads overall to slightly larger channels during flushing and therefore, less transport capacity.

While the construction of the LSS2 dam without drawdown flushing outlets renders the alternative configurations impossible from a practical standpoint, our results illustrate how alternative planning of dam portfolios, which changes either the design of the reservoir or integrates infrastructures for sediment management, may have resulted in different tradeoffs between the considered objectives. Choosing the FullDam_alt portfolio instead of the LSS2 dam would have indubitably led to a stark reduction in hydropower production (see Figure 5b). However, it is difficult to determine the precise benefits that this choice would have had on the sediment contribution to the Mekong, which depends both on the choice of sediment flushing design and on uncertainties in both the sediment budget and flushing efficiency.

5.1. Opportunities and Limitations for Further Research

Our simulations are based on several core hypotheses. First, the hypothesis of spatially uniform sediment delivery rates most likely clashes with real-world conditions. In fact, local rates and composition of soil erosion and detachment will be different according to several factors, for example, meteorological conditions, land use, and lithology. Further study could integrate distributed erosion models (Borrelli et al., 2020) Such models can be complemented with data from remote sensing (Dethier et al., 2020) and isotopic methods (Codilean et al., 2018), which can be used stand-alone or to validate erosion models (Schmitt, 2020). Alternatively, by abandoning the hypothesis of uniform basin-wide grain-size distribution and catchment yield and generating heterogeneous patterns of sediment delivery differentiated by magnitude and GSDs, the D-CASCADE model could explore a

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vaster range of sediment delivery scenarios to compensate for the lack of data, similar to the stochastic approach in Schmitt et al. (2018b).

While in this research we assess primarily dam impact on sediment connectivity, D-CASCADE can also be employed to estimate downstream sediment routing and budget (which can be linked with the morphological evolution of the river channel) in response to sediment alterations brought by reservoirs, and their water and sediment management strategies (similar to the approach seen in Bizzi et al. (2021)). This is thanks to its modeling nature which has a strong focus on generating network scale sediment routing and budgeting per river reach, which sets it apart from other simplified sediment transport models which focus mainly on representing sediment transport in specific locations by sediment rating curve approach (Wild et al., 2016). Future research could also incorporate additional sediment sources into the analysis, such as localized debris flow or sediment stores and sinks on the floodplains and in river channels and banks (Tangi et al., 2022). The use of more accurate DEMs, and field and satellite observations could also improve the accuracy of the model by reducing uncertainties in the estimations of the channel geometry features. Additionally, alternative transport capacity equations could be tested to evaluate the results' sensitivity to such changes.

D-CASCADE successfully integrated reservoir management in the modeling framework by including multiple add-on components that explore the dynamic evolution of the sediment storage in three dimensions and update the hydromorphological conditions of both the flooded and downstream reaches accordingly. The four-parameters rule curve implemented in the model, while simple, allows for the simulation of the effects of time-varying release strategies on the system. Future research may improve the complexity of the representation of the operating strategy, for example, by defining optimal release according to the daily market energy price or inflow forecasts in the case of hydropower dams, or other objectives like flood protection, water supply, or fluvial ecosystems protection.

The evaluation of the trade-offs of sediment management strategy via multi-objective optimization represents a novelty in the application of large-scale conceptual sediment models. The results demonstrate how moving from a static, time-averaged representation of sediment delivery, like in Tangi et al. (2019), to the dynamic one seen in Tangi et al. (2022) can also support the decision-making with regard to both planning and management of anthropic interventions in river systems. The timing and synchronization of flushing operations in multiple reservoirs, as well as the estimation of its effects on the broader network sediment connectivity, can only be accomplished via the spatiotemporal tracing of the material movement throughout the network.

Our analysis of the configuration of drawdown flushing considers a simplified, albeit realistic, modelization of these types of operations. While the resulting PO designs are coherent with the suggestions found in the literature, the limited number of objectives and the necessary simplifications in the methodology lead to significant uncertainty in the results. Nevertheless, the results provide a broad indication of the best timing and duration of flushing, as well as its benefits to the network sediment delivery and reservoir storage capacity conservation.

The variations in the results depending on the type of flushing transport equations, evident in Figure 5a, hint at a more fundamental problem of numerical estimation of flushing efficiency. In this research, the mobilized sediment volume during flushing is determined by the transport capacity of the reservoir's reaches in free-flow conditions. By all accounts, the now-empty reaches are treated by the model as conventional river channels, and erosion is measured according to standard D-CASCADE operations. However, sediment mobilization from reservoir bottoms may require different modeling strategies to account for the 3D evolution of channels in reservoir deposits. Wild et al. (2016), for example, used geometric analysis of the incised channel to calculate sediment scouring, which resulted in an almost complete evacuation of all sediment in the reservoirs during flushing. As a result, Wild et al. (2016) indicate much higher efficiencies for a successful flushing operation. We preferred the transport capacity approach since it synergized better with the D-CASCADE model approach and allows us to explore the effects of different formulas. However, the results stand to indicate that these methods cannot reliably capture such a complex process. Future research with D-CASCADE could integrate a new 3D physics-based add-on component for reservoir sediment storage modeling to estimate trapping and flushing efficiency and reservoir storage losses. This component would dynamically simulate the evolution of the sediment deposit, accounting for its composition and cohesion, its dynamic accretion, layering, and consolidation, as well as the creation and evolution of the scouring channel during flushing (similar to the approach in Lammers and Bledsoe (2018) for channel evolution).

This research described sediment transport disruption in terms of changes in magnitude and type of sediment delivery to the Mekong and reservoir sedimentation. However, further analysis may require more specialized morphological indicators, for example, to evaluate sediment transport in multiple downstream locations to model disturbances in particular hotspots of, for example, biodiversity, or other points of interest. More indicators may also be added to account for the environmental impact of sediment management operations, for example, excessive downstream water turbidity during flushing or shifts in the natural hydrological regime.

Finally, future experiments may include a closed-loop sediment management approach, where the current water and sediment storage of the reservoirs in the system, and forecasts on incoming water inflow, influence whether management operations are performed and how they are synchronized between reservoirs.

The addition of new components to D-CASCADE may increase the reliability of D-CASCADE in providing quantifiable indicators of sediment connectivity disruption, to support the recent efforts in literature to promote the inclusion of this often-overlooked risk in decision-making processes (Kondolf et al., 2022). D-CASCADE's flexibility would also allow for easy implementation of the model in different case studies, to analyze the impacts of reservoir construction in dam development hotspots like the Amazon (Almeida et al., 2019; Anderson et al., 2018; Flecker et al., 2022) or the Balkans (Bizzi et al., 2021).

6. Conclusions

The study presented in this paper showcases how dynamic sediment connectivity modeling can be integrated with reservoir operations modeling and reservoir siting to derive optimal strategies for multi-reservoir sediment management.

This work uses a 3-step methodology, where first, robust estimations of the network sediment budget are made and established as a baseline. The impact of different dam development scenarios on sediment connectivity is then explored. Finally, the design of synchronized sediment management strategies is optimized under two objectives: hydropower production loss and sediment connectivity restoration for the most promising development scenario.

The D-CASCADE model provided reasonable sediment budget estimates for the 3S river system, employing only large-scale data sets and limited validation data, demonstrating the potential of these conceptual models for extracting morphological information in data-scarce environments already seen in other works (Bizzi et al., 2021; Czuba, 2018; Schmitt et al., 2018b).

Integrating reservoirs in the modeling structure, via specific add-on components, allows for daily simulation of dam operational strategies and their cumulative effects on network sediment transport and sediment trapping and storage in the dam basin. We explore different dam configurations scenarios on the 3S system, focusing on the downstream structures, both planned and already existing, as they are regarded as the most impacting on the network sediment connectivity (Schmitt et al., 2018a).

D-CASCADE quantified the reduction of sediment yield to the Lower Mekong River given by these dam portfolios. The current planned configuration would result in a net yield reduction of around 56%, as sediment contribution from the Se San and Sre Pok decreases to 6% of its original value. Sand delivery from these rivers is almost completely halted (99% reduction). The alternative scenario proposed by Annandale (2013) would have presented a viable option to conserve sediment delivery at least partially, as the reduction to the catchment yield would be limited to 26% for the total load. The model also estimates impoundment storage losses due to sediment trapping to be especially worrying for the smaller reservoir due to the high sediment load carried by the 3S system (around 13% of storage losses for the upstream reservoirs).

The design of optimal drawdown sediment flushing operations via multi-objective optimization, which constitutes a major novelty in this paper, shows that sediment delivery to the Mekong might have been increased with strategically-designed and synchronized operations in a series of reservoirs equipped with bottom outlets. The effectiveness of sediment delivery of synchronized flushing operations simulated in the model presents large variabilities due to the uncertainties in estimating upstream sediment delivery and quantifying the mobilized sediment volumes during flushing. Despite that, the obtained PO strategies suggest sediment flushing would have been doable with limited losses in energy production (up to 6,1% of the total average annual hydropower generation). The PO strategies derived as such would also have timed flushing operations during the start of the wet season, in accordance with previous studies on monsoonal rivers (Annandale, 2013; Baran & Nasielski, 2011; Wild et al., 2016).

Data Availability Statement

The data and codes used in this paper are available at https://doi.org/10.5281/zenodo.7276644. The code to run the BORG Multi-objective evolutionary algorithm (Hadka & Reed, 2013) used in the paper is available on request from http://borgmoea.org/.

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