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RESEARCH ARTICLE

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Reservoir operation impacts on streamflow and sediment dynamics in the transboundary river basin, Vietnam

Thao T. P. Bui[1,2] | Samehahmed Kantoush[1,3] | Akira Kawamura[4] | Tien L. T. Du[5] | Nuong Thi Bui[6] | René Capell[7] | Ngoc T. Nguyen[5] | Duong Du Bui[8] | Mohamed Saber[1,3] | Sumi Tetsuya[1,3] | Hyongki Lee[5] | Ali Saleh[9] | Venkataraman Lakshmi[10] | Alena Bartosova[7] | Doan Van Binh[11] | Binh Quang Nguyen[1,12] | Tra T. T. Nguyen[13]

[1]Department of Urban Management, Graduate School of Engineering, Kyoto University, Kyoto, Japan

[2]Research Institute for Resources and Climate Change, Hanoi University of Natural Resources & Environment (HUNRE), Hanoi, Vietnam

[3]Water Resources Research Center, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan

[4]Department of Civil and Environmental Engineering, Tokyo Metropolitan University, Hachiōji, Japan

[5]Department of Civil and Environmental Engineering, University of Houston, Houston, Texas, USA

[6]Faculty of Environment, Hanoi University of Natural Resources & Environment (HUNRE), Hanoi, Vietnam

[7]Hydrological Research Section, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

[8]Water Resource Monitoring Department, National Center for Water Resources Planning and Investigation (NAWAPI), Ministry of Natural Resource and Environment (MONRE), Hanoi, Vietnam

[9]Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas, USA

[10]Engineering Systems and Environment, The University of Virginia, Charlottesville, Virginia, USA

[11]Master program in Water Technology, Reuse and Management, Faculty of Engineering, Vietnamese-German University, Binh Duong, Vietnam

[12]Faculty of Water Resources Engineering, The University of Danang, University of Science and Technology, Da Nang, Vietnam

[13]Advanced Solution JSC, Hai Phong, Vietnam

Correspondence
Nuong Thi Bui, Faculty of Environment, Hanoi University of Natural Resources & Environment (HUNRE), Hanoi, Vietnam.
Email: btnuong@hunre.edu.vn

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Abstract

Human interventions activities around the world, particularly reservoir operation, have dramatically altered hydrological and sediment regimes in most of the major river basins. In the Mekong River, specifically the Upper Srepok River Basin (USRB) which is a main tributary of the river basin connected to the Mekong Delta's rice bowl and the Tonle Sap Lake's top inland fisheries, there are increasing concerns about the impacts of cascade reservoir operations on downstream streamflow and sediment budgets. Previous studies estimating impacts either relied solely on observed data or did not verify simulations of regulated streamflow. Using a process-based hydrological model calibrated and validated for both natural and regulated streamflow in the USRB, it was found that the monthly hydrological changes were up to ±20% compared to pre-dam periods at the most downstream station bordering between Vietnam and Cambodia (i.e., Ban Don station). The basin also experienced a slight decrease (less than 2%) in annual streamflow. Additionally, average and peak suspended sediment concentration decreased significantly in both of the annual and seasonal periods. At the Ban Don station, sediment loads were reduced 140 thousand tons/year (i.e., 15%) compared to pre-dam period. Most of the changes in streamflow and sediment budgets in the basin were driven by the Buon Tua Srah reservoir, which had the highest degree of regulation in the basin. Therefore, integrated and trans-boundary water and sediment management, particularly at Buon Tua Srah reservoir, needs to be developed for the sustainability of the river basin.

KEYWORDS
HYPE, reservoirs, Srepok, streamflow, suspended sediment concentration

1 | INTRODUCTION

Water security is critical for sustainable development, yet it is facing significant challenges due to human activities and climate change. In some areas, including Asia, the impacts of human activities on water security exceed those of climate change (Haddeland et al., 2014; Van Binh et al., 2020). Dams and reservoir operations have a substantial impact on more than half of the world's major river systems (Grill et al., 2019; Nilsson et al., 2005), resulting in reduced species diversity, human resettlement, and socio-cultural disruptions downstream (Tilt et al., 2009).

The Mekong River basin (MRB) was once a pristine watershed, but the past few decades have seen a significant increase in the construction of dams and reservoirs. Previous studies focussed on Srepok River Basin (Tran et al., 2023) have examined the use of gridded precipitation with hydrological models; Lower Mekong River Basin for hydrological modelling (Mohammed, Bolten, Srinivasan, & Lakshmi, 2018a; Mohammed, Bolten, Srinivasan, & Lakshmi, 2018b; Mohammed, Bolten, Srinivasan, Meechaiya, et al., 2018); input precipitation in Vietnam river basins (Le et al., 2020); land use mapping in the Mekong River Basin (Spruce et al., 2020), hydrology in the Vietnam Mekong Delta (Mondal et al., 2022); downscaling of soil moisture (Dandridge, Fang, et al., 2019); precipitation from different earth observations (Dandridge, Lakshmi, et al., 2019); decline of biomass (Vu et al., 2019); flooding (Fayne et al., 2017) and droughts (Lakshmi et al., 2023). Over 60 large dams (>15 m high) have been built or are being operated in the MRB, with eight of them in the mainstream of the Mekong River and the remaining in its tributaries (Van Binh et al., 2021). This rapid expansion has resulted in conflicts among multiple water users between upstream and downstream areas (Hecht et al., 2018). Besides, in the MRB, particularly in the Upper Srepok River Basin (USRB), previous studies have increasingly raised concerns of the impacts of planning and existing reservoir operation on streamflow and sediment budgets (Chua & Lu, 2022; Gunawardana et al., 2021; Kondolf et al., 2014; Kondolf et al., 2018; Lu & Chua, 2021; Ngo et al., 2016; Piman et al., 2012; Piman et al., 2013; Soukhaphon et al., 2021; Tang et al., 2023). Piman et al. (2016) used the HEC ResSim and SWAT models to assess the potential impacts of definite-future and far-future dam planning on the 3S (Sekong, Sesan, and Srepok Rivers) basin. In the definite future scenario, they found out that full hydropower development in the Vietnam Highlands would decrease average dry season flows by 28.2% and increase average wet season flows by 7% at 3S outlet in Cambodia. Meanwhile, in the far-future scenario, all proposed hydropower projects would further increase average dry season flows by 88% and decrease average wet season flows by almost 25%. Seven of the proposed large dams in Cambodia and Laos were found to be responsible for more than half of these changes, and the Lower Srepok 3 project had the greatest impact among them. Meanwhile, Soukhaphon et al. (2021) investigated the 3S river system and found that dam construction had adverse impacts on the migration of fish and the hydrology of the river.

Regarding sediment impacts, Kondolf et al. (2014) used the 3W model to estimate sediment starvation for three scenarios of future dam building. They found that the full build-out of all proposed dams would trap 96% of the river's pre-dam sediment load. However, the main source of sedimentation from soil erosion, which is mobilized from the soil by rain or surface runoff subject to various reservoir operation patterns, was not considered in the 3W model. Instead, they used an empirical relationship between total reservoir storage volumes and trapping efficiency at annual time scale, in addition to the sediment yields estimated from the location of reservoir with respect to nine geomorphological regions in the basin. Similarly, Wild and Loucks (2014) also estimated impacts of existing and planning reservoirs to sediment budget in the region using process-based Soil and Water Assessment Tool (SWAT) model and Sedsim. The study found that over time between 40% and 80% of the annual suspended sediment load could be trapped in reservoirs constructed in the region, but the reservoir storage would not be affected even after 100 years. However, the authors also noted that their SWAT model was not yet accurately calibrated for sediment production in the 3S basin due to data unavailability. As previous studies either relied solely on observed data or did not verify simulation of post-dam streamflow and sediments with consideration of the actual operation rule curves of existing reservoirs, the impact estimation can be of high uncertainty. While results using observed data alone includes effects of both climate variation and dam operation, simulation without verification of post-dam streamflow and sediments is subject to higher errors.

Process-based modelling is a well-established approach for assessing the impacts on natural resources under various scenarios because it can reconstruct alternative realities. Soil and Water Assessment Tool (SWAT) model has been frequently used for modelling streamflow and sediment concentration in various basins, including Mekong (Piman et al., 2012; Piman et al., 2013; Shrestha et al., 2016), Mississippi (Jalowska & Yuan, 2019), and Nigerian basin (Daramola et al., 2019). Meanwhile, Hydrological Predictions for the Environment (HYPE) model is well-known for its process modelling of both streamflow and sediment concentrations at multi-basin and continental scale (Arheimer et al., 2020; Bartosova et al., 2021; Du et al., 2022). Although SWAT can simulate both streamflow and sediment transport (Tran et al., 2022), it is often coupled with US Army Corps of Engineers' HEC-ResSim model to model impacts of reservoir operation on changes in natural regimes of streamflow and sediment concentration (Piman et al., 2012; Piman et al., 2013). Meanwhile, HYPE can model various rule curves of reservoir operation (Du et al., 2022; Pechlivanidis & Arheimer, 2015) so that it can be directly used to assess the impacts of reservoir operation.

Accordingly, this study aims to evaluate the impacts of existing cascade reservoir operation on downstream streamflow and sediment concentration in a main tributary of the MRB, the Upper Srepok River basin, where there are multiple reservoirs and dams in operation and planning. Findings from the study can provide important implications for decision-makers to develop appropriate transboundary water and sediment management plans under growing concerns about negative impacts of human intervention activities in the MRB.

2 | STUDY AREA AND DATA

2.1 | Study area

The Srepok River originates from Vietnam and flows into Cambodian and Lao territories before entering the Mekong Delta (Naeimi et al., 2013). The basin is thus a representative case study of possible emerging conflicts among multiple water users (e.g., hydropower, irrigation, and water supply) as well as among multiple international stakeholders (e.g., Vietnam, Laos, and Cambodia). The river is a major tributary of the Mekong River, contributing a significant volume of water to the Mekong River (Piman et al., 2016). Total annual flow of Srepok is 9.7 billion m^3 (Müller, 2003). The river originates in Vietnam's Central Highlands and flows southwest into Cambodia through the provinces of Mondulkiri (Figure 1). The Srepok River merges

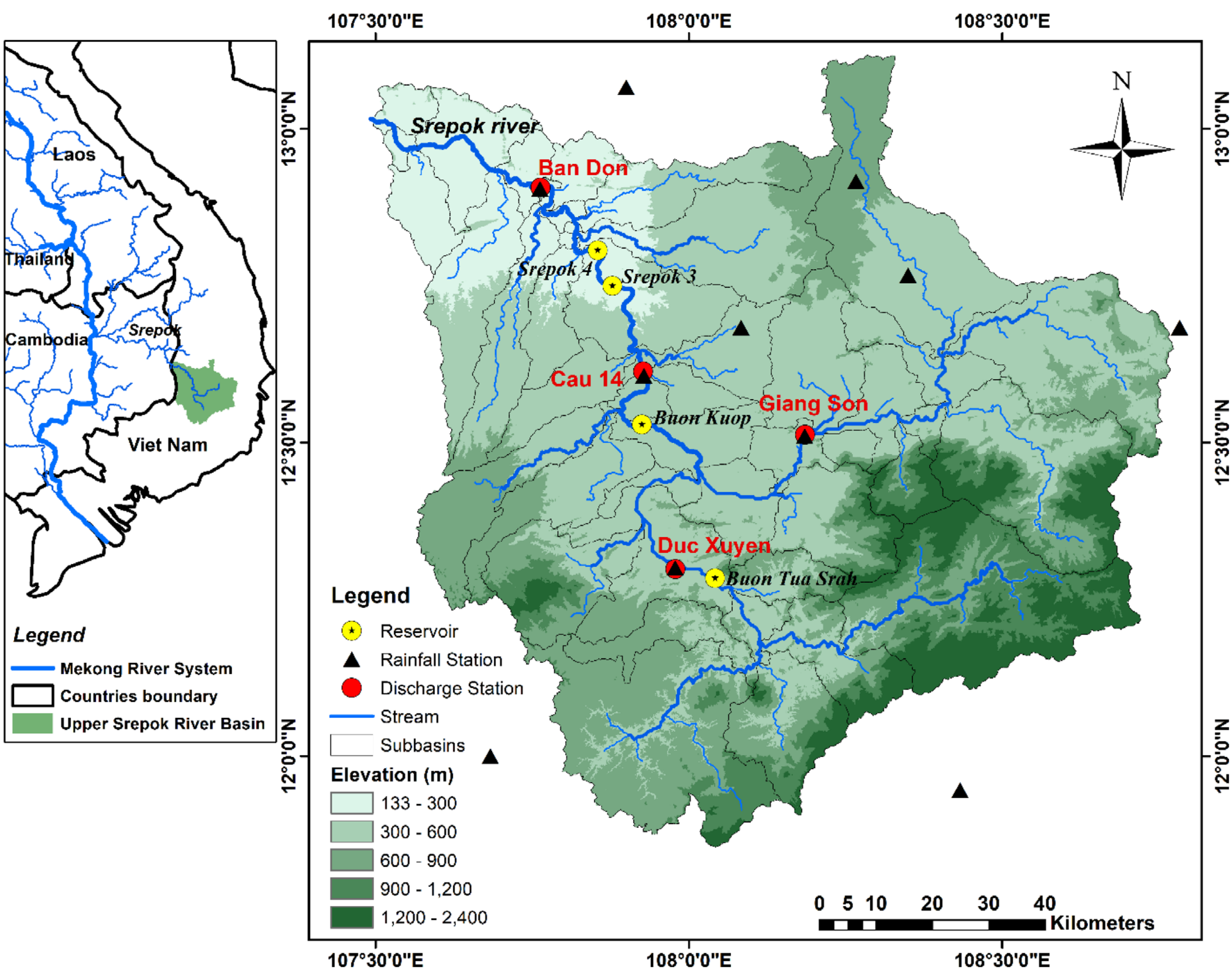

FIGURE 1 Location map of the upper Srepok River Basin.

TABLE 1 List of hydrological stations in the Srepok river basin.

Station name	River name	Longitude	Latitude	Catchment area (km^2)
Ban Don	Srepok	107.76	12.91	10 700
Cau 14	Srepok	107.93	12.61	8610
Giang Son	Krong Ana	108.19	12.51	3180
Duc Xuyen	Krong No	107.98	12.30	2960

TABLE 2 Reservoir information within the USRB.

Reservoir name	Operation	Catchment area (km^2)	Designed discharge (m^3/s)	Installed capacity (MW)	Normal water level (m)	Minimal water level (m)	Total volume (10^6 m^3)	Active volume (10^6 m^3)	Dead volume (10^6 m^3)	Degree of regulation (%)
Buon Tua Srah	2009	2930	204,9	86	487.5	465	786.9	522.6	264.2	23.3%
Buon kuop	2010	7980	316	280	412	409	63.24	14.7	48.54	8%
Srepok 3	2010	9410	412,8	220	272	268	218.99	62.85	156.13	3%
Srepok 4	2010	9560	507,42	80	207	204	25.94	8.44	17.5	3%

with the Sesan River and the Sekong River before flowing into the Mekong River (Ngo et al., 2016). The Srepok River has a drainage area of 31 079 km^2 with 18 130 km^2 (60%) falling inside the Vietnamese territory. The river flows through four provinces of Vietnam, including Gia Lai, Dak Lak, Dak Nong, and Lam Dong (Quyen et al., 2014). The total drainage area in this study is about 12 000 km^2 and is located in the Upper Srepok River Basin (USRB) (Figure 1), which includes four hydrological stations (Table 1) and four main multiple-purpose dams used for water supply, irrigation, and hydropower (Table 2). In terms of land covers, the dominant type was forest (over 60%), followed by crop land (32%), rice (1.4%), urban (0.69%), and water (0.33%).

The USRB has a high humidity of average 78%–83% and a varied annual rainfall from 1400 mm to 2500 mm with a distinct wet and dry season. The wet season is from May to October with peak floods often in September and October, and accounts for over 75%–95% of the annual precipitation. Given high spatial and temporal variations, the region is subject to flash floods in the wet season and droughts in the dry season. The mean annual temperature is 23°C. The Srepok river provides valuable ecosystem services for the Mekong River, downstream floodplains, and the Mekong Delta. Sediments are a major source of nutrients to Tonle Sap and the Mekong Delta, which are important for agricultural productivity and stability of river morphology (Koehnken, 2012). It is one of the most important watersheds in the entire Mekong for maintaining migratory fish populations (Ziv et al., 2012). Given its steep terrain and rich soil content, the basin has high advantages for hydropower development and agricultural productivity. Surface water resources of USRB is essential for socio-economic growth and providing livelihoods for 3.4 million people.

2.2 | Data

Daily meteorological data at 10 gauged stations were collected from the National Centre for Hydro-Meteorological Forecasting (NCHMF) throughout a period from 1990 to 2021 (Figure 1). Due to the sparse distribution of rain gauges in the basin, the merged daily precipitation dataset Greater Mekong Forcing data (GM_Force) that has a long record since 1979 with 0.25° spatial resolution and was robustly validated in the Greater Mekong (Du et al., 2022) was used. Du et al. (2022) found that GM_Force showed a better agreement with rain gauges in the region in terms of temporal correlation and quantitative errors. Additionally, temperature data was collected from the National Centers for Environmental Prediction Climate Forecast System version 2 (NCEP CFS v2; Saha et al., 2014) with the same spatial resolution with GM_Force.

Hydrological data, including streamflow and suspended sediment concentration (SSC) at four stations, including Ban Don, Cau 14, Giang Son, Duc Xuyen (Table 1) from 1990 until 2021, were used to calibrate and validate the model. Data availability of streamflow and SSC was not completely overlapping. While observed streamflow data was available from 1990 until 2018 at all four stations, SSC data was only available from 1998 at Duc Xuyen and from 2004 at Ban Don. Therefore, calibration and validation periods for streamflow and SSC were not the same time due to data availability limitation.

In addition to hydro-meteorological data, characteristics and operation data for four main dams were collected. Table 2 summarizes the main attributes of the four dams. The information was retrieved from the Decision No. 1612/QD-TTg dated November 13th, 2019 regarding regulations on multi-reservoir operation in the Srepok River basin. Daily inflows, outflows and water levels from 2016 until 2018 were collected from the Vietnam Electricity (EVN) and the Department of Water Resources Management from Vietnam Ministry of Natural Resources and Environment. The operation data was only available since late 2014 due to requirements of new regulations. Degree of Regulation (percentage) was calculated as the division of total storage capacity over the average annual inflow.

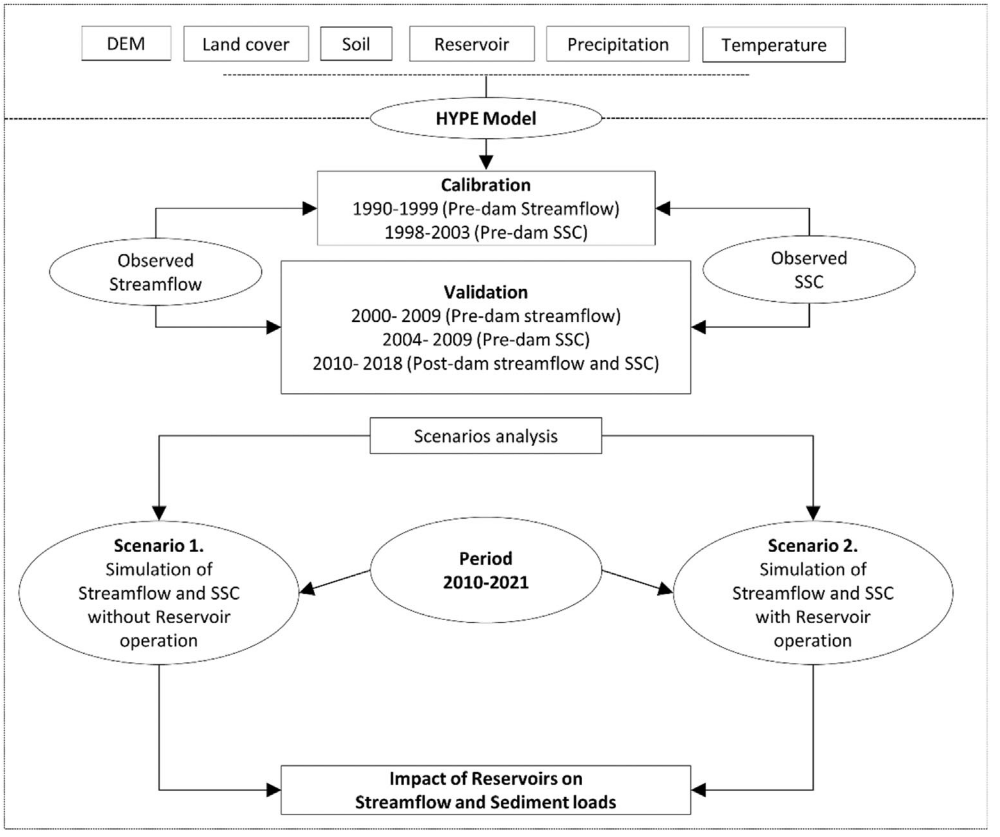

FIGURE 2 Research flowchart.

3 | METHODS

To evaluate the impacts of cascade reservoir operation on downstream streamflow and sediment, there are three main steps in the methodology: (i) calibrating and validating the HYPE model in the USRB (Srepok_HYPE) against observed streamflow and SSC before dam operation for the period 1990–2009; (ii) validating the Srepok_HYPE against observed streamflow and SSC after dam operation for the period 2010–2018; and (iii) evaluating impacts of dam operation on streamflow and SSC for the period 2010–2021. Since all of four dams started to operate since 2010, we chose 2010s to estimate the long-term impacts of dam operation. In this study, the transition state of dam construction was not modelled since its impacts are often temporary while our focus was long-term impacts. Figure 2 describes the overall methodology of the study.

3.1 | Model setup

Hydrological models are useful for a wide range of applications, such as water resources planning and forecasting. Since 2002, the Swedish Meteorological and Hydrological Institute (SMHI), who developed one of the first hydrological model Hydrologiska Byråns Vattenbalansavdelning (HBV), have initiated the development of HYPE model to monitor and forecast the quantity and quality of water resources at high resolution (Arheimer et al., 2020; Arheimer & Lindström, 2014; Lindström et al., 2010). HYPE is a FORTRAN-based open-source software that can simulate multiple hydrological processes, including snow accumulation and melting, surface runoff, groundwater flow, river routing, sediment transport and delivery, and reservoir dynamics. For a detailed description of the HYPE model, refer to Lindström et al. (2010).

Without a specific consideration of soil properties, hydrologic response units (HRUs) in the Worldwide HYPE (WW-HYPE) were formed using land cover, and elevation, and climate (Arheimer et al., 2020). In line with WWH, there are total 169 unique HRUs (details of HRUs can be found in Arheimer et al., 2020). Recent research found that that soil water storage and fluxes are linked to plant type and climate conditions rather than soil attributes (Gao et al., 2014; Troch et al., 2009). For each HRU, there are three soil layers with the first layer of roughly 25 cm thick, the second between one and two meters, and the third can be deep to account for groundwater.

3.1.1 | Simulation of natural and regulated streamflow

Similar to Du et al. (2020) and Arheimer et al. (2020), the topographic data used to set up Srepok_HYPE was kept the same. Table 3 lists the name and sources of datasets used to setup the model. When setting up the HYPE for USRB, force points for catchment delineation were selected according to the locations of gauged stations for streamflow, SSC and constructed dams.

TABLE 3 Sources of datasets used to setup the Srepok- HYPE model.

Data type	Source and resolution	Reference
Topography (Flow accumulation, flow direction, digital elevation, river width)	SRTM (3 arcsec) HYDRO1k (30 arcsec) GWD-LR (3 arcsec)	USGS USGS Yamazaki et al. (2014)
Reservoirs	Global Reservoir and Dam database v1.1 (GRanD)	ESA Climate Change Initiative-land Cover project
Land Cover characteristics	ESA CCI Landcover v1.6.1 epoch 2010 (300 m)	Lehner et al. (2011)
Precipitation	Daily precipitation dataset Greater Mekong Forcing data (GM_Force)	Du et al. (2022)
	In-situ precipitation stations in Vietnam (10 stations, 1990–2021)	National Centre for Hydro-Meteorological Forecasting (NCHMF)
Temperature	National Centers for Environmental Prediction coupled forecast system model version 2 (NCEP CFSv2) (0.25° grid, 1990–2021)	Saha et al. (2014)
Reservoir outflows	Four reservoirs (Daily, 2016–2021)	Vietnam Electricity (EVN) and Ministry of Natural Resources and Environment (MONRE)
Streamflow observations in Vietnam	Four stations (Daily, 1990–2018)	National Centre for Hydro-Meteorological Forecasting (NCHMF)
Suspended Sediment Concentration observations in Vietnam	Two stations (Daily, 1998–2018)	Ministry of Natural Resources and Environment (MONRE)

Figure 3 shows that, in the HYPE model, in the presence of regulating reservoirs and reservoirs (reservoirs for irrigation, power generation, and multi-purpose reservoirs), the outflow of the reservoir (*Qout*) is calculated by subtracting the change in reservoir volume (ΔS) and evaporation (*E*) from the inflow value of the reservoir (*Qin*). Changes in reservoir volume and reservoir outflow can be simulated with an integrated reservoir operation scheme (IROS). The rule curves (*Qrule*) follows the seasonal production flows, whereas reservoir outflow (*Qout*) depends on inflow, reservoir capacity and production flow. Equation (1a) shows that, at low water levels, *Qout* value follows *Qrule* unless the water in the reservoir is less than *Qrule* but more than minimum level. When water is above the spillway level, *Qout* is at least equal to production flow *Qrule* if spillway flows (*Qspill*) is less than *Qrule* (Equations (1b) and (1c)). Spillway flows *(Qspill)* can be determined using rating curve parameters (*k* and *p* as rate and exponent) (Equation (4)) or conversion of water volume above spillway (Equation (1b)). In the last case, no *Qout* value is released (*Qout* = 0) if the reservoir water level is below the minimum level (Equation (1d)). *regvol* represents the regulating volume of the reservoir, minimum water levels or volumes are *hmin* or *Vmin*. Water volumes or levels in spillways are referred to as *Vspill* and *hspill*, respectively. More information regarding IROS can be found in Du et al. (2022) and Arheimer et al. (2017).

For four main reservoirs in the USRB, main characteristics of the dams were retrieved from the public national database, such as the elevation of the spillway *hspill*, and the regulation volume (*regvol*). Whether water is released or discharged is determined by position of water in the reservoir according to *Vmin* or *hmin* as derived from Equation (2), which is a function of reservoir surface areas at the spillway levels (*rarea*) and regulation volumes (*regvol*), rather than the actual minimum water levels of the reservoirs. Simple non-linear regression is used to calculate *Qrule* from Equation (3) using observed reservoir outflows. Additionally, *qamp* indicates the amplitude adjusting production, *qpha* is the phase shift of the production flow, while *doy* is the target day of the year (Equation (3)).

$$Q_{out} = \begin{cases} \min\left(Q_{rule}, \frac{(h - h_{min}) \times r_{area}}{t}\right) & (a) \quad if\, h_{min} \le h < h_{spill}\, or\, V_{min} \le V < V_{spill} \\ \max\left(Q_{rule}, \frac{(h - h_{spill}) \times r_{area}}{t}\right) & (b) \quad if\, h \ge h_{spill}\, or\, V \ge V_{spill}\, and\, k = 0 \\ \max(Q_{rule}, Q_{spill}) & (c) \quad if\, h \ge h_{spill}\, or\, V \ge V_{spill}\, and\, k > 0 \\ 0 & (d) \quad if\, h < h_{min}\, or\, V < V_{min} \end{cases} \tag{1}$$

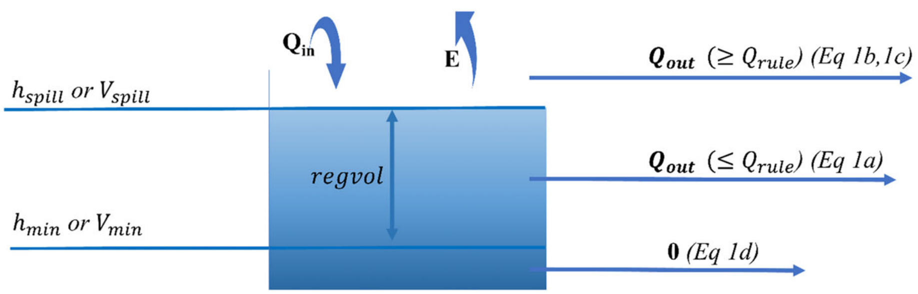

FIGURE 3 Schematic diagram of integrated reservoir operation scheme.

$$h_{min} = h_{spill} - \frac{regvol}{r_{area}}, \quad (2)$$

$$Q_{rule} = Q_{prod} \times \left(1 + q_{amp} \times \sin\left(\frac{2 \times \pi \times (doy(t) + q_{pha})}{365}\right)\right), \quad (3)$$

$$Q_{spill} = k \times (h - h_{spill})^{p}. \quad (4)$$

3.1.2 | Simulation of suspended sediment concentration (SSC) and sedimentation

The main source of sediments in the HYPE model is from soil erosion. There are two erosion modules in HYPE. The default option is based on the Morgan-Morgan-Finney erosion model (Morgan et al., 1984) and calculates particles mobilized by rainfall energy and surface runoff. The second model is based on the Hydrologiska Byråns Vattenbalansavdelning Sediment (HBV-SED) model (Lidén et al., 2001)and calculates particles mobilized by rain using a simpler index-based approach. Both WW-HYPE and E-HYPE use the HBV-SED sediment module (Bartosova et al., 2021). For both options, the mobilized particles are retained in a temporary storage pool and released over time based on the simulated runoffs. The results on sediments presented here represent the first version of calibration using model HBV-SED and are undergoing continued revision and development of both sediment and hydrology that require more observations and further calibration in the future. The web-based documentation (http://www.smhi.net/hype/wiki/) and Bartosova et al. (2021) provide more information on the sediment module, including both equations and graphic schematic diagrams. Sedimentation happens in both reservoirs and rivers. In the reservoirs, sedimentation is calculated as a function of suspended sediment concentration, sediment settling velocity (*sedss*) and the reservoir area. In the river, both sedimentation and resuspension can happen depending on the magnitudes of water flows. At high water flow, sedimentation is lower and, resuspension is higher and vice versa. No particles are removed from simulation by sedimentation in river. Reservoir sedimentation can affect the reservoir storage capacity by using siltation module. Sediments accumulated in a reservoir over time can be removed depending on capacity, sediment age or day of year using sediment flushing module. In this study, we assume natural siltation and regular man-made flushing can cancel the impacts on reservoir capacity. Key parameters control the sediment process in HYPE are shown in Appendix 1.

3.2 | Stepwise parameter estimation

Model parameters are either general or related to soil type or land covers depending on the process. Parameter can be constrained either automatically or manually, often following stepwise 'representative gauged basin' manner (Arheimer & Lindström, 2014). The storages and fluxes of water and water quality constituents among the model components are determined by model parameters linked to the catchments' physiographic features (Bartosova et al., 2021). The parameters are not directly linked to subbasins but may be soil type dependent (e.g., field capacity), land cover dependent (e.g., evapotranspiration coefficient) or general across the domain (e.g., river routing parameters). Parameter calibration and validation can be performed temporally and/or spatially. The most common approach is through temporal split of a long period into two periods for calibration and validation. The other approach is calibration at representative gauged basins and validation at other available and independent monitoring stations.

The parameter calibration process follows the same automatic and manual stepwise parameter estimation used in Du et al. (2020) and Arheimer et al. (2020). For automatic parameter calibration, the differential evolution Markov Chain (DE-MC) method was chosen similarly to previous studies. It is based on the method of Ter Braak (2006) and uses a genetic algorithm to improve parameter values in relation to a performance function. Kling-Gupta-efficiency (KGE) was used as the main function metrics.

3.3 | Model evaluation

The simulated outcomes of the HYPE model were evaluated using the key performance indices including KGE, and their decomposition components including relative errors (RE), relative errors in standard deviations (RESD) and Pearson correlation coefficients (CC) (Equations (5)–(8)). Since Nash-Sutcliffe efficiency (NSE) usually concentrates the evaluations on the top 20% of flows (Pushpalatha et al., 2012), using NSE as priority metrics for calibrating model can result in a parameter choice that understates runoff variability, particularly in catchments with considerable runoff variability (Gupta et al., 2009). Alternatively, KGE can help to intuitively understand the simulation performance through its three components (i.e., correlations, volumetric bias and variability bias) (Gupta et al., 2009). As a result, the median KGE was selected as the main HYPE goal function. A KGE value of one indicates that the simulated and observed values are perfectly aligned. Unlike NSE that uses 0 and 0.5 as thresholds of poor and acceptable model performance, a KGE below −0.41 indicates that model simulation does not improve upon observed streamflow benchmark and a KGE above 0.3 implies that model simulations are considered behavioural (Knoben et al., 2019).

Using the above metrics, the Srepok-HYPE model was evaluated for simulating streamflows at all four stations during (i) pre-dam era: calibration period (1990–1999), validation period (2000–2009); and (ii) post-dam era (2010–2018). As observed SSC was available from 1998 to 2018 at Duc Xuyen station and 2004–2018 at Ban Don station, simulated SSC was evaluated for (i) pre-dam era: calibration period (1998–2003) for Ban Don station, validation period (2004–2009) for Duc Xuyen and Ban Don stations; and post-dam era (2010–2018) for all four stations.

$$\mathrm{KGE} = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2}, \quad (5)$$

$$\mathrm{RE} = (\beta - 1) \times 100, \quad (6)$$

$$\mathrm{RESD} = (\alpha) \times 100, \quad (7)$$

$$\mathrm{CC} = \frac{\sum_{i=1}^{N} \left(OBS_i - \overline{OBS}\right)\left(S_i - \overline{S}\right)}{\sqrt{\sum_{i=1}^{N} \left(OBS_i - \overline{OBS}\right)^2 \sum_{i=1}^{N} \left(S_i - \overline{S}\right)^2}}. \quad (8)$$

In the above equations, N is the total of samples; OBS_i is observation value; S_i represent simulated value by HYPE); $\overline{OBS}$ and $\overline{S}$ represent the mean of the corresponding variables. α, β are ratio of the standard deviation and the mean value of data time series, respectively (Gupta et al., 2009).

4 | RESULTS

4.1 | Overall Srepok-HYPE model

The WHIST developed by SMHI was utilized to delineate catchment boundaries (Arheimer et al., 2020). There are 57 subbasins with an average area of 200 km^2. Among 57 subbasins, there are 49 subbasins downstream of one or cascade reservoirs. This shows that the hydrology of almost the entire USRB is impacted by dam operation.

Step-wise automatic calibration manner narrowed down the most sensitive parameters affecting modelling results. They included parameters related to soil water process, evaporation, runoff, sediment transport, delivery and sedimentation. Compared to previous studies using HYPE in the study areas (Arheimer et al., 2020; Du et al., 2020, 2022), post-calibration parameters related to sediment processes are the most different, such as *erodslope*, *erodsoil*, *erodmon, and sedss* (Table 4). The range of post-calibration parameters related to other processes can be found in details in Du et al. (2020, 2022)). Among sediment related parameters, *erodslope* and *erodsoil* parameters control soil erosion rates and were found to have a significant impact on sediment yield. Increasing *erodslope* and *erodsoil* leads to higher sediment yield. Additionally, the *erodmon* parameter controls the monthly variation in soil erosion rates. Since the region has high sediment yield in the wet season, *erodmon* was higher in these months. Finally, the *sedss* parameter controls sediment settling velocity and can affect sediment transport and sedimentation process. High *sedss* leads to a decrease in sediment transport and an increase in sedimentation. Reservoirs with higher storage capacity were found to have higher *sedss*.

4.2 | Model performance of streamflow and sediment yield simulation

4.2.1 | Before dam operation (1990–2009)

Model calibration and validation

Table 5 summarizes the model performance of simulating daily streamflow during the calibration (1990–1999) and validation (2000–2009) periods. The Srepok-HYPE had KGE of at least 0.67, and all of its components (i.e., correlation, bias in volume and variability) closer to unit during both periods. The simulated streamflow can thus capture the temporal correlation and low biases in volumes and variability compared to observed data. Figure 4 shows the hydrograph of simulated daily streamflow at all four stations. The

TABLE 4 Post-calibration Srepok-HYPE parameters related to sediment processes.

Parameters	Description	Units	Min	Max	Calibrated
erodslope	HBV-SED based model's slope erosion factor (exponent)	–	0	2	0.27
erodexp	HBV-SED based model's erosion precipitation dependent factor (exponent)	–	0	2	1.25
erodindex	HBV-SED based model scaling of subbasin erosion index	–	0	10	1.18
erodluse	HBV-SED based model's landuse erosion factor	–	0	1	[0.01 – 0.20]
erodsoil	HBV-SED based model's soil type erosion factor	–	0	1	[0.17 – 0.98]
erodmon	Correction factor for soil erosion by HBV-SED based model	–	0.01	10	[0.08 – 9.96]
sedss	Sedimentation velocity of suspended sediments in lakes	m/time step	0	10	[0.005 to 1.5]

TABLE 5 Model performance for simulation of daily streamflow for both calibration and validation periods.

	Calibration period (1990–1999)				Validation period (2000–2009)			
Performance indices	Duc Xuyen	Giang Son	Cau 14	Ban Don	Duc Xuyen	Giang Son	Cau 14	Ban Don
KGE	0.68	0.72	0.81	0.84	0.67	0.77	0.84	0.88
CC	0.69	0.75	0.83	0.86	0.70	0.80	0.88	0.88
RE (%)	−2.46	−5.52	−1.49	4.02	−1.72	−6.30	−5.85	3.16
RESD (%)	−2.07	11.97	9.42	7.97	−13.29	−9.25	−8.90	−0.79

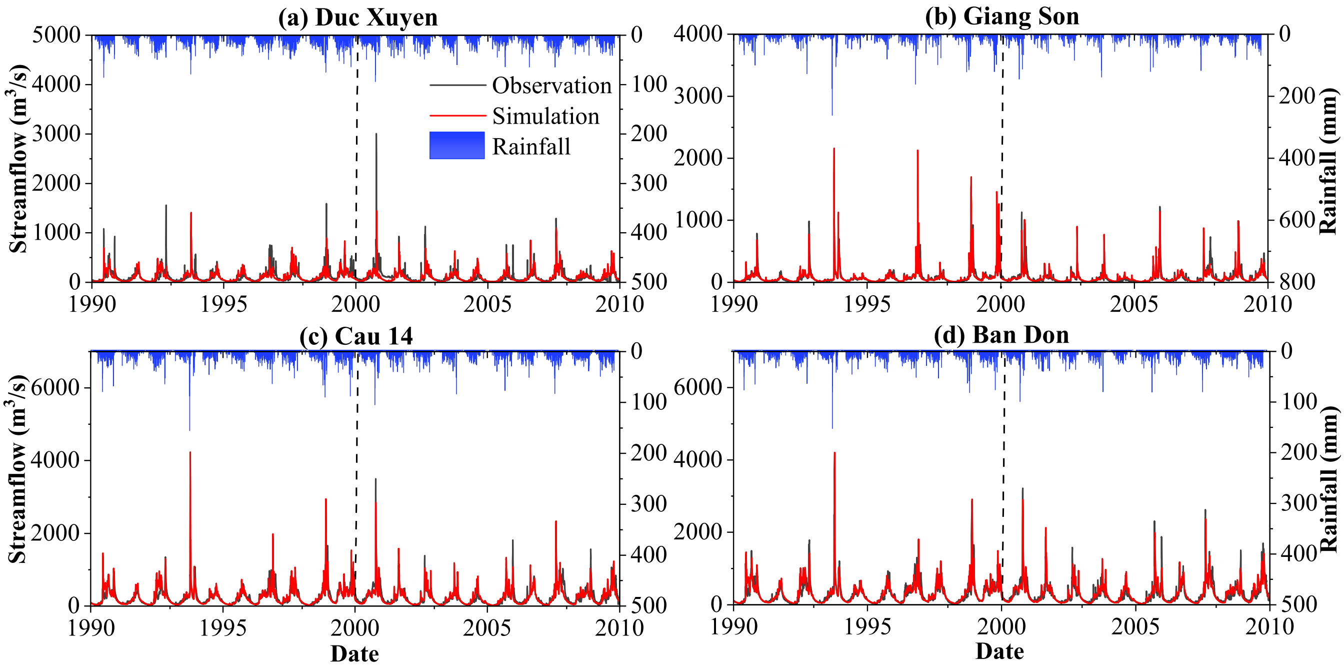

FIGURE 4 Observed and simulated streamflow for four hydrological stations within the USRB in the calibration period 1990–1999 and validation period 2000–2009.

TABLE 6 Model performance for simulation of daily and monthly SSC for both calibration and validation periods.

		Calibration period (1998–2003)	Validation period (2004–2009)	
	Performance Indices	Duc Xuyen	Duc Xuyen	Ban Don
Daily	KGE	0.37	0.35	0.45
	CC	0.4	0.41	0.48
	RE (%)	−4.7	−14.68	−19.24
	RESD (%)	20.01	23.29	5.26
Monthly	KGE	0.43	0.47	0.57
	CC	0.44	0.58	0.62
	RE (%)	−4.25	−14.6	−19.28
	RESD (%)	1.74	29.91	5.32

peak flows were overestimated at Giang Son and slightly underestimated at other stations.

Table 6 summarizes the model performance of simulating SSC for both calibration (1998–2003) and validation (2004–2009) periods. The Srepok-HYPE can model monthly SSC slightly better than daily SSC. Although volumetric and variability biases were low, temporal correlation was also low, resulting in KGE of 0.37 and 0.43 at daily and monthly scale for Duc Xuyen station. At Ban Don station, the Srepok-HYPE can model monthly SSC (KGE was from 0.5 to 0.6) relatively better than daily SSC (KGE was around 0.4). Between two stations, there was lower statistical errors at Ban Don (KGE was 0.4 and 0.6 daily and monthly, respectively) than Duc Xuyen station (KGE was 0.4 and 0.5 daily and monthly, respectively) (Figure 5).

4.2.2 | After dam operation (2010–2021)

Modelling the operation of the existing reservoirs in this period significantly improved the model performance across all stations. The performance of daily streamflow with and without reservoirs compared to observed streamflow from 2010 to 2018 is presented in Table 7. Figure 6 visualizes the observed and simulated streamflow for Duc Xuyen (i.e., at station of which hydrological regimes are affected the most) and Ban Don (i.e., at the most downstream hydrological stations in Vietnam before flowing into Cambodian territory) at both daily and monthly scale with and without modelling reservoir operation from 2010 to 2021. Time series of daily hydrograph for other stations within the USRB are shown in Appendix 2.

Table 8 summarizes the statistical performance of simulating SSC at both daily and monthly time steps when including reservoir operation and reservoir sedimentation from 2010 until 2018 at Duc Xuyen and Ban Don stations. Additionally, Figure 7 shows their hydrographs against observed data. Without modelling the reservoir dynamics, the simulated SSC will be significantly overestimated compared to observed data from 2010 to 2021. Relative errors of volume and variability reduced around 300%–500% for Duc Xuyen station and 17%–25% for Ban Don station. As a result, KGE also improved significantly for both stations (i.e., below 0 to 0.3 and 0.4 daily and monthly step for Duc Xuyen; from 0.07 to 0.4 at daily and from 0.4 to 0.5 at monthly for Ban Don station).

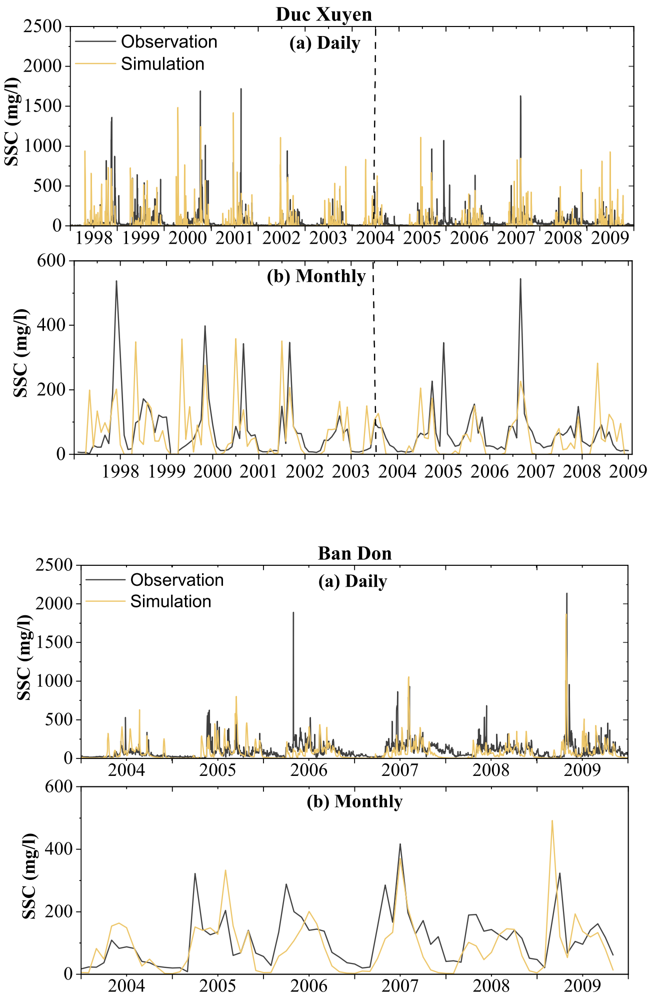

FIGURE 5 Observed and simulated suspended sediment concentration for Duc Xuyen station in calibration period (1998–2003) and both Duc Xuyen and Ban Don station in validation period (2004–2009).

4.3 | Impacts of reservoir operation on streamflow

4.3.1 | Long-term impacts

The long-term impacts of reservoir operation on hydrological regimes without and with reservoir operation at the four hydrological stations in the USRB from the past decades were analysed. Table 9 shows percentage of changes in streamflow between reconstructed 'natural' flow and the current regulated flows at the four stations on the USRB. Difference in average annual streamflow values between two scenarios is also shown in Figure 8, whereas difference in maximum and minimum annual streamflow values are shown in Appendix 3. From the results, following findings were found. First, low flows were increased, and peak flows were decreased at the three hydrological stations where there was upstream dam operation. Second, although the average values of streamflow did not change significantly over the decade (the mean values were all less than 3%), the dam impacts on the maximum and minimum flows were different spatially. More specifically, between stations, the changes in the peak flows (10.43%–29.03%) were slightly less than those of the low flows (39.86%–40.44%). Finally, percentage of changes at the Duc Xuyen was the highest due to the largest degree of regulation of Buon Tua Srah reservoir (Table 2).

4.3.2 | Seasonal impacts

Figure 9 shows the effects of reservoirs operation on the seasonal monthly flows at the three stations in the USRB in terms of magnitudes and percentage of changes from 2010 until 2021. The influences of

TABLE 7 Model performance for simulation of daily streamflow after dam operation (2010–2018).

		Simulated streamflow without reservoirs (2010–2018)				Simulated streamflow with reservoir (2010–2018)			
	Performance Indices	Duc Xuyen	Giang Son	Cau 14	Ban Don	Duc Xuyen	Giang Son	Cau 14	Ban Don
Daily	KGE	0.35	0.68	0.63	0.79	0.44	0.68	0.66	0.80
	CC	0.39	0.76	0.72	0.80	0.44	0.76	0.74	0.81
	RE (%)	1.87	−15.48	−21.49	−4.56	0.30	−15.48	−22.07	−5.60
	RESD (%)	22.91	14.75	9.54	6.68	0.16	14.75	3.86	0.15
Monthly	KGE	0.31	0.78	0.67	0.82	0.47	0.78	0.69	0.84
	CC	0.52	0.86	0.76	0.87	0.58	0.86	0.79	0.88
	RE (%)	1.68	−15.55	−21.64	−4.70	0.08	−15.55	−22.18	−5.72
	RESD (%)	50.26	−5.78	8.72	11.67	32.21	−5.78	6.07	8.09

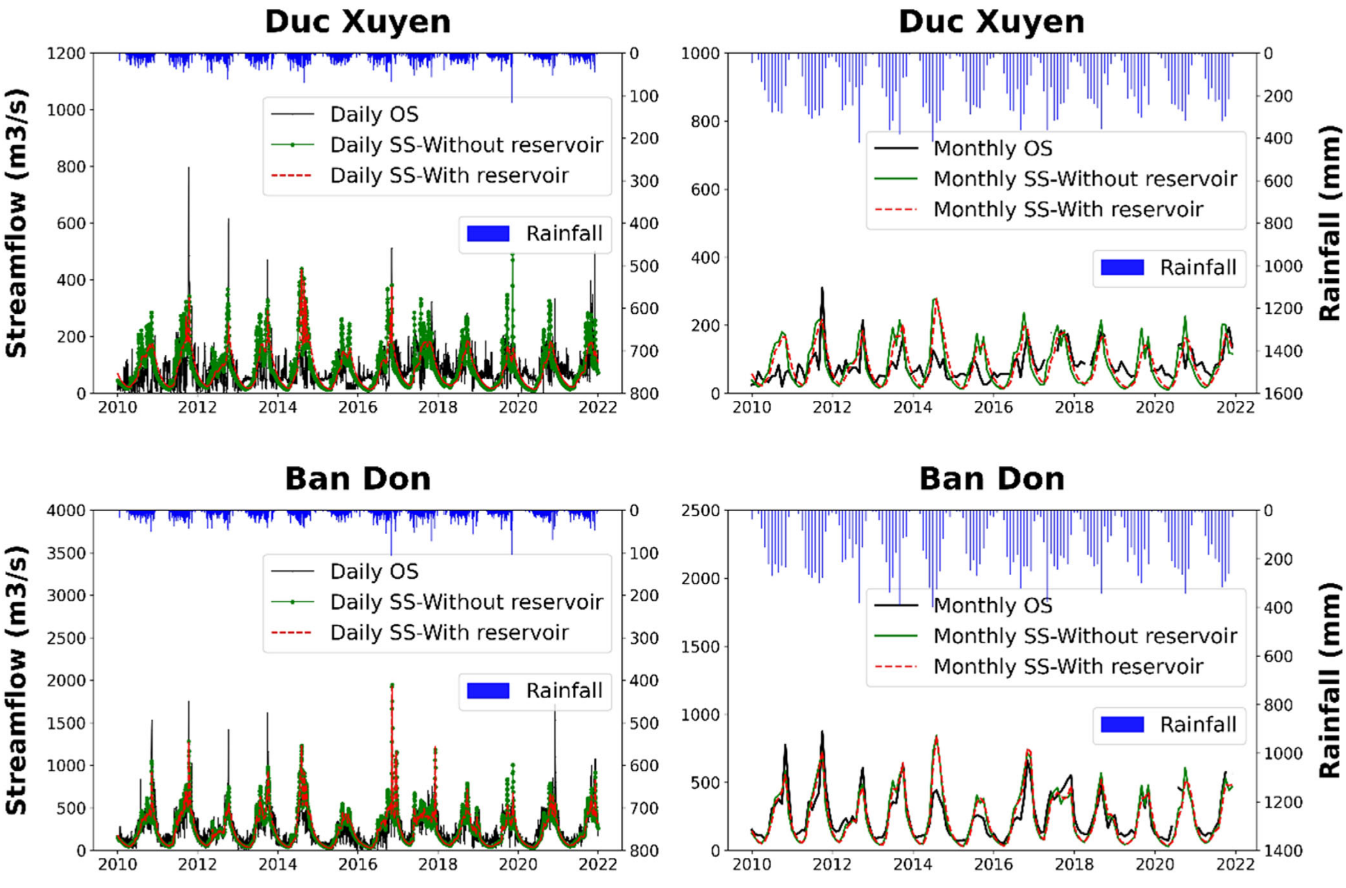

FIGURE 6 Observed (OS) and simulated streamflow (SS) in 2 scenarios without and with reservoirs for stations within USRB in post-dam period (2010–2021).

TABLE 8 Model performance for simulation of daily and monthly SSC after dam operation (2010–2018).

		Simulated SSC without reservoirs (2010–2018)		Simulated SSC with reservoirs (2010–2018)	
	Performance Indices	Duc Xuyen	Ban Don	Duc Xuyen	Ban Don
Daily	KGE	−9.83	0.07	0.25	0.35
	CC	0.12	0.34	0.28	0.35
	RE (%)	302.38	20.10	−0.26	−2.34
	RESD (%)	1036.16	61.99	22.72	−5.24
Monthly	KGE	−5.54	0.39	0.40	0.50
	CC	0.27	0.59	0.41	0.51
	RE (%)	303.26	19.97	−0.37	−2.61
	RESD (%)	575.31	40.36	21.23	14.94

reservoir operating were especially noticeable from June to September (peak months of flood season) and November and December (early of dry season). In term of percentage, changes were the highest for all months at Duc Xuyen (from −34.30% to 50.96% for Duc Xuyen and from −20% to 20% for other stations) since this station had the highest degree of regulation. In terms of magnitudes, changes were quite similar across all stations as river flow from Duc Xuyen to Cau 14 and then Ban Don. Therefore, changes at Cau 14 and Ban Don were thus driven mostly by changes from Duc Xuyen.

4.4 | Impacts of reservoir operation on suspended sediment concentration

4.4.1 | Long-term impacts

To obtain an estimate of the reservoirs' effect on SSC within the USRB, we calculated difference in maximum, minimum, and average annual SSC from the averages for the entire period from 2010 until 2021 between simulated SSC with and without reservoir operation

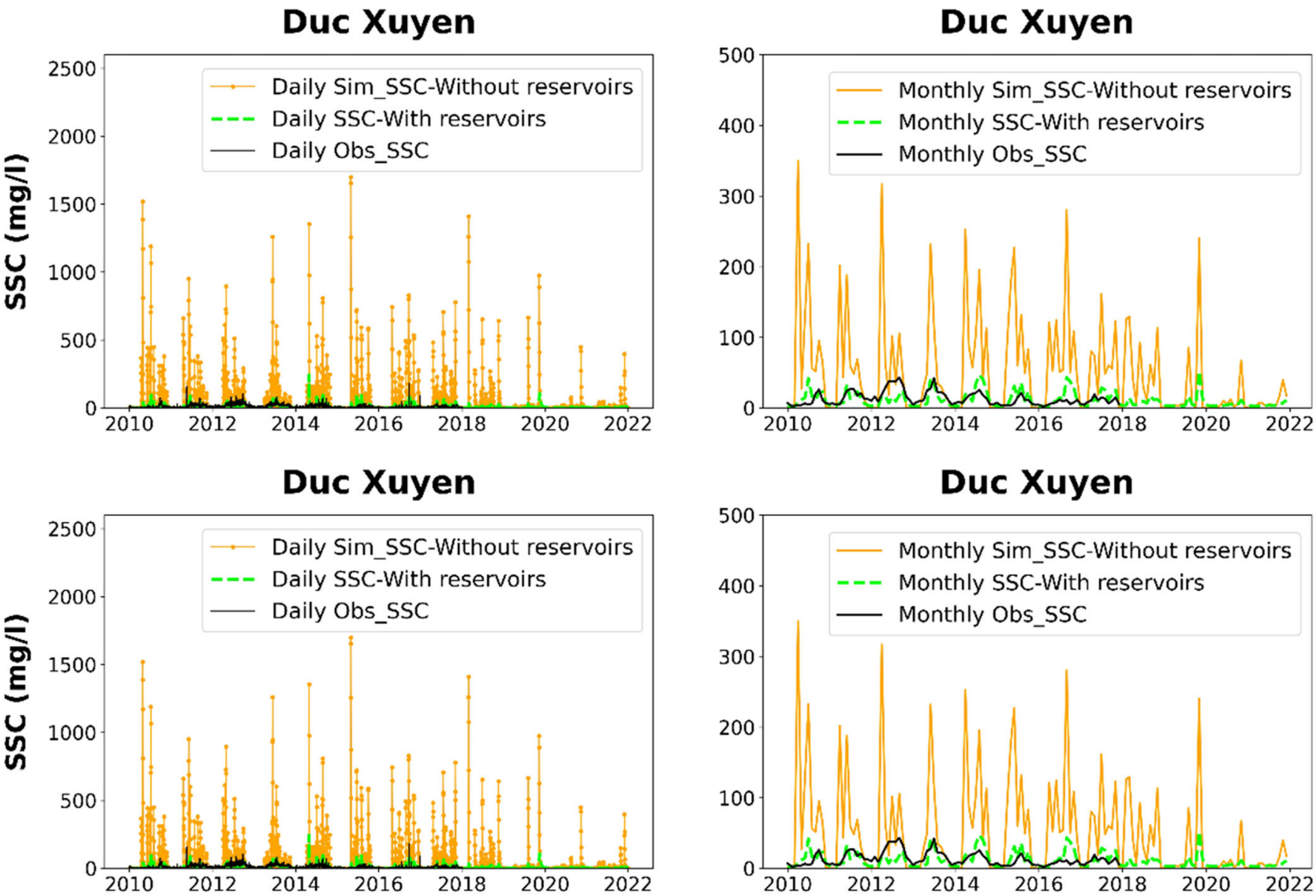

FIGURE 7 Observed (Obs_SSC) and simulated SSC (Sim_SSC) in 2 scenarios without and with reservoirs for stations within USRB in post-dam period (2010–2021).

TABLE 9 Difference in maximum, average, minimum streamflow between 'natural' (without reservoir operation) and regulated flow (with reservoir operation).

		Changes in streamflow (m^3/s) (%)		
Station	Period	Max	Avg	Min
Duc Xuyen	2010–2021	−99.22 (−29.03)	−1.54 (−1.91)	5.47 (40.44)
Giang Son	2010–2021	–	–	–
Cau 14	2010–2021	−77.56 (−10.43)	−1.81 (−0.95)	4.45 (13.45)
Ban Don	2010–2021	−99.00 (−10.65)	−2.73 (−1.15)	3.93 (9.86)

Note: The changes (in magnitudes and percentages in relative to natural flow scenario) were calculated from averages of the entire period from 2010 until 2021. Percentages were shown in parenthesis.

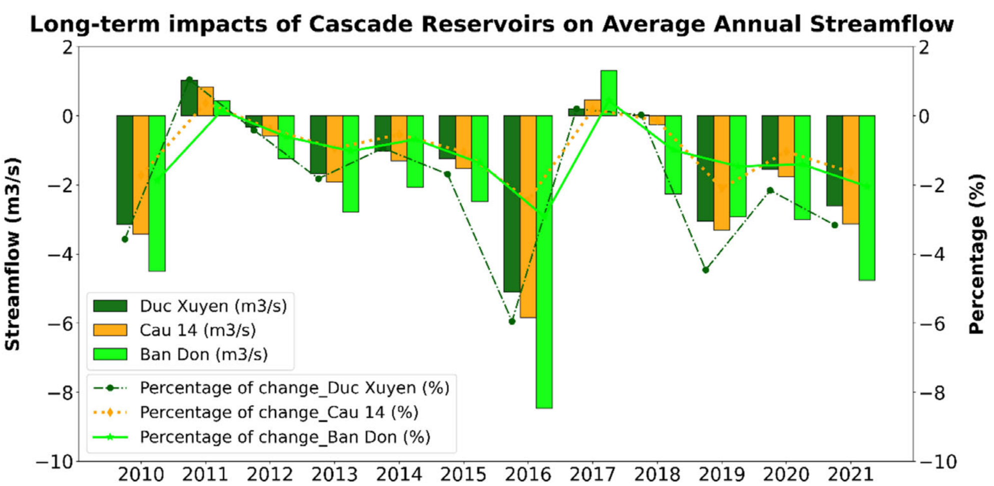

FIGURE 8 Long-term difference in average annual streamflow values between regulated and natural streamflow. Bars (left *y*-axis) show the difference in magnitude (m^3/s) whereas lines (right *y*-axis) show the difference in percentage values.

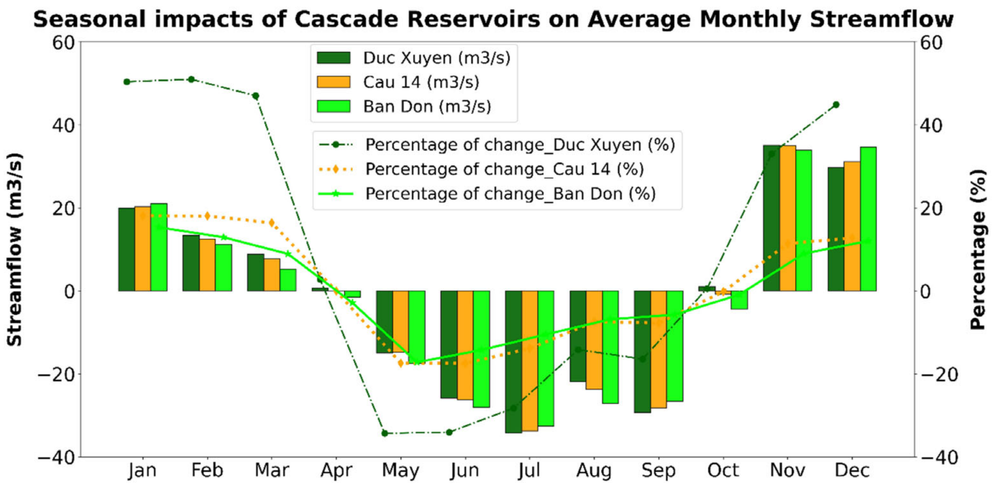

FIGURE 9 Seasonal differences by months between regulated and natural streamflow at three stations in the USRB. Bars (left *y*-axis) show the difference in magnitude (m^3/s) whereas lines (right *y*-axis) show the difference in percentage values.

TABLE 10 Difference in maximum, average, minimum annual SSC between regulated flow (with reservoir operation) and 'natural' flow (without reservoir operation).

		Changes in SSC (mg/L) (%)		
Station	Period	Max	Avg	Min
Duc Xuyen	2010–2021	−960.69 (−92.17)	−29.87 (−67.62)	1.34 (134.41)
Giang Son	2010–2021	–	–	–
Cau 14	2010–2021	−335.21 (−50.12)	−14.33 (−20.32)	1.60 (94.77)
Ban Don	2010–2021	−499.38 (−0.53)	−12.62 (−14.02)	3.10 (175.41)

Note: The changes (in magnitudes and percentages in relative to natural flow scenario) were calculated from averages of the entire period from 2010 until 2021. Percentages were shown in parenthesis.

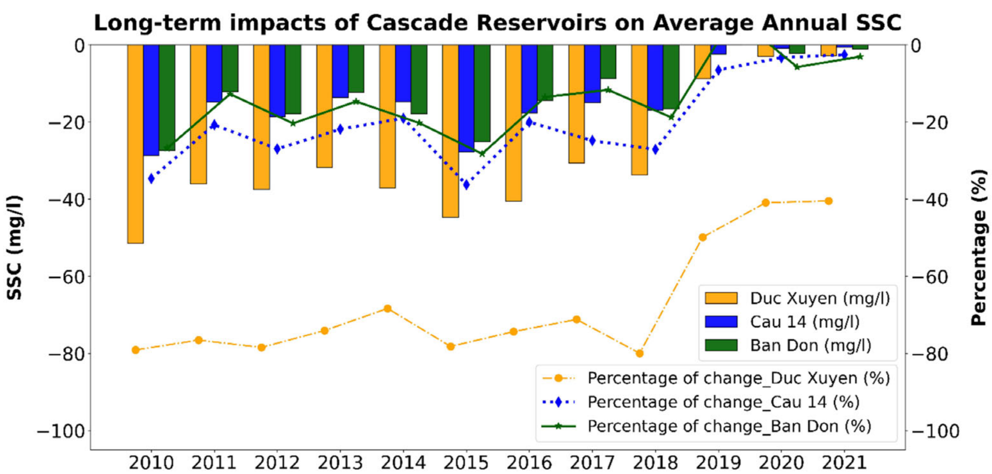

FIGURE 10 Difference in average annual SSC values between regulated and natural SSC. Bars (left *y*-axis) show the difference in magnitude (mg/L) whereas lines (right *y*-axis) show the difference in percentage values.

(Table 10). Figure 10 and Appendix 4 show the changes in both magnitudes and percentages between two scenarios in relative to natural simulation. From these results, following findings were found. First, upstream cascade reservoir operation reduces SSC values at all stations in the basin. The period from 2010 to 2021 experienced a sharp decrease in average SSC values. The values decreased by 14.02%, 20.32%, and 67.62% for Ban Don, Cau 14, and Duc Xuyen stations, respectively. Secondly, when peak flow occurred (maximum values), SSC values sharply decreased, particularly 92.17% (960.69 mg/L) at Duc Xuyen station. In contrast, during period of low flows (minimum values), SSC slightly increased due to increase of the low flows. Duc Xuyen station was also the most affected area of the reservoir operation in the basin. Meanwhile, the Giang Son was not affected since no upstream reservoirs were modelled in this area.

4.4.2 | Seasonal impacts

The variation of the seasonal SSC at three stations along the Srepok river basin has been illustrated in Figure 11. Reservoir operation reduces sediment yields across almost all months in all stations within the study area, except in January and December with a small increase

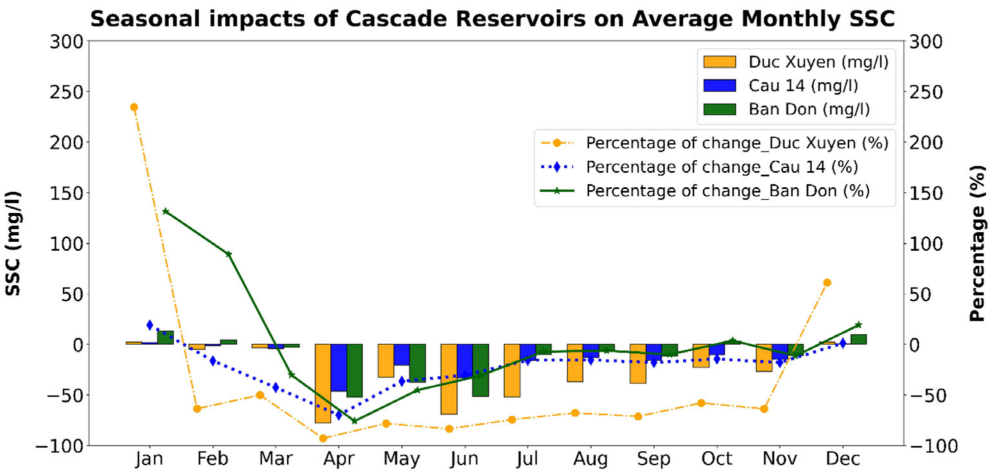

FIGURE 11 Seasonal differences in average monthly SSC values between regulated and natural streamflow. Bars (left *y*-axis) show the difference in magnitude (mg/L) whereas lines (right *y*-axis) show the difference in percentage values.

in terms of magnitude. From Figure 11, the highest decrease in SSC values (approximately 80 mg/L) was found in Duc Xuyen as this area had high topography, steep slope (Figure 1) and the biggest upstream reservoir (Buon Tua Srah). The difference in SSC percentages relative to the natural simulation shows that Duc Xuyen Station is the most affected part with sediment yield decreasing from 50% to 84%.

5 | DISCUSSION

The Srepok-HYPE model reproduced daily streamflow before and post dam operation close to observed data. In addition, the Srepok_HYPE model agreed with monthly observed SSC before and post dam operation better than with daily step. As the impact analysis focuses on seasonal and annual effect, the current performance of the Srepok_HYPE model was sufficient to provide useful insights about impacts of reservoir operation on both streamflow and SSC in the basin.

The lowest simulation agreement was recorded at Duc Xuyen Station and the highest at Ban Don Station. As Duc Xuyen station was located right after the Buon Tua Srah that had high degree of regulation (Table 2), observed streamflow were significantly affected by both the arbitrary decisions of reservoir operators and the designed rule curves. At the Giang Son station, no reservoir operation was modelled so that the performance was constant between the two scenarios. Cau 14 and Ban Don are two downstream stations, where the degree of regulation of upstream reservoirs is relatively small. Accordingly, the improvement of model simulation when including reservoir operation was insignificant.

For impact analysis, since the climate conditions were kept the same between two scenarios (e.g., with and without reservoir operation), changes in streamflow and sediment dynamics were thus driven by changes in reservoirs. For the impacts of reservoir operation on streamflow, regarding the long-term effects, average streamflows only slightly decreased (less than 3 m^3/s), whereas the impacts were more noticeable for peak flows (reduction of 100 m^3/s driven by changes in Buon Tua Srah Reservoir). For seasonal effects, the reservoirs increased the amount of water in the dry season from 20% to 50% and conversely reduced the amount of water in the rainy season from 20% to 35% depending on locations. In the definite future scenario of full hydropower development in the Vietnam Highlands, Piman et al. (2016) found that average dry season flows were decreased by 28.2% and average wet season flows were increased by 7%.at 3S outlet in Cambodia. Since 3S outlet is around 200 km downstream of the USRB outlet and their modelling results did not consider the actual operation rules of the existing reservoirs, there is a relative difference. Additionally, due to the Buon Tua Srah reservoir's largest storage capacity, Duc Xuyen station was the most affected station in the basin. Since there was no reservoir upstream modelled upstream of Giang Son station, this area was unaffected.

Regarding the long-term effects of reservoir operation on SSC and loads, after the operation of upstream reservoirs, average SSC values in the Srepok River basin declined at all stations within the USRB. From Appendix 4, it is evident that the maximum SSC levels have dramatically decreased (e.g., the Duc Xuyen station recorded a decrease in 2015 of roughly 1600 mg/L). The minimum SSC values, on the other hand, tended to rise, but the rise was insignificant (less than 6 mg/L). At all locations in the basin, monthly SSC values, especially from April to July. December and January experienced a slight increase in the SSC value. In terms of suspended sediment loads, the sediment budget decreased by 133 thousand tons per year (i.e., 77% compared to pre-dam periods) and 140 thousand tons per year (i.e., 15% compared to pre-dam periods) at Duc Xuyen and Ban Don stations, respectively, due to upstream reservoir operation, including reservoir sedimentation. Similar to streamflow, Duc Xuyen was the most influenced region by upstream reservoir operations. In comparison to previous studies, our result was closer to findings from Wild and Loucks (2014). However, we have not investigated how reservoir sedimentation would impact on storage capacity of each individual reservoir over time.

Based on the above findings, impacts to sediment regimes are of the highest concern. Downstream agricultural productivity and erosion will be significantly affected while hydropower energy production might be reduced. Sumi and Kantoush (2011) identified three main strategies for managing sediment globally, including reducing sediment yield, routing sediment, and removing sediment. The selection of a suitable sediment management option requires the consideration of various factors, such as the conditions of the sedimentation site, the relationship between annual water and sediment inflow volumes, and the design of suitable volumes to be discharged from dam reservoirs. To reduce sediment yield from upstream, it is essential to minimize the amount of sediment entering the reservoir from the contributing catchment. This can be achieved by implementing erosion control methods and trapping sediment before it reaches the reservoir. Techniques such as reforestation, controlled grazing, and terracing can be used to minimize soil erosion and reduce sediment production in the catchment. Sediment can also be trapped upstream of the reservoir using structures like check dams and detention basins that allow sediment to settle and accumulate in the trapping structure. The implementation of small on-farm structures has proven to be a practical and effective approach to addressing soil erosion and water management challenges. For example, in the United States, approximately 2.6 million small farm ponds have been strategically established, which capture runoff from 21% of the total drainage area (Mekonnen et al., 2015). These ponds play a significant role not only in retaining water but also in mitigating sheet and rill erosion, contributing to a 25% reduction in erosion caused by rainfall (Renwick et al., 2005). The widespread utilization of such structures showcases their value, not only for promoting sustainable agriculture practices but also for broader environmental conservation efforts. By effectively trapping eroding soil and retaining water on the farm, these small on-farm structures support improved agricultural productivity and ecological resilience while conserving land and water resources. Regarding sediment routing, various techniques can be employed to manage flows during periods of highest sediment yields and minimize sediment deposition in the reservoir. These include by-pass channels/tunnels, sluicing, and venting turbid density currents. According to Kobayashi et al. (2018), bypass tunnels, also referred to as sediment bypass tunnels (SBTs), are artificial flow channels to redirect sediment from upstream to downstream, thereby mitigating the issue of reservoir sedimentation. Particularly suited for medium-sized dams situated in steep river systems. Harnessing the inherent energy of natural flows, SBTs facilitate sediment transport at reduced costs. Notably, SBTs ensure the preservation of sediment concentration during transport, thereby minimizing adverse ecological repercussions downstream. Furthermore, SBTs hold promise in their potential to contribute to the restoration of deteriorated ecosystems through the supply of sediment. Nevertheless, the implementation of SBTs necessitates a thorough consideration of challenges such as erosion and maintenance costs. Optimal water allocation and sediment transport efficiency are imperative to maximize the efficacy of SBTs in the realm of sediment management. In more detail, Morris (2020) shown that sediment routing strategies in water management aim to keep inflowing sediment in motion, minimizing deposition. Two main approaches are utilized: sediment bypass and sediment pass-through. Sediment bypass involves diverting clear water into storage (Offstream Reservoir) and redirecting muddy water around storage (Flood Bypass). Sediment pass-through strategies focus on separating clear and muddy flows within the storage zone. This can be achieved through vertical separation (Vent Turbid Density Currents), temporal separation (Drawdown Sluicing), and horizontal separation (Compartmented Reservoir). These strategies are particularly useful in areas prone to high sedimentation events, optimizing sediment management and ensuring the separation of clear and muddy water flows. To redistribute or remove sediment, fluctuating water levels is the principal means of redistributing sediment within the reservoir. As Sumi and Kantoush (2010), reservoir flushing through drawdown is an effective method employed to manage sediment accumulation. Dashidaira and Unazuki dams in the Kurobe River system have implemented coordinated efforts to lower water levels and flush out accumulated sediment. This technique involves controlled water level reduction, facilitating accelerated flow that erodes sediment deposits and carries them out of the reservoir. The success of drawdown flushing in reducing sediment loads, particularly fine sediments, has been notable, while some coarser sediments remain trapped. Monitoring water quality during flushing ensures the assessment and management of potential impacts on the lower river basin's ecosystem. Drawdown flushing has proven to be an effective sediment management approach, enabling sediment removal and maintaining reservoir capacity while mitigating downstream consequences. Besides, hydraulic and mechanical techniques, such as modifying the operating level, pressure flushing, empty flushing, and mechanical excavation/dredging, are commonly used to remove sediment from reservoirs and recover part or all of the initial storage capacity. To maintain reservoir capacity and meet the sediment demand downstream, future researches are needed to evaluate the effectiveness of these techniques and recommend the most effective multi-reservoir management approach. Additionally, most of the impacts were driven by the Buon Tua Srah reservoir, and the development of integrated water and sediment management at Buon Tua Srah is critical. Moreover, since the impacts are transboundary between neighbouring countries (e.g., Vietnam and Cambodia), international collaboration is imperative for the sustainability of the region.

6 | CONCLUSION

Hydrological model is a useful tool to reconstruct reality and provide insights about the impacts of various factors on hydrological and sediment regimes. In this study, we set up the HYPE model in the USRB, evaluated the performance of the model before and post-dam operation, and analysed the impacts of reservoir operation on streamflow and sediment dynamics. The performance of the HYPE model before and post dam showed acceptable results in both modelled streamflow and SSC compared to observations. The Srepok_HYPE model can thus provide useful information to support decision-making process for water and sediment management in the basin. Regarding impacts of reservoir operation on streamflow, although average annual streamflows only slightly decreased, the impacts were more noticeable for the maximum annual streamflows. For seasonal effects on streamflows, the reservoirs within the USRB increased the low flows in the dry season and decreased the high flows in the wet season up to ±20% at Ban Don station. Regarding impacts of reservoir operations on SSC, average and maximum SSC decreased dramatically in both of the annual and seasonal periods. For both variables, the impacts were the most severe in Duc Xuyen station, located at the downstream of the Buon Tua Srah reservoir, which had the highest degree of regulations. Accordingly, it is essential to develop the integrated and transboundary water and sediment management, particularly at Buon Tua Srah reservoir, for the sustainability of the river basin. The findings of this research offer valuable insights to policymakers and water managers, particularly those responsible for reservoir operations, and can facilitate informed decision-making. Future studies are needed to investigate the effectiveness of various sediment management techniques and optimal water allocation strategies that can provide the most relevant actions for mitigating the impacts of cascade reservoirs to downstream hydrology.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Nuong Thi Bui https://orcid.org/0000-0001-8703-3785
Doan Van Binh https://orcid.org/0000-0002-7687-0550
Binh Quang Nguyen https://orcid.org/0000-0001-6292-5349

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