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Original Research

Framework for reservoir sedimentation estimation using the hydrological model and campaign—A case study of A Vuong reservoir in central Vietnam

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ABSTRACT

Sediment estimation would help practice sustainable watershed management and efficient reservoir operation. Different methods exist to estimate reservoir sedimentation based on the differences in sediment yield flowing in and releasing from the reservoir and successive bathymetric field measurements. This paper investigates the variability in sediment yield from watersheds and sedimentation in the A Vuong reservoir in central Vietnam using the soil and water assessment tool (SWAT) compared with bathymetry mapping. Bathymetry data were collected in 2003, 2015, and 2021 and conducted in 2022. SWAT was calibrated from 1996 to 2008 and validated from 2009 to 2020 using monthly observations. SWAT performs well and can accurately simulate monthly streamflow and sediment yield. The goodness-of-fit analyses suggested that the area list representation of the watershed behavior and satisfactory Sutcliffe efficiency (NSE = 0.86) values for streamflow were obtained during the calibration and validation periods. For sediment simulation, the efficiency is lower than streamflow's, with NSE in the validation values of 0.61. The results showed that the sedimentation estimate from the SWAT model is smaller than that from bathymetry. A Vuong reservoir's annual storage capacity loss due to sedimentation accumulation from the SWAT model and bathymetry was 0.08% and 0.38%, respectively. Based on the bathymetry data, we estimated that the average rate of sedimentation deposition of A Vuong reservoir was 1.3 Mm^3/y. The average calculated net deposition value was 4.3 m (0.3 m per year) within fourteen years of operation. The study outcomes demonstrated that the framework approach may transfer to an ungauged catchment and address the complex sedimentation problem in tropical regions.

1. Introduction

Dam reservoirs are vital for freshwater supplies, disturbance management, and hydropower production, among other multipurpose environments (Kantoush et al., 2023; Nguyen et al., 2023; Tran et al., 2023). However, reservoir capacity loss due to sedimentation is an economic, social and environmental challenge (Lee et al., 2022; Sumi et al., 2004, pp. 1036–1043). The increased extreme rainfall events associated with climate change have significantly affected erosion rate and sediment production from the watershed (Gould et al., 2016; Li & Fang, 2016; Stryker et al., 2018). The rich sediment loads are transported to the dam reservoirs where most sediment is trapped. Reservoir sedimentation significantly affects the original reservoir capacity dam's lifespans and deteriorates water quality (Michalec & Cupak, 2022; Tundu et al., 2018). Over time, sediment accumulates in reservoirs, leading to a loss of active storage volume, increasing the risk of post-dam flooding, and reducing water supplies (Mekonnen et al., 2022). Currently, the interrelation between sediment yield and reservoir sedimentation rates is poorly understood due to limited bathymetric data and challenges in watershed modeling for sediment production (Buendia et al., 2016; Moges et al., 2018; Tamene et al., 2006). In particular, a series of cascading dams and water transfers heavily manage the tropical rivers in the central region of

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Vietnam (Nguyen et al., 2023a). Losing the storage capacity due to reservoir sedimentation adds complexity to the dam operation when coupled with climate change (Nguyen et al., 2024). Therefore, quantifying the sediment yield and reservoir sedimentation rates is highly needed for the current cascading dam operation for the synergies between catchment management while maximizing power production. Accurate prediction of sediment delivery from the catchment and siltation rates is essential knowledge for flood, drought, and hydropower management under present and future climate conditions (Khoi et al., 2014; Tadesse et al., 2019; Vu et al., 2024).

The rates of sedimentation are poorly monitored due to observational and modeling challenges. The research has shown that a bathymetric survey is a more accurate indirect method for evaluating the volume deposited in reservoirs (Maina et al., 2018). However, the monitoring is expensive, and it is difficult to repeat all cascading dams. In addition, there are challenges in the model parameterization for calibration, validation, and uncertainty for modeled sediment volumes. Climate, and various watershed characteristics such as elevation, slope, drainage, soil type, and land use conditions influence sediment yield (Atulley et al., 2022; Dutta, 2016; Moussa, 2003; Vente et al., 2005). Therefore, understanding the sediment transport processes to reservoirs is essential to evaluate the impacts of watershed management practices. However, it is difficult to quantify the complex relationships between hydrological variables without actual field monitoring, which is a vital tool to address a broad spectrum of watershed management issues. Many physics-based hydrological models with different characteristics have been developed and applied in many catchments to simulate hydrological processes and estimate soil erosion (Yesuf et al., 2015). Compared with streamflow, simulating erosion and sediment transport is a challenging task using numerical modeling (Bui et al., 2023). Specifically, all erosion and sediment transport processes on land surfaces and rivers are complex to capture (Merritt et al., 2003; Xu et al., 2009). Currently, semi-distributed hydrological models have been applied to assess human impacts on streamflow and sediment transports (Chattopadhyay et al., 2017; Le et al., 2022; Li et al., 2020; Moradkhani et al., 2010; Tran et al., 2023, p. 2024). These models determined the contribution rates of sediment yield from sub-basins. Based on that, managers will make policies related to land use planning and future watershed management.

Meanwhile, various empirical and semiempirical methods exist for estimating the sediment erosion rates (Auerswald et al., 2014; Pal & Chakrabortty, 2022; Abdul Rahaman et al., 2015; Renard, 1997; Salles & Duclaux, 2015). However, the lack of measured sedimentation data for model parameterization and calibration often leads to incorrect sediment volume estimates. Recent studies combining land surface and empirical models have shown strong effectiveness in modeling spatio-temporal sediment variability (Al-Mamari et al., 2023; Stewart et al., 2017). However, limited measurement data for parameterizing and calibrating hydrological models has inhibited them from widespread applications. The semi-distributed soil and water assessment tool (SWAT) is a physically based hydrological model and is an appropriate model to investigate the impacts of climate conditions; land use land cover (LULC), human activities, and agricultural production (Yesuf et al., 2015). Sediment transport includes two essential components in the SWAT model: landscape and channel. The SWAT model predicts the sediment yield within each HRU and each subbasin from the landscape composition. The SWAT model has been tested worldwide with different climate characteristics, topography, LULC, soil type, area, etc (Tran et al., 2023a; Tran et al., 2023b). Statistics have shown that SWAT is the most commonly used hydrological model with acceptable accuracy to simulate hydrological processes and sediment dynamics of the catchment (Le et al., 2022; Tran et al., 2018b, 2022). However, evaluating the sediment production and cascading dam reservoirs is a challenge. Therefore, using a hydrological model and campaign is a framework approach for estimating sediment load in the catchment and reservoir sedimentation rates. The model is well-validated and calibrated for spatiotemporal data series from 1996 to 2020. Based on the calibrated model, sedimentation estimates can be expanded to basin reservoirs or other catchments with the same characteristics, especially in tropical monsoon regions, where measurement data are limited.

Identifying the sedimentation rate in the reservoir is vital to optimize the dam operation rule and propose a suitable sediment management technique. A comprehensive evaluation of reservoir siltation is needed to predict storage losses and the remaining reservoir life. Maintaining a reservoir's storage capacity by estimating sediment yield, sediment dispersion, and deposition patterns is critical. Therefore, this study aimed to examine the temporal and spatial changes in sediment delivery into the reservoir and the loss of the reservoir's original capacity of the A Vuong reservoir in central Vietnam during 14 years of operation. The paper proposes a framework approach to evaluate the performance of the SWAT model and the ability to apply this model to simulate streamflow processes and sediment transport at the basin scale. Based on that, we assess sediment yield from the watershed and interrelation spatiotemporal distribution of sedimentation. The proposed approach provides insight into the erosion processes and sediment yield prediction at the catchment scale, especially in basins with limited monitoring and field survey data. These results are expected to be of significant value for practical management at the basin scale, developing strategies to control sediment transport and sediment management techniques in tropical regions.

2. Study area

The A Vuong River basin, located in central Vietnam, is the primary water supply for the Vu Gia Thu Bon (VGTB) basin (Fig. 1) (Nguyen, Kantoush, van Binh, & Sumi, 2024). The A Vuong River originates from a northwestern mountain with an elevation of 1400 masl. In the A Vuong River basin, land use is forest and grassland, and the soil type of the basin is mainly clay (Figs. 3(c) and 3(d)). Downstream is a central agricultural region, with rice field land comprising most of the basin area. Consequently, variations in the A Vuong reservoir water supply can significantly affect the water resources of the middle and downstream areas (Da Nang City and Quang Nam Province) (Nguyen et al., 2023b; Nguyen et al., 2023a). A Vuong reservoir's water quality and quantity are essential concerns as a significant drinking water source in the two provinces. However, climate change, land-use practices, and human activities have significantly impacted downstream water resources (Nguyen, 2022; Viet, 2014). The region's climate is tropical monsoon, with an annual rainfall of approximately 2200 mm. The rainy season is concentrated in four months (September–December) and causes flooding downstream (Nguyen et al., 2022).

The A Vuong reservoir was completed in 2008 after six years of construction (began in 2003), with a basin area of 682 km^2. The dam height will be 80 m, creating a reservoir with an area of 9.09 km^2 at the normal operating water level. The volumes corresponding to dead and normal water levels are 77.07 and 266.48 Mm^3, respectively (Nguyen et al., 2024c). The elevations of the dead water level and normal water level are 340 and 380 m, respectively. The reservoir's primary purpose is power generation, and it was assigned other tasks such as flood control, agricultural production, water supply, and reducing downstream salinity (Government, 2019).

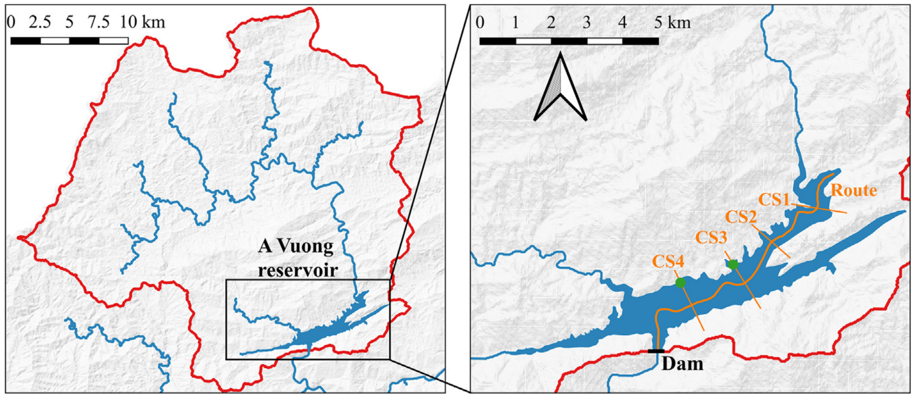

Fig. 1. A Vuong reservoir, the position of 4 cross-sections (CS1, CS2, CS3, and CS4), and longitudinal route.

The experimental results of sediment samples in the A Vuong reservoir show that the suspended sediment is silt with $d_{50} = 0.02979$ mm (Fig. 2).

3. Methodology

In the study area, the Thanh My hydrological station has measured streamflow and sediment from 1996 to 2020 (Fig. 3(a)). Therefore, the study will set an area larger than the A Vuong reservoir basin (Fig. 3). In the first step, the model will be calibrated and validated for streamflow and sediment at Thanh My. In the validation period, the model will be further evaluated independently of the A Vuong reservoir's inflow and release since the reservoir began operation in 2009.

3.1. SWAT model

The SWAT model was developed by the U.S. Department of Agriculture (USDA) and Agriculture Research Service (ARS) (Arnold et al., 1998). SWAT model segments a watershed into smaller units called sub-basins. These sub-basins are then further divided based on distinct soil characteristics, land use patterns, and slope gradients into what are known as hydrological response units (HRUs). This division allows for a detailed understanding of the hydrological processes within a watershed. Many studies have used SWAT to reveal the effects of LULC, climate change, and agricultural production on streamflow or sediment loads (Le et al., 2022; Tran et al., 2022; Vo et al., 2018a).

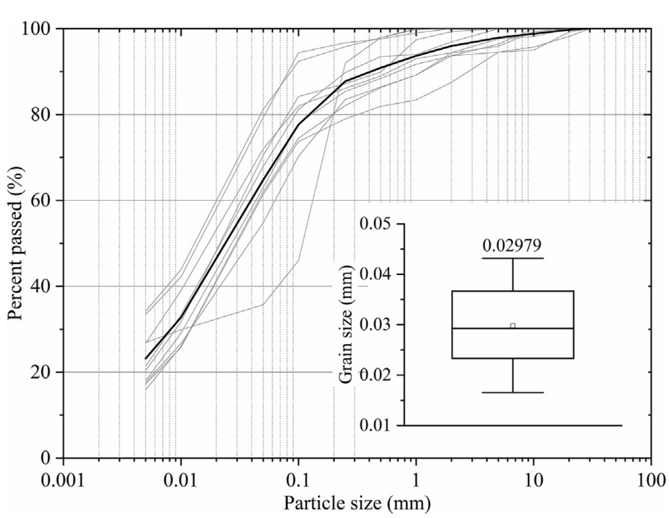

Fig. 2. Grain size of suspended sediment in A Vuong Reservoir (the black line indicates the average value). Box plot of d_{50} from nine sediment samples.

3.2. Data collection

The digital elevation model (DEM) was extracted from the Land Use and Climate Change Interaction in central Vietnam (Lucci) project, with a 30 m × 30 m spatial resolution in 2014 (Fig. 3(b)). DEM was created by combining isolines and SRTM digital data (Nguyen et al., 2023c). Land use and soil type data were extracted from Lucci with a 30 m × 30 m resolution (Figs. 3(c) and 3(d)). In this study, the authors reclassified the land use into six main classes (Fig. 3(c)). The leading five soil types are presented in Fig. 3(d) with characteristics that could be used in the hydrological SWAT model.

The daily rainfall data were obtained from the Mid-Central Regional Hydro-Meteorological Center (MCRHMC, 2022) from 1990 to 2020 at four meteorological stations as follows: Kham Duc, Thanh My, Hoi Khach, and Hien (Fig. 3(a)). Daily minimum temperature (T_{min}) and maximum temperature (T_{max}) data were obtained at the Tra My meteorological station. The observed monthly streamflow data at Thanh My hydrological station were collected during the 1990–2020 period (Fig. 3(a)). The inflow and outflow of the A Vuong reservoir (2009–2020) were also collected to validate the simulation result of the SWAT model. The characteristics and operating rules of ten dams were collected to set up, calibrate, and validate the model (Fig. 3(a)). The data were collected from the Vietnam Government (Decision 1865/QD-TTg) (Government, 2019) and Quang Nam province (NDPAC, 2022). Experimental data on grain size, sample drilling, and riverbed elevation were collected from A Vuong Company at different times.

3.3. Campaign

The campaigns were conducted on the entire surface of the A Vuong reservoir in June 2022 to study sedimentation issues and their impact on storage capacity (Nguyen, Kantoush, van Binh, & Sumi, 2024). The sedimentation volume was estimated from the bathymetric mapping differences in 2003, 2015, 2021, and 2022. Bathymetric surveys were conducted using a single-beam echosounder (Odom Hydrotrac II) accompanied by the Trimble R5 and R8 GPS system. These machines have mean horizontal and vertical survey errors of ±0.003 and ±0.005 m, respectively. The hourly water level data was also collected at the A Vuong dam. From the water level data, the reservoir riverbed elevations were calculated by subtracting the water levels. The bathymetric datasets

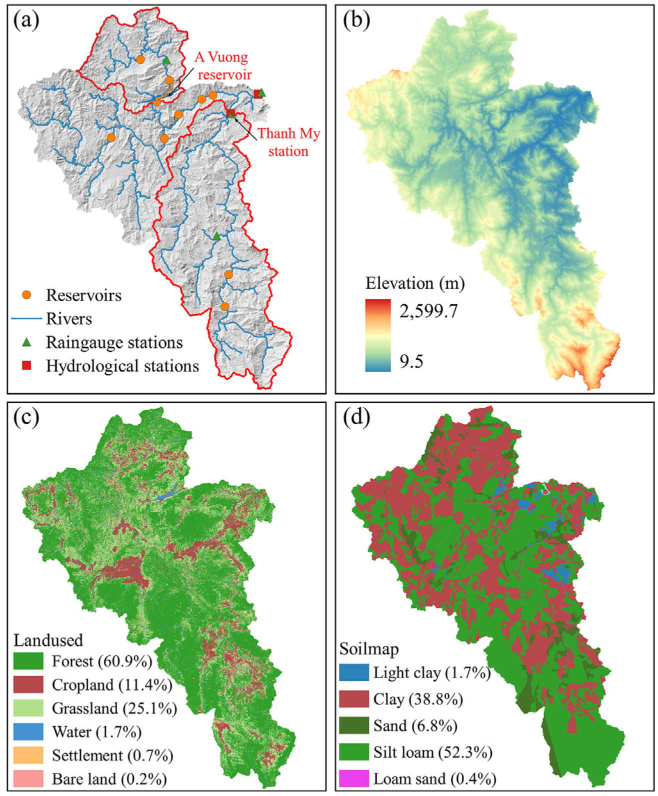

Fig. 3. (a) River network, rain gauge station, and hydrological station. (b) Digital elevation model (m). (c) Land-use map. (d) Soil type map.

were converted to the WGS 1984 UTM, with zone 48 North projection.

3.4. Model setup

The subbasins were divided into 134 subbasins and 1898 HRUs based on five slope classes, six land classes, five soil classes, dam locations, and hydrological stations (Nguyen et al., 2023d). In this study, a 6-year warm-up period (1990–1995) was chosen over the 31-year simulation period (1990–2020), in which thirteen years would be chosen (1996–2008) for the calibration, and the validation period would be from 2009 to 2020. The location of calibration and validation is the Thanh My hydrological station (Fig. 3(a)). The input and output streamflow of the A Vuong reservoir from 2009 to 2020 was also validated to evaluate the model's performance.

3.5. SWAT streamflow and sediment simulation

The SWAT model calculates surface runoff using the Soil Conservation Service curve number, a function of land use, soil permeability, and soil moisture content. For streamflow routing, the Muskingum method is used. Potential evapotranspiration (PET) was calculated by using Penman–Monteith. The hydrological cycle simulated by SWAT is based on the water balance equation (Setegn et al., 2009):

$$\mathrm{SW}_t = \mathrm{SW}_0 + \sum_{n=1}^{t}\left(R_{\mathrm{day}} - Q_{\mathrm{surf}} - E_{\mathrm{a}} - W_{\mathrm{seep}} - Q_{\mathrm{gw}}\right) \tag{1}$$

where SW_t is the soil water content (mm), SW_0 is the water available to plants (mm), R_{day} is the precipitation (mm), Q_{surf} is the surface runoff (mm), E_{a} is the evapotranspiration (mm), W_{seep} is the percolation (mm), Q_{gw} is the low flow (mm), and t is the time (d).

The modified universal soil loss equation (MUSLE), a function of runoff factors, was used to predict sediment yield on a given day in the SWAT model (Wischmeier & Smith, 1965). MUSLE assumes a simple hydrograph shape to estimate daily runoff volume, thereby predicting variation in runoff erosive energy. Simulated sediment yield regarding total sediment loadings and the sand, clay, and silt fractions from each sub-watershed. The equation is as Eq. (2):

$$\mathrm{sed} = 11.8 \times \left(Q_{\mathrm{surf}} \times q_{\mathrm{peak}} \times \mathrm{area}_{\mathrm{hru}}\right)^{0.56} \times K_{\mathrm{USLE}} \times C_{\mathrm{USLE}} \times P_{\mathrm{USLE}} \times \mathrm{LS}_{\mathrm{USLE}} \times \mathrm{CFRG} \tag{2}$$

where sed is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm H_20/ha), q_{peak} is the peak runoff rate (m^3/s), $\mathrm{area}_{\mathrm{hru}}$ is the area of HRU (ha), K_{USLE} is the soil erodibility factor, C_{USLE} is the cover and management factor, P_{USLE} is the support practice factor, $\mathrm{LS}_{\mathrm{USLE}}$ is the USLE topographic factor, and CFRG is the coarse fragment factor.

3.6. Performance evaluation of model

This study uses the R-SWAT for calibration, validation, parameter sensitivity, and uncertainty analysis for the SWAT model (Nguyen et al., 2022). The calibration, validation, and sensitivity approach using Sensi_Cali_(uniform_Latin_Hypercube_Sampling). The method uses a multivariable regression approach with parameters generated by uniform Latin hypercube sampling. The authors have chosen five reliable statistical metrics based on key findings of Babalola et al. (2021), Gupta et al. (2009), Kouchi et al. (2017), and Moriasi et al. (2007) for the model performance metrics: square correlation coefficient (R^2), Kling–Gupta efficiency (KGE), Nash–Sutcliffe coefficient (NSE), root mean square error (RMSE), and percentage of bias (PBIAS) (Table 1).

3.7. Estimating reservoir sediment deposition

Reservoir riverbed data for three periods were used to assess sediment distribution: one before dam construction (2003), the next period (2015), and the other in 2021. The 2003, 2015, and 2021 data are collected from A Vuong Company. The difference between these data represented the variation of sedimentation within the reservoirs. In addition, the sediment yield data are also estimated using the SWAT model. The results will be compared with bathymetry data to evaluate the ability to estimate the sediment yield coming to and out of the A Vuong reservoir from the SWAT model. From there, we evaluate the sedimentation of the A Vuong reservoir. In addition, the results from SWAT also show the distribution of sediment yield and sediment load from subbasins and reaches.

4. Results

4.1. SWAT calibration and validation

Fig. 4 shows that calibration and validation performed well for streamflow and sediment simulation. SWAT performs well and can accurately simulate monthly streamflow and sediment yield. The goodness-of-fit analyses suggested an area list representing the watershed behavior and satisfactory values for streamflow (Table 2). The R^2, KGE, NSE, RMSE, and PBIAS coefficients at the Thanh My station in the calibration and validation periods were 0.93, 0.91, 0.86, 63.92 m^3/s, and −6.56% and 0.93, 0.81, 0.86, 50.60 m^3/s, and −13.47%, respectively. The efficiency of sediment simulation is lower than that for streamflow. The model was underestimated during the years of storm events and heavy rainfall (e.g., 2009, 2020). In the calibration period, the R^2, KGE, NSE, RMSE, and PBIAS coefficients were 0.83, 0.55, 0.61, 5.25 $\times$ 10^3 tons, and −41.43%, respectively.

The validation of the monthly streamflow inflow and release from the A Vuong reservoir also agrees with the observed data (Figs. 4(c) and 4(d) and Table 2). The NSE and PBIAS values were 0.72 and 0.23% and 0.56 and 0.72%, respectively. Overall, the results indicate that the established model is suitable for conducting assessments on hydrological processes, sediment transport, and impacts of reservoirs.

4.2. SWAT sediment yield simulation

Fig. 5 identifies the subwatersheds that produce high sediment yields. According to the simulation results, the areas where soil erosion was severe can be identified. Seventeen SWAT subbasins produce average annual sediment yields ranging from 0.045 to 0.06 tons/ha/y. Between 2009 and 2020, the erosion intensity was more significant than the 1996–2008 period.

4.3. Reservoir sedimentation from SWAT model

Fig. 6 shows that the average annual sediment load was estimated from the SWAT model in the periods at the dam site. The average annual sediment load in the 2009–2020 period was higher than that in some subbasins in the 1996–2008 period.

The annual average amount of sedimentation in the A Vuong reservoir in the 2009–2020 period was 0.35 Mt/y, and the total amount was approximately 4.2 Mt. Based on Fu et al. (2008), the estimation of bedload accounting for 3%–15% of the suspended load, the annual amount of sedimentation in the A Vuong reservoir was approximately 0.4 Mt/y, and the total amount from 2009 to 2021 was 4.6 Mt. It is assumed that the average bulk density of sediment to be 1.4 tons/m^3, the total storage capacity loss of the A Vuong reservoir was approximately 3.29 Mm^3, which accounts for 0.96% (0.08% per year) of the total storage capacity in 343.55 Mm^3.

4.4. Reservoir sedimentation from bathymetry

We mapped the bathymetry and estimated how much sediment was deposited and the reduction capacity of the A Vuong reservoir from 2003 to 2021 along the main route from upstream to the dam and four typical cross-sections (Fig. 7). Fig. 8 shows the detailed riverbed elevation of the A Vuong reservoir from the campaign in June 2022. We estimated the average calculated net deposition value was 4.3 m (0.3 m per year) within fourteen years of operation. The highest sediment thickness values were observed at the dam site. Therefore, the capacity of the storage reservoir of A Vuong was reduced by 18.7 Mm^3 as a result of sediment deposition. The reservoir has lost approximately 5.4% of its practical capacity. Assuming the rate remained constant during the entire period, the yearly sedimentation rate was 1.3 Mm^3/y. According to this rate, the annual storage capacity decreases by approximately 0.38% per year due to sedimentation. This value is lower than the projected global average rate of 0.5%–1% worldwide (Ayele et al., 2017; Froehlich et al., 2017; Schellenberg et al., 2017; Zimale et al., 2016). Furthermore, the average loss rate is approximately equal to that of Indian reservoirs (0.44% per year) (Asthana & Khare, 2022).

In Japan, based on annual data from 877 reservoirs, Sumi, 2006; Sumi & Kantoush, 2018 found that the reservoir sedimentation rate is approximately 0.24%, especially for reservoirs located on tectonic lines in the central region, the rate is higher (0.42%). Based on

Table 1
Indicators to evaluate performance of SWAT model.

Metric equation	Optimal value
$R^2 = \dfrac{\left[\sum_i (Q_{m,i}-\overline{Q_m})(Q_{s,i}-\overline{Q_s})\right]^2}{\sum_i (Q_{m,i}-\overline{Q_m})^2 \sum_i (Q_{s,i}-\overline{Q_s})^2}$	1
$\mathrm{KGE} = 1-\sqrt{(\mathrm{CC}-1)^2+\left(\dfrac{Q_s{}^d}{Q_m{}^d}-1\right)^2+\left(\dfrac{\overline{Q_s}}{\overline{Q_m}}-1\right)^2}$	1
$\mathrm{NSE} = 1-\dfrac{\sum_{i=1}^{n}(Q_m-Q_s)^2}{\sum_{i=1}^{n}(Q_m-\overline{Q_m})^2}$	1
$\mathrm{RMSE} = \sqrt{\dfrac{\sum_{i=1}^{n}(Q_m-Q_s)^2}{n}}$	0
$\mathrm{PBIAS} = 1-\dfrac{\sum_{i=1}^{n}(Q_m-Q_s)}{\sum_{i=1}^{n}(Q_m-\overline{Q_m})^2}$	0

Note: Q is the streamflow (m^3/s); m and s stand for measured and simulated, respectively, and d stands for deviation of it; i is the ith measured and simulated; $\overline{Q}$ indicates the mean value, and the number of values is n.

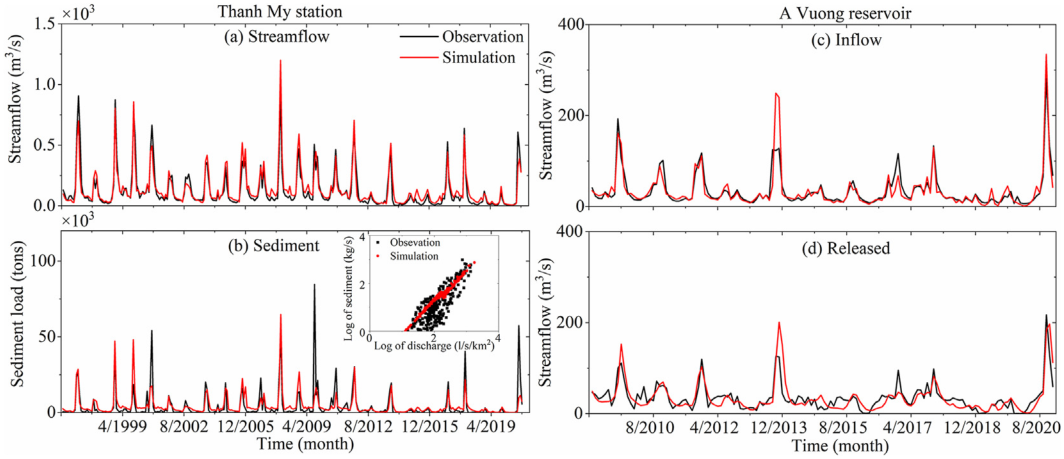

Fig. 4. (a, b) Hydrographs of the monthly streamflow and sediment at Thanh My station in calibrated period (1996–2008) and validated period (2009–2020). (c, d) Hydrographs of A Vuong reservoir's monthly streamflow inflow and release in validated period (2009–2020).

Table 2
Statistical indices of streamflow and sediment at Thanh My hydrological station and A Vuong reservoir.

Statistical index	Thanh My station				A Vuong reservoir	
	Streamflow		Sediment		Streamflow	
	Calibrated (1995–2008)	Validated (2009–2020)	Calibrated (1995–2008)	Validated (2009–2020)	Inflow Validated (2009–2020)	Released Validated (2009–2020)
R^2	0.93	0.93	0.83	0.69	0.89	0.82
KGE	0.91	0.81	0.55	0.30	0.80	0.76
NSE	0.86	0.86	0.61	0.40	0.72	0.56
RMSE (m^3/s, 10^3 tons)	63.92	50.60	5.25	7.96	19.74	19.54
PBIAS (%)	−6.56	−13.47	−41.43	21.12	0.23	0.72

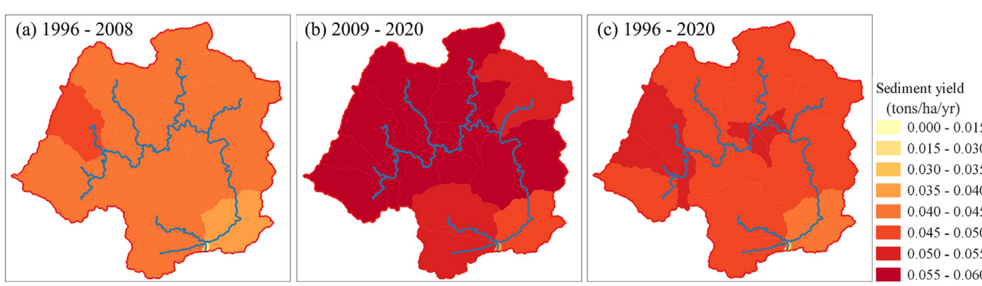

Fig. 5. Sediment yield of subbasins in three periods: (a) 1996–2008, (b) 2009–2020, and (c) 1996–2020.

bathymetric survey data completed for many central states and 24 constructed reservoirs in the central U.S. Great Plains. In 2016, these reservoirs had an average age of 52 years and collectively had an average rate loss of approximately 0.33%, with the highest average rate loss of 0.87% (Rahmani et al., 2018).

Ivanoski et al. (2019) performed a long-term model to evaluate the sedimentation rate of the Tikvesh reservoir, one of the largest reservoirs in the Republic of Macedonia. The analysis results show that the reservoir sedimentation rate changes over different periods, depending on the weather conditions in the catchment. The average annual sedimentation rate was 0.02%–1.28% from 1969 to 2016.

Based on bathymetric data collected from two reservoirs in the White Volta Basin drains in Ghana, Burkina Faso, and Togo in 2020 and an analysis of Landsat satellite images (1986, 1996, 2006, and 2020), Atulley et al. (2022) assessed the sedimentation rate of two reservoirs named Vea and Tono. The authors found an annual sedimentation rate of 0.304% in the small reservoir and 0.17% in the medium-sized reservoir.

Haregeweyn et al. (2012) estimated an annual total capacity loss of 0.18%–4% for thirteen reservoirs in northern Ethiopia. New studies in the same Tana subbasin show that the annual capacity reduction of the Shina microearth reservoir and Selamko reservoir is 1.67% and 2.295%, respectively (Berihun et al., 2022).

Past studies show that the sedimentation problem in the A Vuong reservoir is similar to that in most other reservoirs worldwide. We want to highlight that this is the first sedimentation estimated for the tropical river in central Vietnam based on bathymetric maps. Therefore, the results of our study will provide evidence of the characteristics and sedimentation rates of reservoirs in Vietnam. Based on the new findings, sedimentation

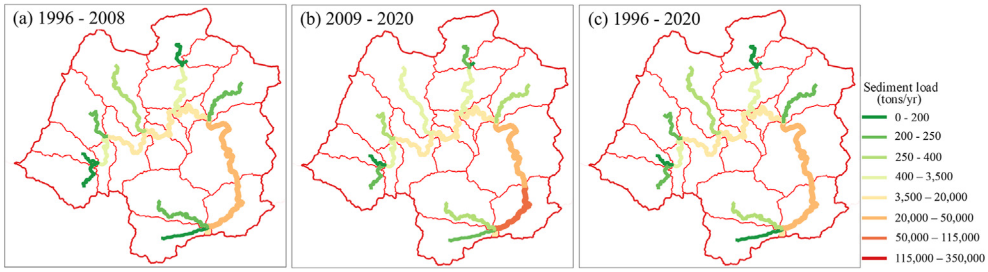

Fig. 6. Sediment load of subbasins in three periods: (a) 1996–2008, (b) 2009–2020, and (c) 1996–2020.

estimates can be expanded to basin reservoirs or other basins with the same characteristics, especially in tropical monsoon regions with limited measurement data. From there, managers and authorities will actively look for solutions to minimize sedimentation's impact on the reservoir's life and operation, including downstream.

We distinguish the soil layers with different thicknesses at cross-sections 3 and 4 (CS3 and CS4) to better understand the

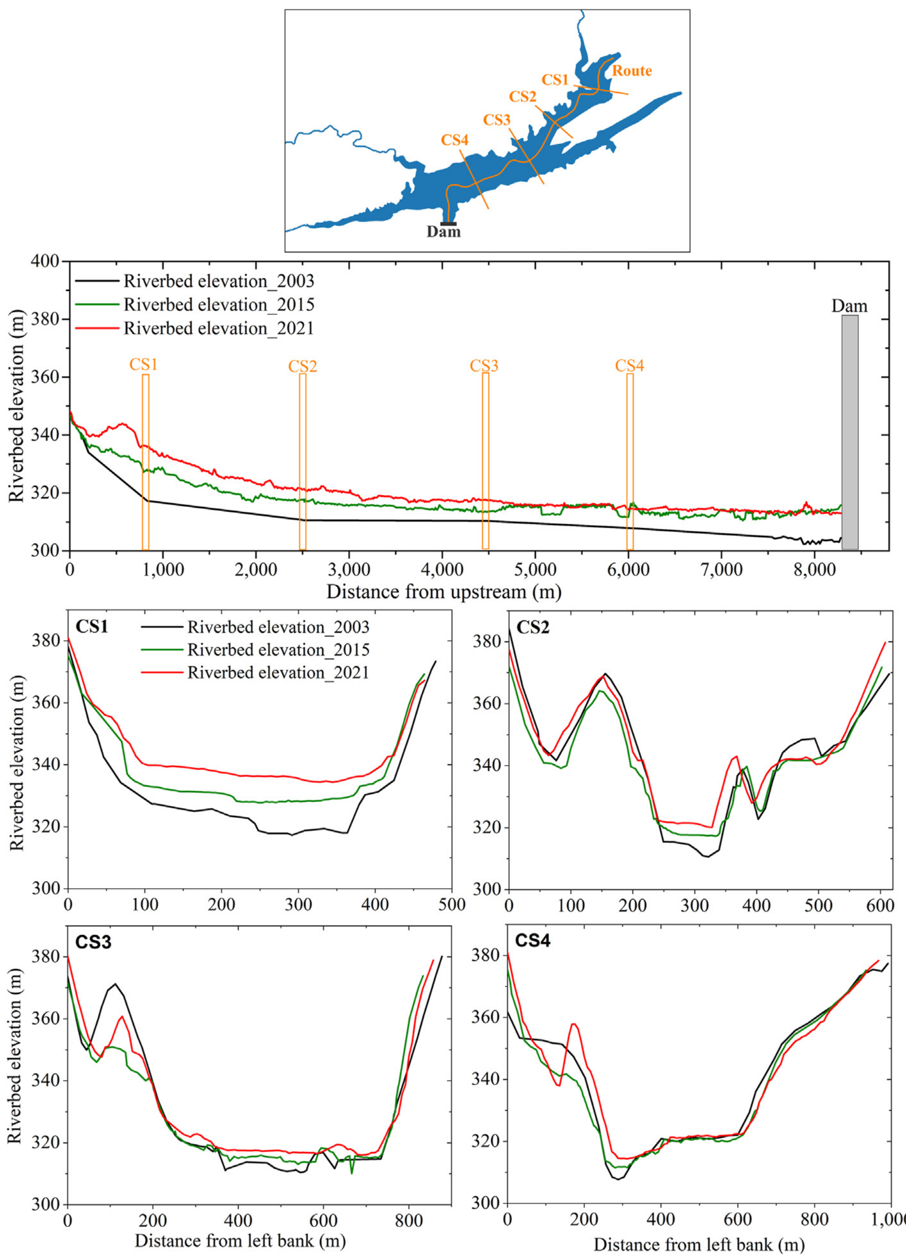

Fig. 7. Riverbed elevation in 2003, 2015, and 2021 along main route from upstream to dam site and four typical cross-sections.

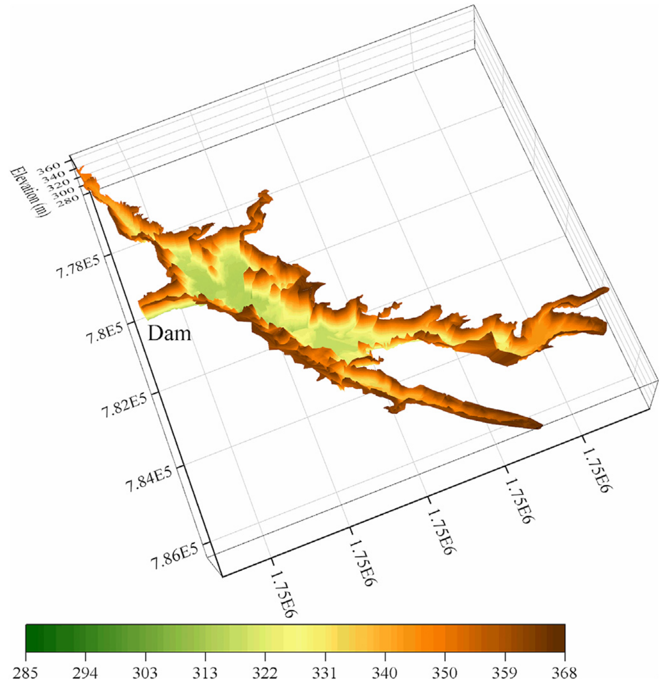

Fig. 8. Bathymetry of A Vuong reservoir from the campaign in June 2022.

influence of factors such as streamflow, the reservoir's operational procedure, mobility, and properties on sediment distribution (Fig. 9). The 1st layer is the vegetative cover (pdQ), the ruins layer (edQ) is the 2nd, and the weathering layer (IA1) is the third. In 2015, the soil properties were the ruins layer (edQ); in 2021, they were vegetative cover (pdQ). Fig. 9 also shows the soil layers at different locations of the A Vuong reservoir taken from the campaign in June 2022 (details of the locations are shown in Fig. 1).

5. Discussion

5.1. Comparing sedimentation from campaign and SWAT model

The sedimentation quantities and rate calculations presented in the previous sections represent our best estimates based on the hydrological model and bathymetry. Comparing each other in two ways, the annual average sedimentation estimated from the SWAT model was relatively lower than the result from the bathymetry. The annual amount of sedimentation in the A Vuong reservoir from the SWAT model was approximately 0.4 Mt/y. Meanwhile, the yearly sedimentation rate from bathymetry was 1.3 Mm^3/y. Therefore, A Vuong reservoir's annual storage capacity loss from the SWAT model and bathymetry was 0.08% and 0.38%, respectively. This difference may be due to several reasons when using the SWAT model. SWAT uses one input dataset and parameter in the simulation period, while the basin characteristics change in reality (e.g., topographic characteristics, LULC, …). Therefore, we will discuss the uncertainties and limitations of the input data, model structure, and analysis leading to the above differences. First, we will determine why the estimates from the SWAT model are underestimated compared with bathymetry.

Hydrological models are increasingly used to propose and evaluate strategies to improve water resource management in basins (Tapas et al., 2024). However, the processing and parameterization of parameters in hydrological models is challenging because of the overparameterization of hydrologic models (El-Nasr et al., 2005). Therefore, various sources of uncertainty in hydrological modeling must be considered to increase reliable runoff and sediment yield predictions. SWAT is a physics-based model for continuous watershed simulation, intending to minimize modeling errors due to assumptions. However, the SWAT model still has prediction uncertainties even when the model has been well-calibrated and validated. The reason is believed to be due to incomplete information about the quantity and quality of input data to set up, calibrate, and validate the model, the capability and appropriateness of search algorithms or support tools to parameter estimates, and the model's ability to represent natural watershed processes (Abbaspour et al., 2007; Muleta & Nicklow, 2005). In addition, SWAT uses a curve number method that assumes constant parameter values throughout the entire watershed to estimate streamflow based on the relationship between precipitation, LULC, and soil types. However, the value and order of parameter sensitivity can vary significantly depending on the climate, LULC, and soil type spatial detailing at the HRU scale, and higher are the subbasins (Tran et al., 2023). In addition, surface erosion mainly occurs during higher-rainfall days, while high flows mostly drive bank erosion and sediment transport (Baniya et al., 2024; Buendia et al., 2016b). Therefore, the model sediment calibration should be biased towards high rainfall and high flow periods.

Topographic characteristics (slope form, length, and steepness) also influence erosion and sediment transport. Additionally, another factor to consider is the shape of the catchment. Many studies have shown a close relationship between catchment shape and hydrological processes, such as peak discharge and lag time (Moussa, 2003). It is assumed that circular catchments have more significant sediment than elongated catchments, usually only one river, because of the denser drainage networks, shorter travel distances, and more direct slope runoff. A Vuong River basin is an elongated basin with various reaches entering the mainstream (Fig. 1). DEM of the basin has changed over time due to natural tectonic and human activities (Tran et al., 2014; Vu et al., 2017). Changing DEM will affect surface characteristics such as drainage

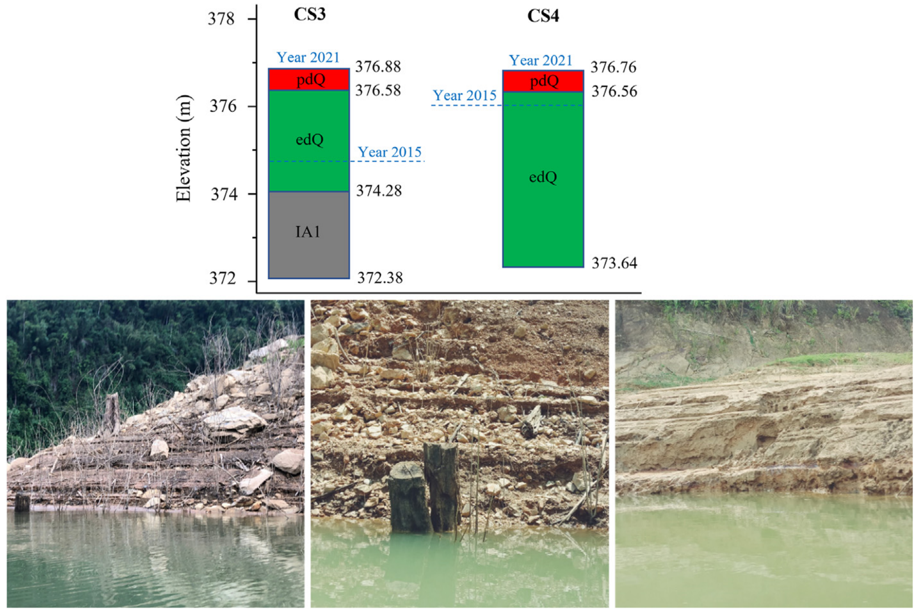

Fig. 9. Image of soil layers at different locations in the A Vuong reservoir. The image was taken from the campaign in June 2022 (credit by authors).

density, surface slope, slope length, and channel slope (Lakshmi, 2024). The SWAT model is susceptible to these factors in predicting sediment yield (Setegn et al., 2010).

In the SWAT model, only one set of parameters is used during the simulation. However, studies have shown that sediment yield varies for different storm events in practice (Dutta, 2016). Extreme events significantly impact sediment yield more, especially in tropical monsoon climates. In addition, from the calibration and validation results of sediment (Fig. 4(b)), we can see that the most significant error in the model predictions was always related to the peak. Abbaspour et al. (2007) discuss that the “second storm effect” may be partly responsible for poor sediment simulation results. The A Vuong reservoir has no long-term streamflow or sediment measurements. Therefore, we set up the SWAT model in a larger area, including a location with complete data observation (Fig. 3(a)). Both A Vuong reservoir and Thanh My subbasin belong to the upstream of Vu Gia River basin (Kantoush et al., 2023; Nguyen et al., 2023). Although the two locations are close and proximity in geographical terms, this approach leads to uncertainty in the estimated sediment yield for the A Vuong reservoir basin.

LULC has been demonstrated in various studies to be essential in watershed erosion. LULC characteristics within a watershed significantly affect the sedimentation rate in the reservoirs. Specifically, it indirectly affects soil structure and infiltration capacity or directly by protecting the soil (Vente et al., 2005). By evaluating 60 basins in Spain, the authors have shown that the erosion process is closely related to LULC. Atulley et al. (2022) noted that extensive tree removal increased sedimentation rates in small reservoirs in the White Volta basin. Globally, LULC changes over time, especially in areas where production is changing, and there are many human impacts, such as in Vietnam. The VGTB basin, including the A Vuong reservoir basin has been recorded as a major change in LULC, especially in recent times, which has affected the process of erosion and the downstream sediment yield (Nguyen, 2023; Ribbe et al., 2017). Part of the upstream forest area has been converted into other land uses. However, we used only one LULC map in the SWAT model in 2014 (Fig. 3(c)). This leads to the estimated results from the SWAT model being underestimated compared with bathymetry.

Landslides affect sediment transport; they frequently occur in mountainous areas with steep slopes and tectonic activities (Cloetingh et al., 2005; Montgomery & Brandon, 2002). There are many reasons leading to landslides, possibly due to land leveling for agricultural production and road construction purposes. In addition, there may also be other factors, such as mining or bank erosion of the reservoir itself (Fig. 10). Many studies have shown that the A Vuong basin has frequent landslides, especially recently (Duc et al., 2020; Handwerger et al., 2022; Pham et al., 2021, 2022). Few studies are quantifying the contribution of landslides, but it is

Fig. 10. Landslides in the A Vuong reservoir area (credit by authors).

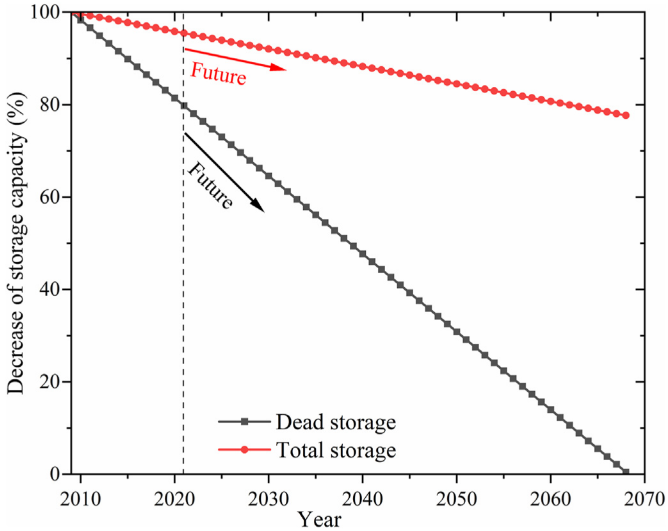

Fig. 11. Decrease in storage capacity of the A Vuong reservoir.

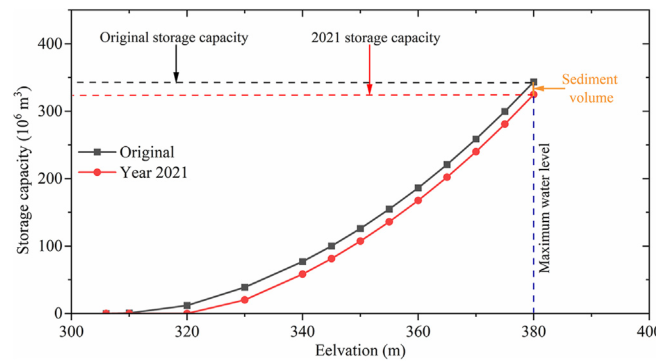

Fig. 12. Elevations and storage capacity curve of the A Vuong reservoir.

known that they can contribute significantly to sediment yield (Bathurst et al., 2005; Korup et al., 2004). Although landslides can move large amounts of sediment in slope areas, they do not transport sediment directly to a reservoir or basin outlet but provide sediment for other transport processes (e.g., bank erosion) (Vente et al., 2006). In other words, interactions between landslides and bank erosion generally result in high sediment yields at the reservoir or basin outlet.

A Vuong reservoir was completed in 2008 and started operation in 2009. During this period, only bathymetry survey data were available in 2003. Therefore, we have assumed that these data are from the year that started operating (2009), considering the stable bathymetry from 2003 to 2009. With this assumption, the results of the analysis of the volume and sedimentation rate of a Vuong reservoir will be limited and lead to a difference from the estimated results from the SWAT model. However, despite the differences and uncertainties, the results from the SWAT model provide insight into the erosion process and sediment yield prediction at the watershed scale, especially in basins with limited monitoring and field survey data. These findings are expected to be of significant value for developing strategies to control sediment transport to ensure the sustainable development of the basin and increase the A Vuong reservoir's life.

5.2. Evaluation of area storage capacity curve

Sedimentation rates are controlled by sediment produced in the watersheds and the amount of sediment trapped by the reservoir. We used bathymetric survey data to estimate the A Vuong reservoir lifespan. Research assuming the annual rate loss of storage capacity remains constant to determine the remaining useful life of A Vuong reservoir (Patro et al., 2022) (Fig. 11).

The most straightforward remaining life calculation was based on the sedimentation rate in the dead storage area. The dead storage volume was 77.07 Mm^3, while the mean sedimentation rate was 1.3 Mm^3/y, so the reservoir's life could be obtained by approximately 59 years. Thus, the life of the A Vuong reservoir is until 2068 if calculated from 2021, to 48 years remain. The total and dead storage capacity in 2021 were left at 79.8% and 95.5%, respectively. Fig. 12 shows the elevations and storage capacity curve of A Vuong reservoir.

It is time for agencies to consider the sedimentation problem in the A Vuong reservoir. Based on experience worldwide, we can reduce sedimentation effects and increase reservoir life. Various strategies are available to improve the sediment problem across reservoirs and adapt to the storage loss due to sediment encroachment, especially under the impact of climate change. Strategies can be used at a single reservoir or multiple reservoirs, applied simultaneously or over time (Morris, 2020). Adaptive strategies can be crucial because restoring and maintaining original reservoir capacities is rarely possible.

The findings of this study indicate that the planning and implementation of various techniques to control and remove sediment deposition in A Vuong reservoir are most important. The sediment control mechanisms depend on estimating sediment production from the watershed and reservoir' outlet. Because A Vuong reservoir is affected by sediment accumulation generated from different directions, it is necessary to control the sediment flow rate into the reservoir. Therefore, a multidisciplinary approach to land use management is necessary to maintain reservoir storage. Encourage conservation activities in upstream areas such as afforestation, change of land use purposes, soil erosion control, and construction of structures such as check dams, bypass, and sluicing (Auel et al., 2016).

6. Conclusions and recommendations

The study evaluated the sedimentation status of the A Vuong reservoir after fourteen years of operation using bathymetry mapping and the SWAT hydrological model. The authors evaluated the sedimentation rate, sediment distribution, amounts of sediment deposited, capacity loss, and life of A Vuong reservoir. The results showed that the sedimentation estimate from the SWAT model is smaller than that from bathymetry. A Vuong reservoir's annual storage capacity loss due to sedimentation accumulation from the SWAT model and campaign was 0.08% and 0.38%, respectively. Based on the bathymetry data, we estimated that the average rate of sedimentation deposition of A Vuong reservoir was 1.3 Mm^3/y. The average calculated net deposition value was 4.3 m (0.3 m per year).

The study outcomes demonstrated that the strategic modeling framework may address the complex sedimentation problem in tropical regions. Combining a hydrological model and a bathymetry survey will be helpful for reservoir sedimentation estimation. Based on that, sedimentation estimates can be expanded to reservoirs in the basin or other basins with the same characteristics, especially in tropical monsoon regions, where measurement data are limited.

The results can help managers proactively make decisions to ensure sustainable development of reservoirs, planning, and rational use of water resources in the basin. The findings of this study indicate that the planning and implementation of various techniques to control and remove sediment deposition in A Vuong reservoir are most important.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Binh Quang Nguyen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sameh A. Kantoush:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Ngoc Duong Vo:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Tetsuya Sumi:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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