Sediment management for reservoir sustainability and cost implications under land use/land cover change uncertainty

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Key Points

- Costs of sediment management options are linked to the economic value of the loss in hydropower production and the avoided cost of dredging.
- The sediment management strategy best at increasing the life span of a reservoir may not be the most cost-effective option to implement.
- Integration of suitable sediment management options can reduce the amount and variability in reservoir storage loss and associated cost.

Abstract

Addressing uncertainty in sediment predictions due to land use/land cover (LULC) change could better inform the selection of sediment management options for reservoir sustainability. We used the Nam Kong catchment of the Mekong River Basin in Southern Laos, with two hydropower dams in series, to understand the implications of LULC change uncertainty for catchment-level and reservoir-level sediment management options. The catchment-level sediment management options of terracing, vegetative filter strips and no tillage were evaluated applying the Soil and Water Assessment Tool (SWAT). The reservoir-level sediment management option of flushing was assessed using the Sediment Simulation Screening Python Model (*PySedSim*). Costs of sediment management options were assessed via the economic value of the loss in hydropower production and the avoided cost of dredging. Our results suggest that LULC projections resulted in high variability in loss of reservoir capacity and cost of sediment management. Terracing was found to be the best catchment-level management option at decreasing both the magnitude and variability in loss of reservoir storage for both dams, but it was also the most expensive option. Flushing was also effective in reducing sedimentation, but it was less economically beneficial compared to catchment-level sediment management options. Combinations of catchment-level and reservoir-level management strategies, however, can be effective in reducing the magnitude and variability in loss of reservoir storage and associated costs in response to LULC change uncertainty.

Key words: reservoir, sediment management, land use/land cover, uncertainty

1. Introduction

Dams and reservoirs provide storage for reliable supply of water for irrigation and hydropower generation in addition to flood control, fishing and recreation. Recent statistics suggest that dam generates 16% of global electricity (IEA, 2018) and irrigate 40% of global irrigable land (FAO, 2016). Reservoir sedimentation results to loss of reservoir storage and hence affecting the benefits of dam (Smith et al., 2013). Over half of the world's large river systems are intercepted by dams and half of these have sediment trapping efficiency of 80% or more (Grill et al., 2019; Nilsson et al., 2005; Vorosmarty et al., 2003) . Nearly 1% of global reservoir storage capacity is lost per year due to trapping of sediment (McCartney et al., 2000). Trapping of sediment by reservoirs can also significantly influence natural sediment fluxes, downstream river morphology, and ecosystem health and productivity (Arias et al., 2014; Brandt, 2000; Grant et al., 2003; Kondolf, 1997; Kummu et al., 2010; Petts and Gurnell, 2005; Schmidt and Wilcock, 2008; Wohl et al., 2015). Catchment erosion is important because it is one of the main sources of sediment to surface water bodies. Human alteration to a catchment accelerates erosion and sediment fluxes to lakes and artificial reservoirs (Moehansyah et al., 2002; Walter and Merritts, 2008; Yang et al., 2019). Climate change and land use/land cover (LULC) changes can also alter sediment yields (Shrestha et al., 2018b), which could substantially alter reservoir sediment trapping. Ultimately, excessive rates of erosion in catchments could significantly reduce energy generation (Arias et al., 2011; Kaura et al., 2019).

Reservoir storage capacity lost due to sedimentation can be mitigated, in general, by three strategies: minimizing sediment yield, routing sediment and removing sediment (Annandale, 2013; Morris and Fan, 1998; Sumi and Kantoush, 2011). The first strategy do not address the issue of sediment starvation downstream of the reservoir in contrast to the remaining strategies (Kondolf et al., 2014). The cost and applicability of each strategy will vary from one site to another, as a function of sediment accumulation (Morris and Fan, 1998), as well as physical, hydrological and financial parameters (Palmieri et al., 2001).

Uncertainty in future catchment sediment load production due to factors such as LULC change and climate change need to be considered in implementation of any sediment management plans for reservoir sustainability. Sediment projections provided without addressing the associated range of potential future changes could mislead the selection of sediment management strategies and associated costs. Assessment of uncertainty in hydrological predictions is crucial for effective and efficient management of resources (Brown et al., 2012; Milly et al., 2008). In basins where rapid conversion of forest to agricultural lands is expected, the sediment projection uncertainty due to LULC change is usually larger than the climate signal (Shrestha et al., 2018a; Shrestha et al., 2016). While studies have analysed the cost of sediment management options (for example, Palmieri et al., 2001; Smith et al., 2013), studies assessing the implications of uncertainty in sediment projections on sediment management options and costs are limited. The purpose of this study is to assess the effect of sediment management options for reservoir sustainability and associated cost under uncertainty in sediment projections due to LULC changes. The Nam Kong catchment of the Mekong River in Southern Laos was used as a case study. This study focused on sediment prediction uncertainty associated with LULC change only, for purposes of isolating and evaluating this key driver in detail.

2. Study Area

The Nam Kong catchment covers part of Laos and drains an area of 1281 km^2 (Figure 1). This particular study area was selected so that a pristine catchment can be explored to assess the effects of potential future LULC changes. Further, Nam Kong River is a tributary of the Sekong, which is the last unobstructed major tributary of the Mekong River and is incredibly important from a fishery perspective (Thomas et al., 2018). The fishery value of Sekong River is under threat by intensive hydropower development plans. In order to balance the hydropower and ecological concerns the government of Laos recently adopted a sustainable hydropower master plan that includes a careful dealing with sediment management. However, this plan does not address uncertainty in LULC change. Thus, this paper provides a timely and important input to the sustainable hydropower development, from a conceptual perspective.

The elevation of the Nam Kong catchment ranges between 298 and 1447 m above mean sea level. Based on 2003 LULC data, obtained from the Mekong River Commission (MRC), the catchment was dominated by forest (mostly dryland bush type forest), which covered almost 99% of the total area. Soil in this catchment is predominantly sandy clay loam. The proposed hydropower facilities (Nam Kong 1 and Nam Kong 3), with total combined active storage capacity of 804 million cubic meters, are expected to have an average electricity generation of 639 GWh/yr (Table 1). Both dams were assumed to be operational by 2020, a hypothetical notion as there was no evidence that the dams had been completed at the time this paper was written.

3. Methodology

The conceptual framework used to evaluate the sediment management options and estimate the cost of sediment management in the Nam Kong catchment is presented in Figure 2. The framework includes the following stages: (1) LULC change projection; (2) catchment erosion modelling; (3) catchment-level management evaluation; (4) reservoir sedimentation estimation; (5) reservoir-level management evaluation; and (6) cost of sediment management. Each element of this conceptual framework is discussed in detail below.

3.1 Land use/land cover change projection

LULC change projections were adopted from Shrestha et al. (2018a), which covered the broader Sekong, Srepok and Sesan River (3S) Basin. The Land Change Modeler (LCM; (Eastman, 2009) was used to project future LULC change for 2030, 2060 and 2090. LCM uses Markov chain prediction method to predict the amount of LULC change and uses either logistic regression or machine learning methods to model the transition potentials of land (Mas et al., 2014). The Markov chain provides the model with the estimated areas of each land use category for future dates and the amount of change for each transition (Mas et al., 2014). Transition potentials are the likelihood for areas to transition from one land use type to another, for example from forest to agriculture or from grass to agriculture. Transition potentials are derived from the relationship between land use transitions and explanatory variables (drivers). LCM is used in this study because of its wider application in simulating LULC dynamics (Fuller et al., 2011; Rodríguez Eraso et al., 2013; Sangermano et al., 2012). For details on LCM readers are referred to Eastman (2009). An ensemble forecasting method, as suggested by Santini and Valentini (2011), was used to generate twelve likely LULC change scenarios for the 3S basin by combining two transition potential models namely SimWeight (SR) and Logistic Regression (LR), three LULC demands (high, medium and low) and two constraints to LULC allocation (the remaining or not protected areas). The details on these 12 LULC change scenarios are presented in Shrestha et al. (2018a). For this study, we used two extreme LULC scenarios primarily driven by LULC demand, which capture the maximum possible range of uncertainty in LULC change from Shrestha et al. (2018a). The two future LULC scenarios considered were: (a) low LULC demand/change scenario and (b) high LULC demand/change scenario. The land demands for low- and high-LULC scenarios were estimated through simple extrapolations of past LULC trends in the 3S Basin for the 1993 – 1997 and 1997 – 2010 periods, respectively, when conversion of forest to agriculture (maize and cassava) was the primary land use transition. Based on past historical trends, the annual rate of change for the primary LULC for the 3S Basin was lowest for the period 1993–1997 (2.6% for agriculture and -0.2% for forest) and highest for the period 1997–2010 (6.2% for agriculture and -1.1% for forest). The transition potentials were modeled using Logistic Regression (LR), which generates change/transition potential using a logit function to derive relationships between LULC change and drivers. All the data sets used for LULC change modelling were obtained from the MRC.

3.2 Catchment erosion modelling

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Srinivasan et al., 1998), was used for simulating catchment soil erosion and sediment yield under baseline and LULC change scenarios. This model was selected because it has been widely evaluated in the Mekong Basin (Mohammed et al., 2018; Oeurng et al., 2016; Shrestha et al., 2017; Trang et al., 2017), thus limiting the uncertainty associated with applying a new model to a basin for the first time. SWAT subdivides the catchment into several hydrological response units (HRUs). Each HRU consist of lumped area with unique LULC, slope, soil and management combination. SWAT calculates erosion from each HRU using the Modified Universal Soil Loss Equation (MUSLE), lumps them and routes the sediment loads in channels to the catchment outlet using a simplified version of the Bagnold (1977) stream power equation. Readers are referred to Neitsch et al. (2011) for details on SWAT model. All the meteorological data (i.e., daily rainfall, temperature, wind speed, humidity and solar radiation) and spatial input data (like digital elevation model, soil and LULC) for the SWAT models were obtained from the MRC. For this study a 20-year simulation period (1986 – 2005) was used for the SWAT model for the baseline LULC and for each LULC change scenario. In the SWAT model simulations, the meteorological data from 1986 to 2005 was used for all the future simulation horizons, while changing the LULC parameters according to the scenarios. The mean annual sediment load at each dam location was estimated based on the average over the 1986-2005 series. The mean annual sediment load is estimated till 2120 to conduct a future 100-year simulation to represent the typical lifetime of a dam. Mean annual sediment inflow for the baseline period (1986-2005) and year 2030, 2060 and 2090 was obtained from SWAT model. After 2090 the mean annual sediment inflow pattern was kept constant because the catchment reached full agriculture cover. For the remaining years in between the baseline period, 2030, 2060 and 2090, the mean annual sediment inflow was estimated by linear extrapolation in order to represent the temporal (annual) variability in sediment inflow as a result of agriculture expansion.

3.3 Evaluation of catchment-level management

Sediment load to the reservoirs can be reduced by catchment management practices. Three catchment management practices were evaluated: terracing (TERR), vegetative filter strips (VFS) and no tillage (NOTILL) (Table 2). These management practices were evaluated using built-in SWAT modules. The selected catchments have steep slopes and long slope lengths; hence, terracing was selected as one of the catchment management practices because terracing is generally effective for such terrain. Terracing decreases hillslope length, which prevents gully formation and hence erosion (Tuppad and Srinivasan, 2008). Terracing was simulated in SWAT by adjusting the MUSLE practice factor (TERR_P) and average slope length (TERR_SL). The average slope length was reduced by 50% to represent potential implementation of terracing in the region. Vegetative filter strips (VFS) are areas of vegetation that filter runoff and trap sediment. VFS were analyzed in this study because of their high efficiency in minimizing sediment transfer to rivers (e.g Hann et al., 1994). VFS is also one of the recommended methods for reducing soil erosion because it is less labor intensive compared to other soil conservation practices such as contour plowing (GoLPDR, 2012). SWAT-defined threshold values (Table 2) were used for simulating the effect of VFS on catchment sediment yield. The strategy of eliminating tillage practices (i.e., No tillage) was evaluated because it is a widely adopted management practice to control erosion, reduce input cost, and maintain crop yield for long-term (Pittelkow et al., 2015). No tillage reduces soil erosion by limiting soil disturbance activities, which increases the soil water permeability and encourages accumulation of soil organic matter (Li et al., 2019).

3.4 Reservoir sedimentation estimation

PySedSim was used in this study to evaluate sedimentation, as well as to evaluate reservoir sediment management potential. *PySedSim*, is an object-oriented, Python-based, one-dimensional model developed to simulate flow and sediment in river reaches and reservoir(s) and estimate hydropower production in reservoir(s) (Wild et al., 2021). *PySedSim* can be used to model multiple reservoir sediment management techniques, and has been applied in case studies in the Mekong River Basin (Wild et al., 2016; Wild et al., 2019b). The model is open-source and available at https://github.com/FeralFlows/pysedsim. *PySedSim* has similar simulation functionality to the original SedSim model (Wild and Loucks, 2015; Wild et al., 2019a) with respect to sediment production, transport, reservoir trapping, and reservoir management.

PySedSim calculates the amount of sediment trapped by individual reservoirs by estimating trapping efficiency. The method developed in Brune (1953) is used to estimate the trapping efficiency for each reservoir for each day as a function of the reservoir's residence time. In *PySedSim* the residence time for each simulation day is determined as the ratio between the average total water storage in the reservoir divided by the outflow or release of water from the reservoir. The model computes the volume of deposited sediment by dividing the trapped sediment mass by the bulk density of deposited sediment. The model assumes that the bulk density of deposited sediment remains stable and does not change due to compaction. For this study the bulk density value of 1.2 tons/m^3 was used which is based on the major soil type in the catchment. Further the bulk density value used for this study lies between the reasonable range (1.1-15 tons/m^3) for the sediment deposited in reservoir as suggested by Lara and Pemberton (1963). For this study, we used the total reservoir storage for our analysis, which means that dead storage was also included. The major hydrological inputs to *PySedSim* are flows and sediment loads, which were obtained from the SWAT model. Other major inputs include reservoir characteristics data, reservoir operation rules, reservoir volume, elevation curve and reservoir operation rules, and reservoir outflows. Most of these data were obtained from MRC or from (Piman et al., 2013). A simulation period of 100 years was used in order to capture the long-term impact of sedimentation processes on reservoir storage capacity and hydropower generation over the commonly assumed 100-year lifetime of a dam (Wild et al., 2016).

3.5 Reservoir-level sediment management

3.5.1 Overview

Reservoir-level sediment management techniques consist of two general categories: minimizing sediment deposition in the reservoir by sediment routing, and directly removing sediment from the reservoir (Annandale, 2013). Flood bypass, off-channel reservoirs, sluicing and turbid density current venting from reservoirs are four major sediment routing strategies (Morris and Fan, 1998).

Bypassing was not evaluated because it requires expensive infrastructure such as tunnels and the technique is most practical for short reservoirs with adequate slope to transport the sediment through the bypass channel or tunnel (Kondolf et al., 2014). Off-channel reservoir and density current venting techniques were not considered either; off-channel reservoirs are rarely used because they require particularly favorable conditions (topography, available space, technology) and are expensive (Batuca and Jordann, 2000). The sediment removal efficiency of density current venting is less than 50% even in ideal conditions (UDWR, 2010) and there is uncertainty in the flow path of density currents (Tiˇgrek and Aras, 2012). Sluicing was not considered for this study because it was hypothesized to be ineffective from the beginning of the study due to the large size of reservoirs considered for this study. Reservoirs with dam height more than 15 m and storage capacity more than 3 million cubic meters are considered to be large-size reservoirs (Asmal, 2000). Sluicing is most suitable for narrow, elongated-shaped and small to medium-sized reservoirs (Batuca and Jordann, 2000), where flood discharge exceeds reservoir capacity (Morris and Fan, 1998).

Deposited sediment can be removed using two basic processes; hydraulic and mechanical. Hydraulic removal includes sediment flushing, while mechanical removal (not considered in this study) includes dredging, hydrosuction removal systems (i.e., siphoning), and trucking (i.e., dry excavation). Flushing is done by creating river-like velocities in the reservoir which scour and transport deposited sediment through low-level outlets (Tiˇgrek and Aras, 2012). Flushing can be conducted in two ways: pressure flushing (partial drawdown) and empty (free-flow) flushing (full drawdown) (Annandale, 2013). Pressure flushing releases water through the bottom outlets by keeping the reservoir water level high. On the contrary, empty (free-flow) flushing releases water by emptying the reservoir and routing water inflow from upstream by providing riverine conditions. For this study empty flushing was evaluated because this technique has been widely and successfully implemented (Atkinson, 1996; Kondolf et al., 2014; Morris and Fan, 1998; Palmieri et al., 2003). Pressure flushing was not considered because it is not commonly used and is less effective as compared to full drawdown flushing (Annandale, 2013; Morris and Fan, 1998). Mechanical removal like dredging and trucking were not considered viable options because of their high operation cost, and siphoning is ineffective for anything but very small reservoirs (Batuca and Jordann, 2000). The avoided cost of dredging, however, was considered for comparative purposes only.

Although reservoir sediment management techniques can be simulated with *PySedSim*, this model is not capable of determining the technical and economic viability of candidate reservoir sediment management techniques. Thus, the REServoir CONservation (RESCON) model (Efthymiou et al., 2017; Palmieri et al., 2003) was used to evaluate the technical and economic viability of multiple sediment management techniques, while *PySedSim* was used only to simulate the hydropower, hydrology, and sedimentation implications of those techniques deemed feasible by RESCON. Furthermore, RESCON is an effective tool for obtaining the flushing durations and frequency data required for *PySedSim* simulation. Only sediment flushing emerged as a reasonable option as a result of the RESCON analysis. RESCON does not assess sluicing and bypassing, but can assess hydrosuction, traditional dredging and trucking.

3.5.2 Flushing simulation in *PySedSim*

The *PySedSim* model simulates flushing in a three-stage process, namely drawdown, flushing, and refill (Wild et al., 2021). *PySedSim* initiates drawdown when two conditions are met: 1) the user-specified date for flushing has been met, and 2) the reservoir inflow exceeds the user-specified minimum inflow target. For this study, only a date was specified in the model to initiate the drawdown process (Table 3). The flow threshold was not considered for the initiation of drawdown. The target drawdown start date in May-June was selected because this time of year is appropriate in the Mekong to avoid conducting flushing during the main portion of the wet or dry season (Wild et al., 2016). Flushing during the dry season is likely to see limited sediment removal due to limited natural discharge rates, and also creates the possibility that the reservoir cannot be refilled. Flushing during the wet season is difficult because safe drawdown may be difficult to achieve, and because low-level outlets are not sized to accommodate full pass-through of wet season discharge. After initiation of drawdown the model uses the reservoir's low-level outlets to drain the reservoir to the specified maximum flushing water level elevation. The targeted flushing water level elevation is the maximum reservoir water level that will still result in successful flushing. It is to be noted that low-level outlets are not currently proposed as design elements at Nam Kong 1 and Nam Kong 3 per the available feasibility studies for these dams. However, low-level outlets will be needed to manage sediment effectively at these dams. The national government of Laos has committed to a strategic hydropower development plan that includes sediment management at its core. So, the lack of proposed outlets does not necessarily mean that the dam will not ultimately be required to have these outlets albeit at a potentially prohibiting cost if they need to be retrofitted. The model drawdown the reservoir water level based on user specified daily drawdown rate. For this is study, the drawdown rate was restricted to a maximum of 2–3 m/day (Table 3) to ensure that the water released during drawdown does not exceed the typical wet-season flow and avoids destabilizing bank soil in the reservoir.

After completion of the drawdown process, the model initiates flushing for a user-specified duration. For successful flushing to occur, two criteria must be satisfied: (1) the reservoir water level should not exceed the specified maximum flushing water level elevation, and (2) the discharge through the low-level outlets must equal or exceeds the minimum target flushing discharge. The target flushing discharge rate for Nam Kong 1 and Nam Kong 3 was 1.1 and 1.3 times the mean annual inflow to the dams, respectively. The flushing durations and frequency provided in Table 3 were obtained from the RESCON model. For this study the flushing frequency of every 5 years is used. The selection of flushing frequency (annual, every two years, etc.) creates a tradeoff between hydropower loss and magnitude of sediment load released downstream (which is ecologically important). During a flushing event, some fraction of the volume of sediment deposited since the previous flushing event is removed (Wild et al., 2019a). The fraction of sediment removal is empirically determined by the ratio of trapezoidal cross-sectional area of the incised channel formed by flushing to the cross-sectional area of the reservoir (Wild et al., 2016), which varies over time as the incised channel evolves. This method of estimating the amount of sediment removal is based on the approach suggested by Atkinson (1996). Once the flushing is completed, the refilling of the reservoir initiates. Figure 3 demonstrates the flushing process as simulated in *PySedSim* for Nam Kong 1 dam in the study area. During flushing, operating policy diverges from a normal state to drawdown (emptying) policy, which takes some time and power generation declines during emptying. After the target level of drawdown is achieved, the reservoir stays empty during the flushing duration and sediment is removed. After the targeted flushing duration, the reservoir fills up and returns back to a normal operating policy. It is to be noted that we assumed the reservoirs are flushed in a coordinated fashion (simultaneously). The flushing operation of downstream dam (Nam Kong 1) is carried out is such a way that the flushed sediment from upstream dam (Nam Kong 3) pass through the Nam Kong 1 dam.

3.6 Cost of sediment management

The cost of sediment management for both dams considered in this study was determined from the sum of two different costs: (1) the cost of reservoir sediment removal at the end of the dam's assumed lifetime of 100 years, and (2) the cost of loss in hydropower production that results from reservoir sedimentation and management. It is to be noted that the cost of sediment management does not include the implementation cost of sediment management options. Regarding the first cost component, we assume that all sediment that has accumulated in the reservoir by the end of each dam's lifetime will need to be removed to recover the site for use by future generations. Viable reservoir sites are limited in number and are thus a non-renewable resource. Forcing future generations to bear the cost of recovering this non-renewable resource, however, is unequivocally unsustainable because it does not promote intergenerational equity (Annandale, 2014). Thus, we account for this recovery cost as part of the cost associated with each dam. The cost of reservoir sediment removal (C_{sr}) was taken to be the avoided cost of dredging, which can be very expensive (Morris and Fan, 1998; Palmieri et al., 2003). The concept of relating cost of sediment retained in the landscape to the avoided cost of dredging has been successfully used in the InVEST model (Sharp et al., 2014). The C_{sr} at the end of 100 years of reservoir operation is estimated as:

$$\mathrm{C_{sr}} = \mathrm{C}_d \, . \mathrm{X} \tag{1}$$

where X is the total amount of sediment removal at the end of 100 years of reservoir operation (m^3), and C_d is unit cost of dredging (US\$/m^3). A literature review was carried out for an appropriate unit cost of dredging. For this study a unit cost of dredging was assumed to be US\$ 3/m^3 as suggested by Annandale et al. (2016).

The second cost component accounts for the fact that hydropower generation is affected by sedimentation (via storage capacity loss and thus less effective reservoir operating policies), as well as by the process of emptying the reservoir for flushing. The flushing process, which is described in detail in the previous section, reduces both the turbine discharge and hydraulic head as a result of drawdown, flushing, and refill. The method of estimating the cost of loss in hydropower production is based on the framework suggested by Arias et al. (2011). The cost of loss in hydropower production for individual years ($C_{hp,t}$) is calculated as the difference in hydropower revenue between the baseline case and scenarios:

$$\mathrm{C_{hp,t}} = (\mathrm{MHPG_{baseline}} - \mathrm{HPG_{scenarios}}) . \mathrm{ELEC} \tag{2}$$

where $MHPG_{baseline}$ is the maximum hydropower generated in the baseline case (kWh); $HPG_{scenarios}$ is the hydropower generated for scenarios (kWh); ELEC is the electricity selling price per kilowatt-hour (US$ kWh^{-1}); A fixed electricity rate of US $ 0.20 kWh^{-1}, which represents the highest electricity rate among the Lower Mekong countries, was used in this study. The total cost of loss in hydropower production for 100 years of reservoir operation (C_{hp}) was then estimated by adding up all individual $C_{hp,i}$.

The hydropower generated (HPG) was estimated using the *PySedSim* model. *PySedSim* calculates the hydropower production (MW) at reservoir j in period t as:

$$\mathrm{HPG}_{(j,t)} = \frac{9.81}{1000} \cdot \mathrm{e}_{(j)} \cdot \mathrm{h}_{(j,t)} \cdot \mathrm{Q}_{(j,t)} \tag{3}$$

where $h_{(j,t)}$ is the hydraulic head above the turbines at reservoir j in time period t, $Q_{(j,t)}$ is the turbine discharge in units of m^3/s, and $e_{(j)}$ is the efficiency (fraction) of the turbines at reservoir j, assumed not to vary over time. It is to be noted that the storage loss due to reservoir sedimentation affects the hydropower generation. The hydraulic head is not really changed by the sedimentation. Rather, the volume of water stored in the dead and active zones are effectively reduced because sediment occupies volume that was once available for water. The result is that less water is available to run through the turbines (Q). In a reservoir that is heavily affected by sedimentation, the same release of Q through the turbines thus lowers water levels much more significantly, which affects the hydraulic head (h) in future time periods. For this study the $e_{(j)}$ was assumed to be 0.9. For this study the net present value (NPV) of the cost of reservoir sediment removal at the end of 100 years of reservoir operation is calculated as:

$$NPV\ of\ C_{sr} = \frac{C_{sr}}{(1+r)^{100}} \tag{4a}$$

It is to be noted that since C_{sr} from year 1 to 99 of reservoir operation will be zero, the present value during these periods will also be nil.

The net present value (NPV) of the cost of loss of hydropower over 100 years of reservoir operation is quantified as:

$$NPV\ of\ C_{hp} = \sum_{t=0}^{N} \frac{C_{hp,t}}{(1+r)^{t}} \tag{4b}$$

where r is the annual discount rate, which is assumed as 5% per year for this study, N is total number of years in the period and t is time (yr).

As pointed out by other studies in the region (Arias et al., 2011; Kaura et al., 2019), economic benefits of sediment management are sensitive to discount rates and electricity prices. Hence, the uncertainty in discount rate and electricity price was also included in the NPV analysis of the cost of sediment management. For discount rate, the range of 2 – 8% was used and for electricity cost per kWh, the range of US$ 0.1 – 0.3 was considered to capture the maximum possible range of uncertainty. The approach suggested by Chen et al. (2011) was used to assess uncertainty (i.e. to identify which parameter resulted the largest variability in NPV). The NPVs were first grouped into respective sources of uncertainty (i.e., LULC change, discount rate and electricity price) and then means for each group were estimated and compared. For the NPV of cost of reservoir sediment removal the uncertainty in LULC change and discount rate was assessed and for the NPV of cost of loss in hydropower the uncertainty in LULC change, discount rate and electricity price were evaluated. It is to be noted that the impact of uncertainty in discount rate and energy price on cost of sediment management is explicitly discussed in section 4.6.

Each of the sediment management options considered for this study resulted in different time-patterns and magnitudes of sediment accumulation in the reservoir, and thus had different costs of reservoir sediment removal at the end of 100 years, and different costs associated with lost hydropower production over time. Note that the costs of sediment removal after 100 years, and the costs of lost hydropower production were first estimated for the baseline case (i.e., do-nothing option). Each of the sediment management options considered for this study were then compared to the baseline cost.

4. Results and Discussion

4.1 Land use/ land cover (LULC) change and catchment sediment load

LULC change results presented here were adopted from Shrestha et al. (2018a), which cover the broader 3S Basin. Based on the predicted future LULC (Figure 4), forested land in the Nam Kong catchment is expected to decrease 18%, 33% and 39% by 2030, 2060 and 2090, respectively, under the low-LULC change scenario. Under the high LULC change scenario, forest is estimated to decrease 45%, 66% and 100% by 2030, 2060 and 2090, respectively, due to agricultural expansion.

Under the baseline scenario with the 2003 LULC map, a mean sediment load of 0.02 million tons per year (Mt/yr) at the Nam Kong 3 dam location is estimated, while at the Nam Kong 1 dam location it was estimated at 0.29 Mt/yr. There is a stark difference in sediment load between the two dams. The catchment area of Nam Kong 1 is roughly twice the size of Nam Kong 3, but sediment load is an order of magnitude larger. The reason for this big difference is that area downstream of the Nam Kong 3 dam is the main source of sediment in the catchment (Shrestha et al., 2018a). As expected, the sediment load increases over time as conversion of forest to agriculture occurs. By 2120, in year 100, the annual mean sediment load is estimated to range between 0.46 and 1.06 Mt at the Nam Kong 3 dam location and between 1.17 and 3.56 Mt at the Nam Kong 1 dam location in response to LULC changes (Figure 5). The sediment load for high-LULC change flattens out after 2090 because the catchment has reached full agriculture cover. The high variability in sediment loads due to LULC changes was observed, which is largely due to the higher sediment yield under the high LULC change scenario. Model parameter uncertainty can influence the LULC change impact results. Our assessment of uncertainty in future flow and sediment due to global climate models (GCMs) and representative concentration pathways (RCPs), model parameters and LULC change scenarios for the 3S basin suggested that uncertainty in LULC changes can significantly outweigh model parameter uncertainty affecting future sediment projections. The results of a range of annual sediment loads under these four sources of uncertainty is provided in the Supplementary Material (Figure S1).

4.2 Reservoir sedimentation due to land use/land cover (LULC) change

Figure 6 presents the resultant decrease in the reservoir's capacity for the two dams operating in series under the two LULC change and the baseline (no LULC change) cases. Loss of storage capacity for the reservoirs due to reservoir sedimentation under baseline conditions is not significant. The initial reservoir volume is estimated to decrease by nearly 4% and 0% for Nam Kong 1 and Nam Kong 3 reservoirs, respectively, after 100 years. For Nam Kong 1 reservoir the reduction in reservoir storage capacity due to sedimentation ranges from 8 to 28% after 100 years across the LULC change scenarios. By 2120, the Nam Kong 3 reservoir volume is estimated to decrease by 11-26% due to LULC change.

The results indicate that variability in projected future sediment yield results in large uncertainties in reduced reservoir capacity, which are due to differences between LULC change projections (Figure 5-6). The results also indicate that variability in loss of reservoir capacity increases with time for both dams. This analysis is based on two dams operating in series; hence it is worth noting that the loss of reservoir volume for Nam Kong 1 is influenced by the magnitude of sediment trapped in Nam Kong 3. Increased sediment load due to LULC changes generally can result in significant reduction of reservoir storage capacity, which can affect power generation capacity. The reduction in storage capacity, considering LULC change, can be a significant factor in the cost-benefit ratio of hydropower projects. Hence, the dam designer and planner should take potential LULC change into account in the design and operation of dams.

4.3 Impact of catchment-level sediment management on reservoir storage

The loss of reservoir volume after testing three different catchment management options suggest that terracing is the most effective option to minimize reservoir storage capacity loss (Figure 7). For Nam Kong 1, implementation of terracing can reduce the loss of reservoir volume from 8-28% to 1-3%. Interestingly, terracing also reduced the wide variability in loss of reservoir volume due to the LULC scenario. In general, vegetative filter strips are the least effective catchment-level reservoir sedimentation management option evaluated in this case study. Terracing is likely more effective in reducing sediment/soil erosion because terracing reduces hillslope length and gradient, which results in decreasing surface runoff and velocity, while vegetative filter strips were only implemented in agricultural land bordering the river reaches. The effectiveness of filter strips to minimize sediment transfer to rivers is a function of the location and amount of permanent vegetative cover (Zhou et al., 2009), and implementation in large areas (i.e., the filter strips themselves are large) can increase sediment load reduction (Woznicki et al., 2011).

4.4 Impact of flushing on reservoir storage

Figure 8 shows the effect of flushing on the reservoir storage capacity of both dams operating in series. The results indicate that periodic flushing (i.e., every five years) can minimize the loss of reservoir storage capacity and significantly reduce variability in loss of reservoir capacity. Our model simulation results show that over 100 years of reservoir flushing operations (4-13 days every 5 years) can remove more than 90% of the total sediment inflow to the reservoirs. For example, under the high LULC change case for Nam Kong 1, if flushing is not implemented the reservoir will trap 176.3 Million Tons (Mt) of sediment over 100 years, which is nearly 93% of the total sediment inflow to the reservoir. Implementation of flushing can remove 95% of total sediment inflow (246.5 Mt) to the Nam Kong 1 reservoir (Table 4). This high degree of flushing effectiveness is a function of both the magnitude of flushing discharge available during the target flushing time period of May-June, as well as the extensive width of the incised channel created by flushing relative to the reservoir width**.**

In general, flushing can be successfully implemented and is an effective reservoir-level management option to reduce the lost reservoir storage of both dams when efforts are coordinated. Unlike catchment-level management options, flushing also releases the trapped sediment back to the river crucial for the riverine ecosystem. However, flushing can significantly alter the sediment and flow pulse of the river which can have ecological (Espa et al., 2016; Grimardias et al., 2017) and geomorphological (Brandt and Swenning, 1999) implications. In this study, for flushing to be successful, its frequency was set at 5-year intervals. This simply means that the sediment trapped for 5 years will be flushed in a short duration, ranging from 4 – 13 days depending upon the dam and LULC scenario (please refer to Table 3 for details). This can suddenly introduce large amounts of sediment to the river. Morris and Fan (1998) suggest that flushing, in general, can suddenly increase sediment concentration with magnitudes exceeding 100 g/L, which can last for several weeks. Hence, the amount, timing and frequency of sediment released during flushing should be carefully planned in order to minimize adverse effects to riverine ecosystems (Wild et al., 2016). Dams can be flushed more often to minimize the release of large amounts of sediment to the river, but the impacts on power generation can be even sharper.

4.5 Cost of sediment management

The annual estimated revenue from hydropower generation from the Nam Kong 1 and Nam Kong 3 reservoirs is US$ 119 million and US$ 34 million, respectively. For Nam Kong 1, the cost of reservoir sediment removal (taken as avoided cost of dredging), after 100 years of operation (i.e., at the end of the dam's lifetime), ranges from US$ 123.53 to 440.73 million without sediment management strategies. The net present value (NPV) of the cost of reservoir sediment removal ranges from US$ 0.94 to 3.35 million if no sediment management options are implemented (Table 5). The total cost of loss in hydropower production due to loss of reservoir volume is estimated to range from US$ 25.81-77.73 million, and the NPV for the cost of loss in hydropower ranges from US$ 1.46 – 4.50 million, for Nam Kong 1 without sediment management strategies. For Nam Kong 3, over 100 years of operation, the total cost of loss in hydropower generation ranges from US$ 7.80 to 20.14 million and the NPV ranges from US$ 0.42 – 1.25 million if no sediment management options are implemented. The total cost of loss in hydropower for both dams due to loss of reservoir capacity is not significant compared to total revenue generated by both dams operating over 100 years. This result suggests that for high dams, with large storage and loss in reservoir storage due to sedimentation, reduced power generation revenues may not be significant. This might not encourage dam developers or operators to take measures to reduce sedimentation in order to regain the lost reservoir storage. However, the lost revenue due to sedimentation could be used for catchment conservation practices and reservoir-level options which would offset sedimentation and thus reservoir volume loss. Further, trapping sediment for 100 years may ultimately adversely impact critical river ecosystems. Maintaining riverine ecosystems, rather than storage capacity and energy production, might be the reason to motivate the dam developer and operators to implement sediment management, which is likely the case for most reservoirs in the 3S basin (Wild and Loucks, 2014). For dam developers and operators to view sediment management as an economic benefit, the cost of maintaining the critical riverine ecosystem must be accounted in the traditional paradigm of economic analysis (Wild et al., 2016). Catchment-level sediment management options also provide multiple upstream ecosystem service benefits (such as pest control, agricultural productivity, buffering and attenuation of mass flow) (Arias et al., 2011; Benisiewicz et al., 2020) in additional to sustainable hydropower production. Nevertheless, for smaller storage dams, the reduced power generation revenues may be significant (Kaura et al., 2019) and hence, the financial benefits of sediment management options will be important.

Through this study we are not assessing the most economically feasible or most optimal catchment management strategies, but present how the cost of sediment management changes when various interventions are made with the aim to reduce erosion from the catchment and hence increase the life span of the reservoirs (i.e., quantify the economic benefit of catchment management to hydropower and reservoir storage). Out of three catchment management practices used in the study, terracing is the most effective method, decreasing the magnitude and variability of the cost of sediment management significantly for both dams (Figure 9). Terracing provides greater economic benefit to dam developers and operators as compared to other options considered in this study. For instance, over 100 years of operation, terracing will provide a benefit of US$ 134.60 – 461.60 million (NPV of US$ 2.2 – 7.1 million) and US $76.40 – 179.8 million (NPV of US$ 0.9 - 2.4 million) for Nam Kong 1 and Nam Kong 3 dams, respectively. Vegetative filter strips is the least effective method in reducing the cost of sediment management.

The selection of management practices for reducing erosion from the catchment depends not only on the technical effectiveness, but also on the financial viability of the measures (Verstraeten et al., 2002). Hence, the estimation of actual cost and complete cost-benefit analysis for each option is required. The catchment management option which is most effective in reducing the loss of reservoir volume, and decreasing the costs of sediment removal and loss of hydropower generation may not be the most cost-effective option to implement. The large-scale implementation of terracing can be very expensive despite its high benefit as compared to other options. Terracing is labor intensive and does have high implementation and maintenance costs. Yang et al. (2014) suggested the cost per hectare of terracing in China ranges from US$ 1900 to US$ 4000 depending on slope gradient (the higher the slope gradient the higher the cost of terracing). Options such as no tillage and vegetative filter strips would be easier, less labor intensive and less costly to implement. For instance, a study conducted in an Iowa agricultural catchment found the annual cost of implementation and maintenance to be lowest for vegetative filter strips (US$ 3.2 per hectare) and highest for terracing (US$ 126.4 per hectare) (Zhou et al. (2009). It is to be noted that the cost of terracing in Iowa is much less than in China as mentioned above due to differences in the type of terracing. In the Iowa case, terracing is on low slopes. Further, the integration of different catchment management practices may provide most cost-effective results. Management of increased sediment due to LULC changes in catchments with multiple dams often requires an integrated sediment management approach. Several studies (for example Bosch et al., 2013; Li et al., 2019) have suggested that integration of various catchment-level management practices can produce the most effective result.

Our results suggest flushing, although effective in minimizing the loss in reservoir capacity, may provide the least economic benefit to dam developers and operators as compared to catchment-level management options in the case study dams in Southern Laos. For example, for Nam Kong 1 dam over 100 years of operation, while catchment-level management options will provide an economic benefit with NPV ranging from US$ 0.90 to 7.10 million, flushing provides none. The cost of loss in hydropower is higher with flushing as compared to catchment management options (Table 5), as there is lost opportunity to generate energy during the flushing process. Since the dams are high in our study area, the total duration of the flushing process, more specifically drawdown and refill, is quite significant (more than 19 days for Nam Kong 3 and more than 25 days for Nam Kong 1 dam). Hence, during the flushing period the dam operator will not be able to produce energy for a considerable period. Flushing with long duration is expensive mainly due to significant loss of hydropower generation (Espa et al., 2016). For high dams the drawdown and refill period will be similar for both cases (i.e, high LULC change and low LULC change) even though the flushing duration varies (Table 3). For more optimal reservoir sediment management solutions, a combination of reservoir-level management techniques may be required because the effectiveness of each technique can change over time (Annandale et al., 2016).

4.6 Uncertainty analysis of discount rate and electricity price

The uncertainty analysis of discount rate and electricity price suggests that discount rate is the major source of uncertainty for the NPV of the sediment management cost (Figure 10). While NPV of the cost of loss in hydropower production was quite sensitivity to electricity price for flushing, it may not be so for business as usual (i.e., do nothing case) and catchment-level sediment management options. The land use land cover (LULC) change scenario was found less sensitive as compared to discount rate and electricity price which is aligned with a previous study in the region (Kaura et al., 2019). In general, the NPV of cost of sediment management can vary considerably in response to changes in discount rate (especially when considering sediment removal with dredging to be a single cost in 100 years) and electricity price. Hence it is noted that although the NPV of cost of sediment management was estimated using an assumed discount rate of 5%, it may be different in reality at the time of operation. Further sensitivity/uncertainty in discount rate and cost of electricity should be carried out while assessing the economic benefit of sediment management options.

5. Limitations of the study

In this study, hydrologic regime changes as a result of LULC changes were not taken into account, but only changes in sediment load were considered. For the area undergoing rapid development the range of changes in sediment load is much larger than streamflow in response to uncertainty in LULC changes (Shrestha et al., 2018a) and hence changes in sediment load in response to LULC would have more influence on reservoir sedimentation. However, we acknowledge that LULC changes can have an influence on the water runoff and ultimately the streamflow. Further, changes in the streamflow can affect the reservoir-level sediment management option considered in the study as the optimal flushing regime will be slightly different across the LULC scenarios.

The 2090 high LULC scenario is an extreme case where the entire study catchment is converted to agriculture and also considers conversion of protected areas (Shrestha et al., 2018a). However, the conversion to agriculture may not be possible in locations with steep slopes or protected areas, where erosion rates might be very high.

6. Conclusions

This study aimed to understand the effect of catchment sediment management options for reservoir sustainability and associated cost due to sediment projections variability caused by LULC changes. We explored this critical issue in the Nam Kong Catchment in Laos, which is situated in the ecologically critical Se Kong, Se San, and Sre Pok ("3S") river basins of the Mekong basin in Southeast Asia. Due to planned intensive and pervasive hydropower development plans in the Mekong (many of which are planned in Laos), this region is facing critical challenges with respect to balancing hydropower and ecological concerns (Grumbine et al., 2012; Moran et al., 2018; Wild et al., 2019b; Zhong and Hao, 2017; Ziv et al., 2012). Thus, this study evaluates sediment management options (both catchment management and reservoir management), in the context of LULC change, in one of the world's most critical river basin development contexts. The national government of Laos recently adopted a sustainable hydropower master plan that includes a significant focus on sediment management. Thus, this paper provides timey input to an ongoing policy discussion in Laos regarding development of the ecologically rich Sekong river basin. The results of the study's simulations suggest that uncertainty in LULC changes can result in high variability in loss of reservoir capacity and cost. Increased sediment load due to LULC changes can generally result in significant reduction of reservoir storage. Hence, dam planners should consider future potential LULC changes in the design and operation of dams.

For high dams with large storage, loss in reservoir storage due to LULC change-induced sedimentation may not significantly reduce power generation revenues, because loss of reservoir storage is relatively low even in the worst-case scenario. This may not motivate dam developers to implement measures to manage sediment. However, for smaller storage dams, loss in power generation revenues due to sedimentation would be significant and the financial benefits of sediment management options (both catchment-level and reservoir-level) will be substantial as well. It is also important to address the issue of conservation of land as a way to reduce sedimentation of reservoirs. Establishing conservation areas will also help achieve the goal of reducing reservoir volume loss. Further, the benefit of maintaining riverine ecosystems may be the incentive which might encourage dam developers to implement sediment management options (Wild and Loucks, 2014). Hence, the economic value of maintaining the riverine ecosystem and other upstream ecosystem service benefits should also be included in estimating the cost of sediment management.

Catchment management can significantly reduce long-term reservoir volume loss. For the Nam Kong case study, terracing was the most effective method and vegetative filter strips the least effective in increasing the life span of the reservoirs and hence reducing the cost of sediment management. Terracing can also decrease the wide variability in lost reservoir capacity and the cost of sediment management. However, terracing would undoubtedly be the most expensive measure to implement as compared to other options considered in the study. This suggests that the best erosion control measures that provide the most benefit may be too expensive to implement and thus other alternatives may be more feasible. Hence, the estimation of actual cost and complete cost benefit analysis for each catchment management options are critical for the selection of the best catchment management option(s) for minimizing the effects of uncertainty in LULC changes. Identifying high sediment sources within subbasins using a more spatially detailed model would help target soil conservation strategies and decrease implementation costs.

Flushing can be an effective reservoir-level management option to minimize loss of reservoir storage, but it may be less economically beneficial as compared to catchment management options. However, catchment-level management options do not address the issue of sediment starvation downstream, which is crucial for downstream riverine ecosystem and morphology (Kondolf, 1997). Hence, a combination of both catchment-level and reservoir-level sediment management approaches is required to maintain reservoir capacity as well as meet the sediment demand downstream. This is especially true for the high LULC change case where excessive erosion from the catchment can have adverse effects for both reservoir storage and river morphology and ecology. Further, flushing can provide increasing economic benefits to dam developers and operators as the loss in reservoir storage increases. There is also a need to study other sediment management options.

The findings presented in this study may only be true for the site-specific Nam Kong case study because the cost and effectiveness of any sediment management option may vary depending upon reservoir size and location (Morris and Fan, 1998). The result suggests that uncertainty in discount rate and cost of electricity should be carried while assessing the economic benefit of sediment management options. The result also highlights that it is difficult to generalize what sediment management option will work at any particular dam, which creates a challenge for assessing sediment management potential at the basin scale. However, the method presented in this study can be used globally to assess sediment management options for reservoir sustainability considering uncertainty in LULC change.

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Tables

Table 1. Characteristics of the Nam Kong 1 and Nam Kong 3 hydropower schemes.

Parameter	Nam Kong 1	Nam Kong 3
Installed capacity (MW)	150	75
Mean energy production (GWh/yr)	469	170
Active storage (10^6 m^3)	505	299
Catchment area (km^2)	1281	648
Dam height (m)	105	62
Mid or low level flushing outlets	Unknown	Unknown

Source: Mekong River Commission, 2008

Table 2. Catchment management practices analyzed in this study.

Practices	Variable name	Definition	Value
TERR: Terracing	TERR_P[a]	USLE practice factor adjusted for terraces	Slope range 0-2% = 0.12 Slope range 2-10% = 0.10 Slope range >10% = 0.16
	TERR_SL	Average slope length (m)	Slope length 0-2% = 60m Slope length 2-10% = 30m Slope length >10% = 10m
VFS: Vegetative Filter Strips	FILTER_RATIO[b]	Ratio of field area to filter strip area.	50
	FILTER_CON[b]	Ratio of the HRU which drains to the most concentrated 10 percent of the filter strip area	0.5
	FILTER_CH[b]	Ratio of the flow within the most concentrated 10 percent of the filter strip which is fully channelized	0.0
NOTILL: No Tillage	$C_{tillage}$[c]	Tillage method factor	0.25

Source: [a] Hann et al. (1994), [b]Neitsch et al. (2011), [c]

Table 3. Input data for flushing process.

Input data	**Nam Kong 3**	**Nam Kong 1**
Flushing discharge (m^3/s)	42	70
Duration of flushing after complete drawdown (days)	13/6*	13/4*
Frequency of flushing events (yrs)	5	5
Start date	1-Jun	26-May
Drawdown rate (m/day)	2	3
Duration of drawdown (days)	19	25

Note: *Different values used for the High/Low LULC change scenarios

Table 4. Reservoir sediment budget over 100 years of operation for the Nam Kong 3 and the downstream Nam Kong 1 reservoirs (flushed simultaneously).

Sediment Budget	**Nam Kong 3**		**Nam Kong 1**	
	No Flushing	**Flushing**	**No Flushing**	**Flushing**
High LULC change scenario				
Total sediment inflow (Mt)	79.2	79.2	189.6	258.3
Total sediment outflow (Mt)	6.6	75.3	13.3	246.5
Trapped Sediment (Mt)	72.6	3.9	176.3	11.8
Low LULC change scenario				
Total sediment inflow (Mt)	33.0	33.0	52.8	82.3
Total sediment outflow (Mt)	2.6	32.0	3.4	79.8
Trapped Sediment (Mt)	30.4	1.0	49.4	2.5

Table 5. Details on cost of sediment management over 100 years. The units of cost is in Million US$.

Sediment management options	Nam Kong 3				Nam Kong 1			
	Cost of reservoir sediment removal	Net present value of cost of reservoir sediment removal	Total cost of loss in hydropower production	Net present value of cost of loss in hydropower production	Cost of reservoir sediment removal	Net present value of cost of reservoir sediment removal	Total cost of loss in hydropower production	Net present value of cost of loss in hydropower production
High LULC change scenario								
Do nothing	181.50	1.38	20.14	1.25	440.73	3.35	77.73	4.50
Terracing (TERR)	19.88	0.15	1.96	0.11	49.58	0.38	7.25	0.37
Vegetative Filter Strips (VFS)	81.02	0.62	8.25	0.50	272.00	2.07	38.04	2.07
No Tillage (No Till)	96.36	0.73	10.42	0.68	245.60	1.87	40.72	2.39
Flushing	9.85	0.07	77.49	13.76	29.55	0.22	530.50	95.01
Low LULC change scenario								
Do nothing	76.01	0.58	7.80	0.42	123.53	0.94	25.81	1.46
Terracing (TERR)	6.65	0.05	0.78	0.06	12.37	0.09	2.41	0.14
Vegetative Filter Strips (VFS)	27.63	0.21	2.81	0.15	65.02	0.49	10.86	0.60
No Tillage (No Till)	40.21	0.31	4.10	0.22	75.13	0.57	14.85	0.90
Flushing	2.48	0.02	61.58	10.98	6.21	0.05	477.36	85.58

Figures

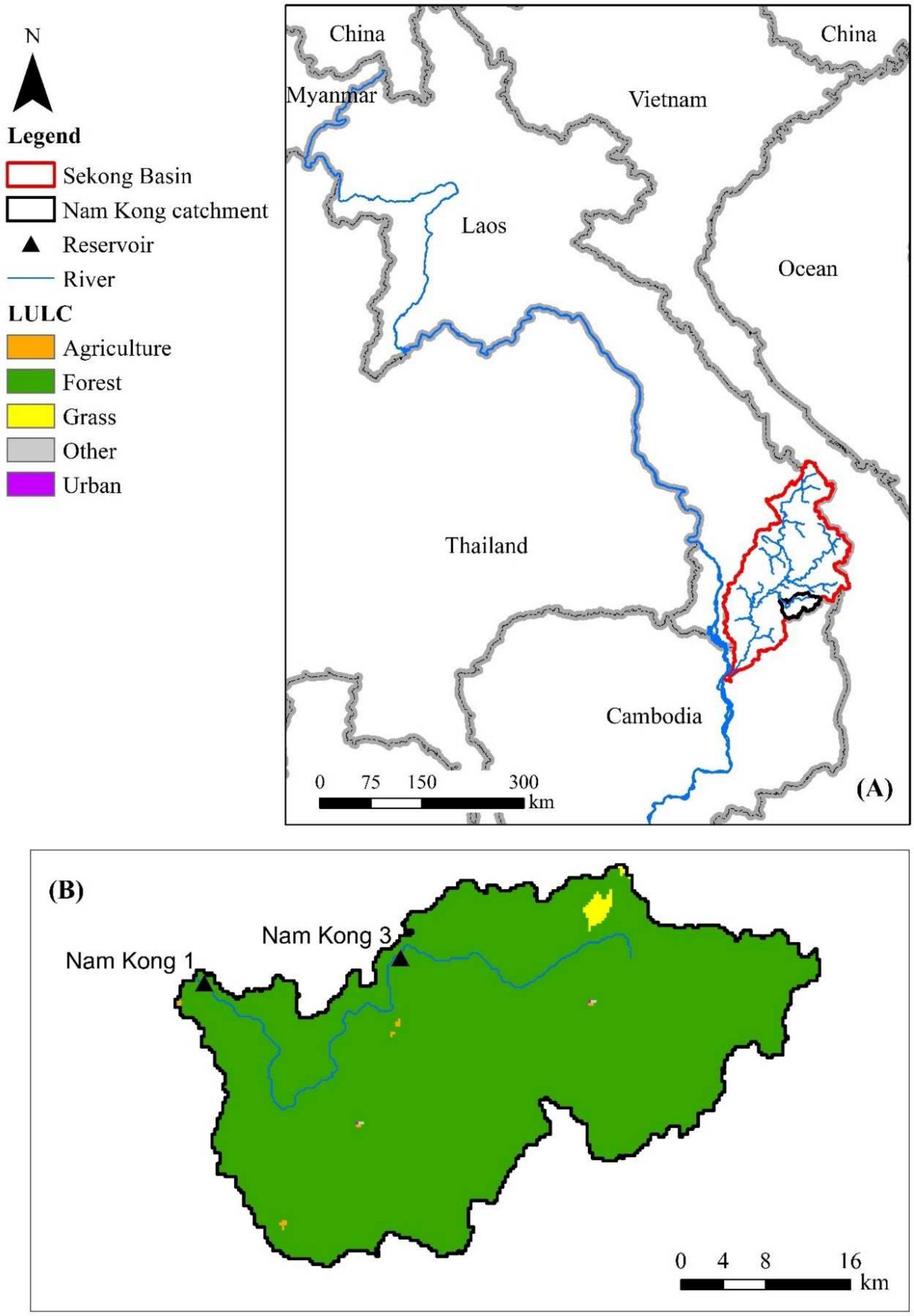

Figure 1. Nam Kong catchment location map (A), and LULC (2003) and hydropower dam sites (B)

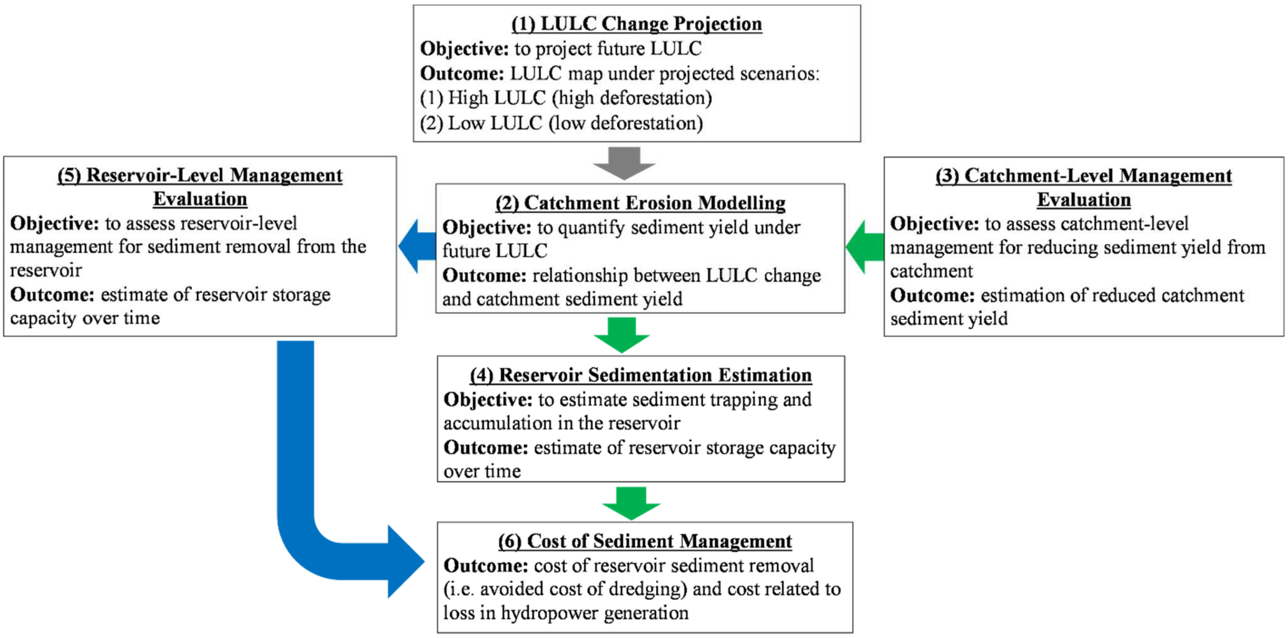

Figure 2. Conceptual framework for evaluation of the sediment management options and estimation of the cost of sediment management. Note: Green arrow refers to flow path for catchment-level management evaluation process and blue arrow refers to flow path for reservoir-level management evaluation process.

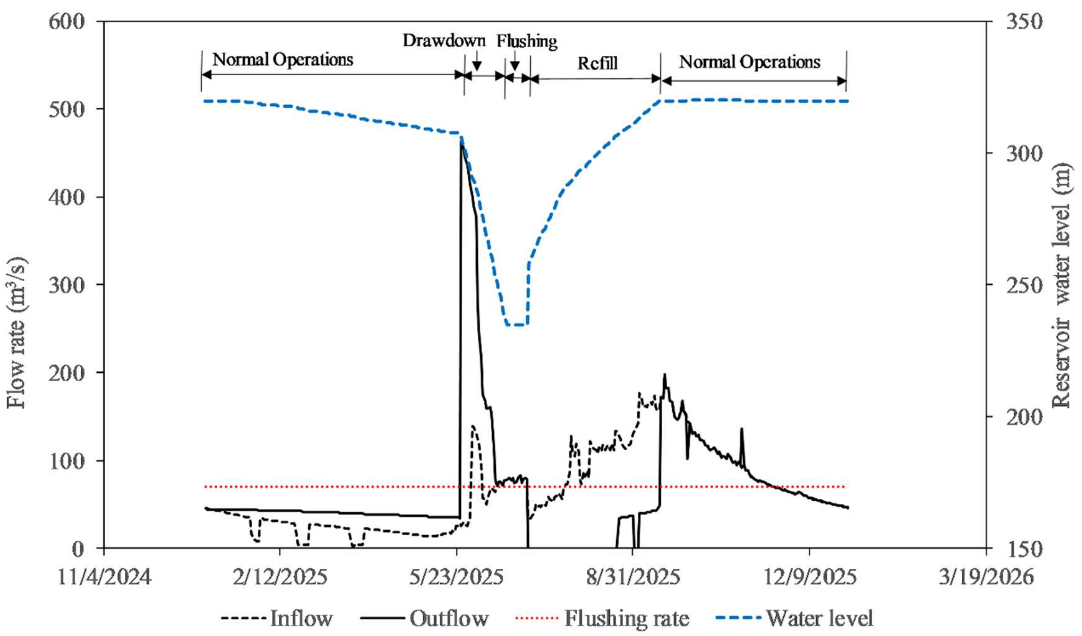

Figure 3. Flushing simulated by the *PySedSim* model for Nam Kong 1 dam under the high LULC change scenario.

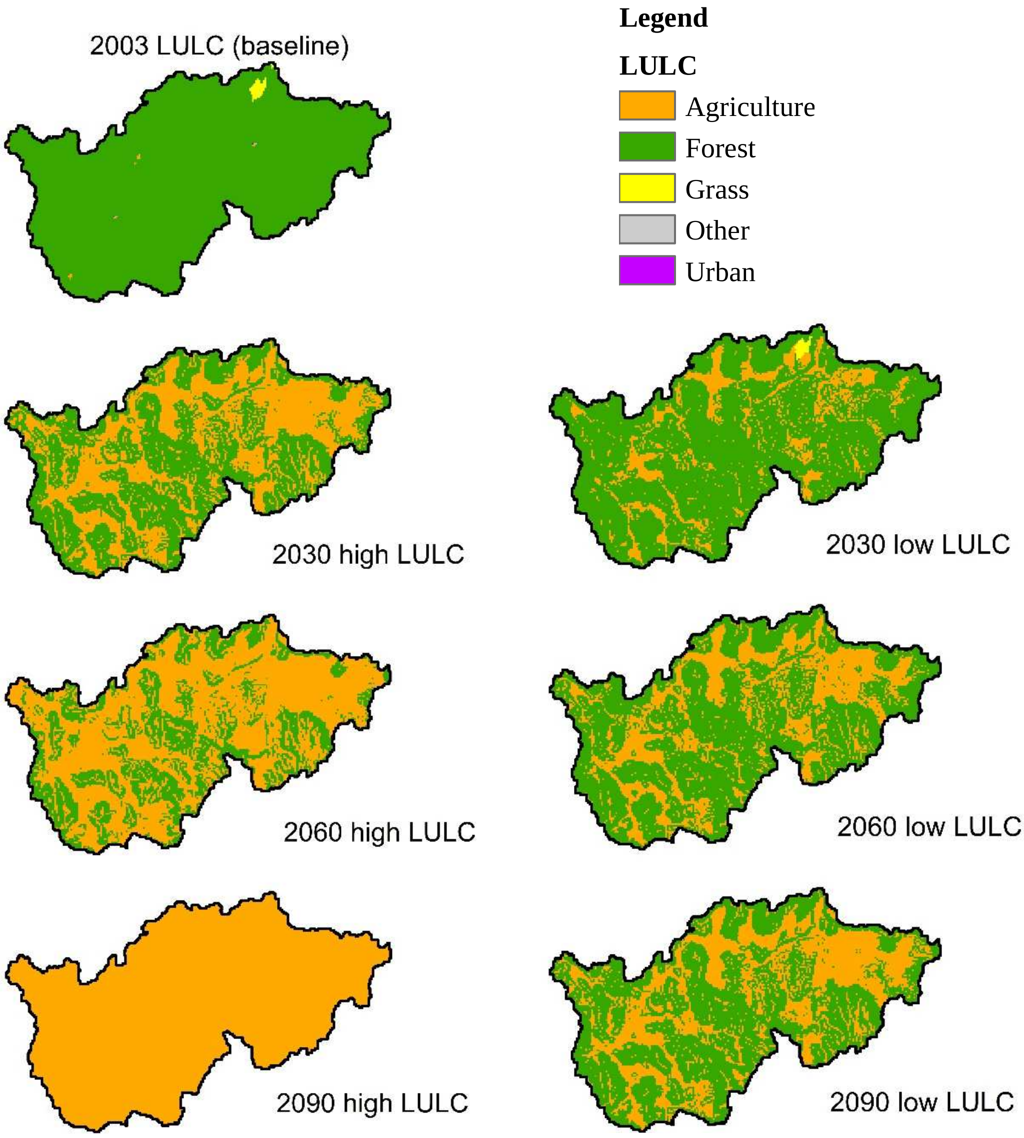

Figure 4. Baseline and projected LULC in the Nam Kong catchment.

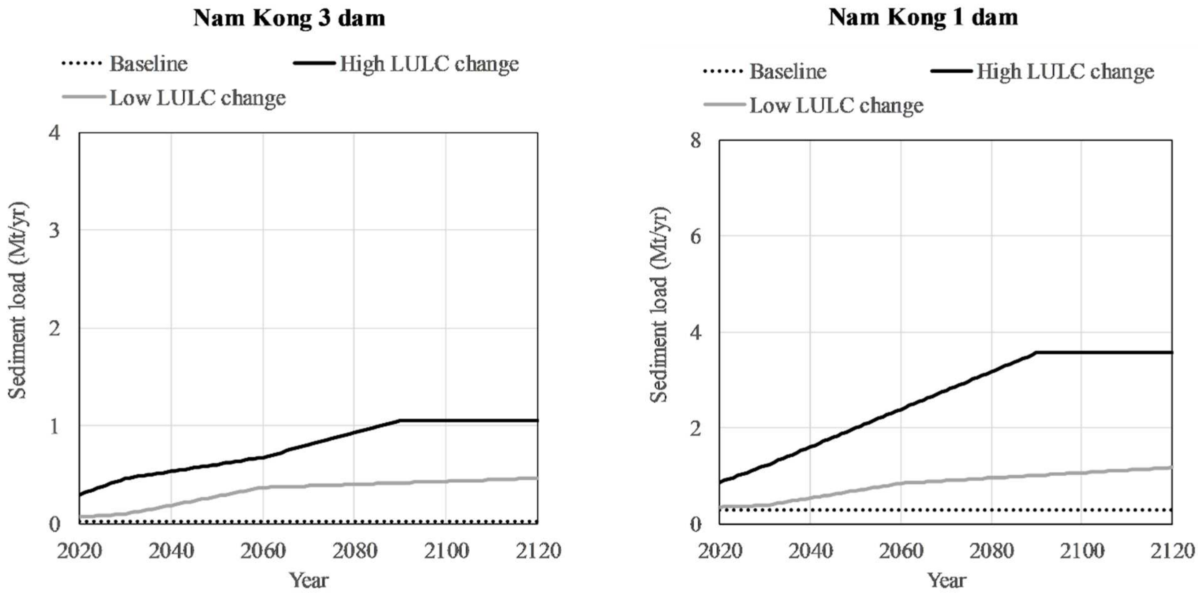

Figure 5. Mean annual sediment load over time for Nam Kong 3 dam location (left) and Nam Kong 1 dam location (right).

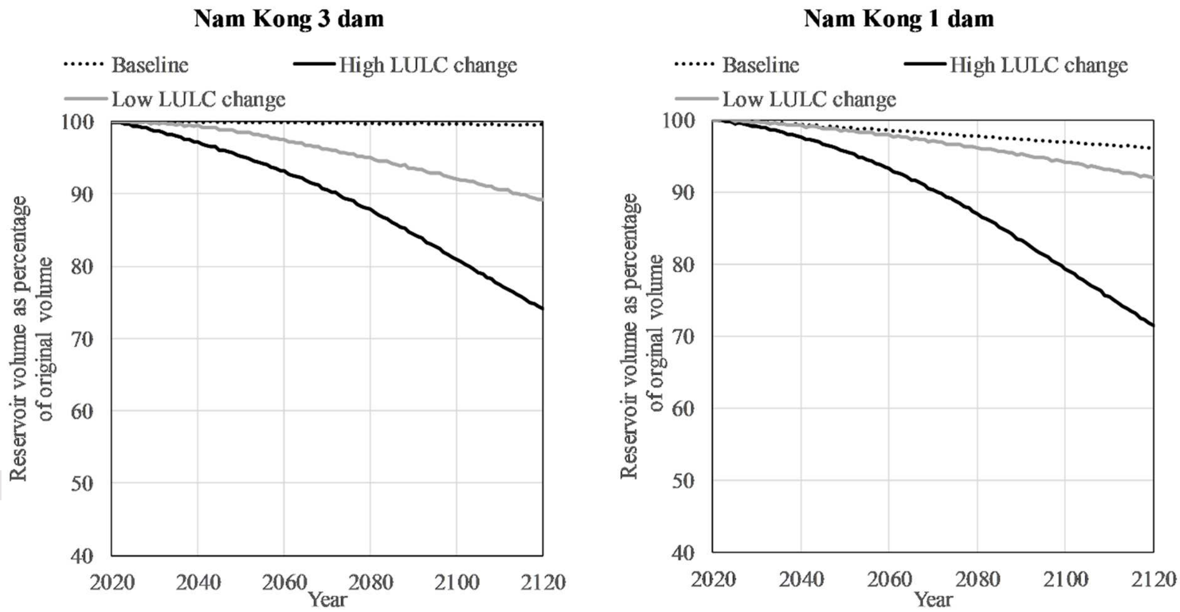

Figure 6. Reservoir total water storage capacity (volume) for Nam Kong 3 and Nam Kong 1 reservoirs over time, expressed as a percentage of initial reservoir total water storage capacity.

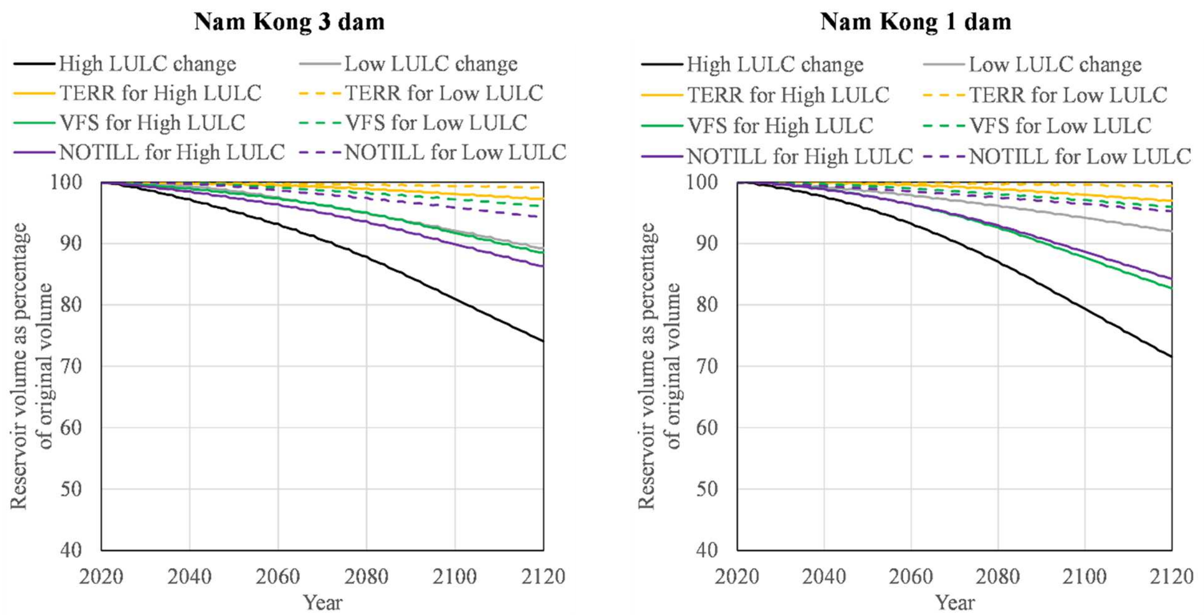

Figure 7. Reservoir total water storage capacity (i.e., volume) for Nam Kong 3 and Nam Kong 1 reservoirs over time for various catchment-level reservoir sediment management options under LULC change uncertainty. Storage capacity is expressed as a percentage of initial reservoir total water storage capacity. TERR = Terracing, VFS = Vegetative Filter Strips and NOTILL = No Tillage.

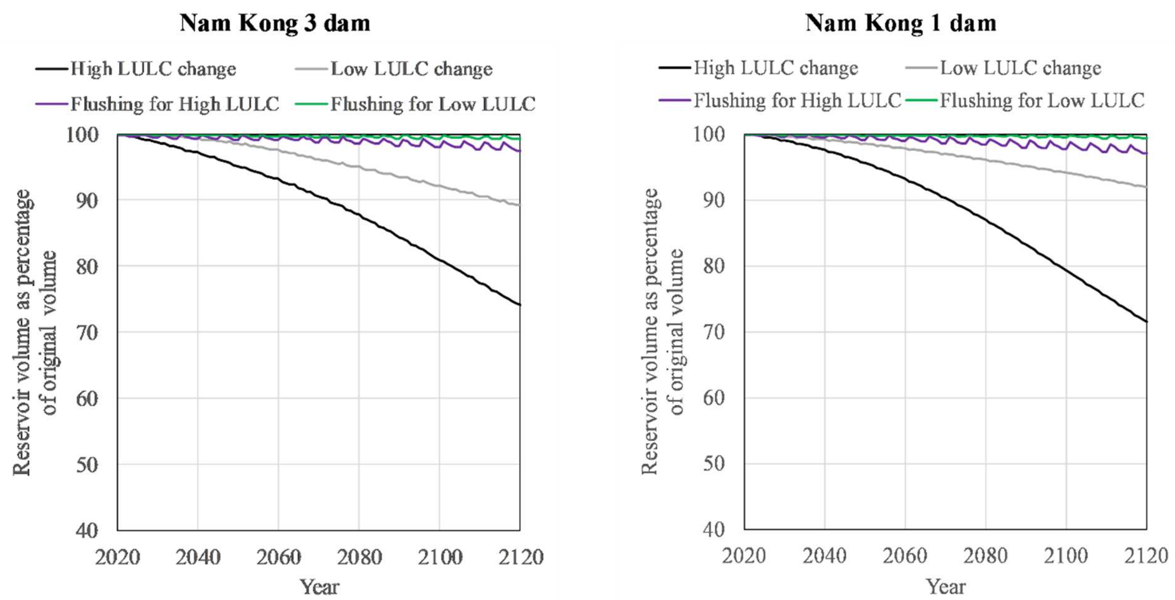

Figure 8. Reservoir volume for Nam Kong 3 and Nam Kong 1 reservoirs over time for flushing options under LULC change uncertainty.

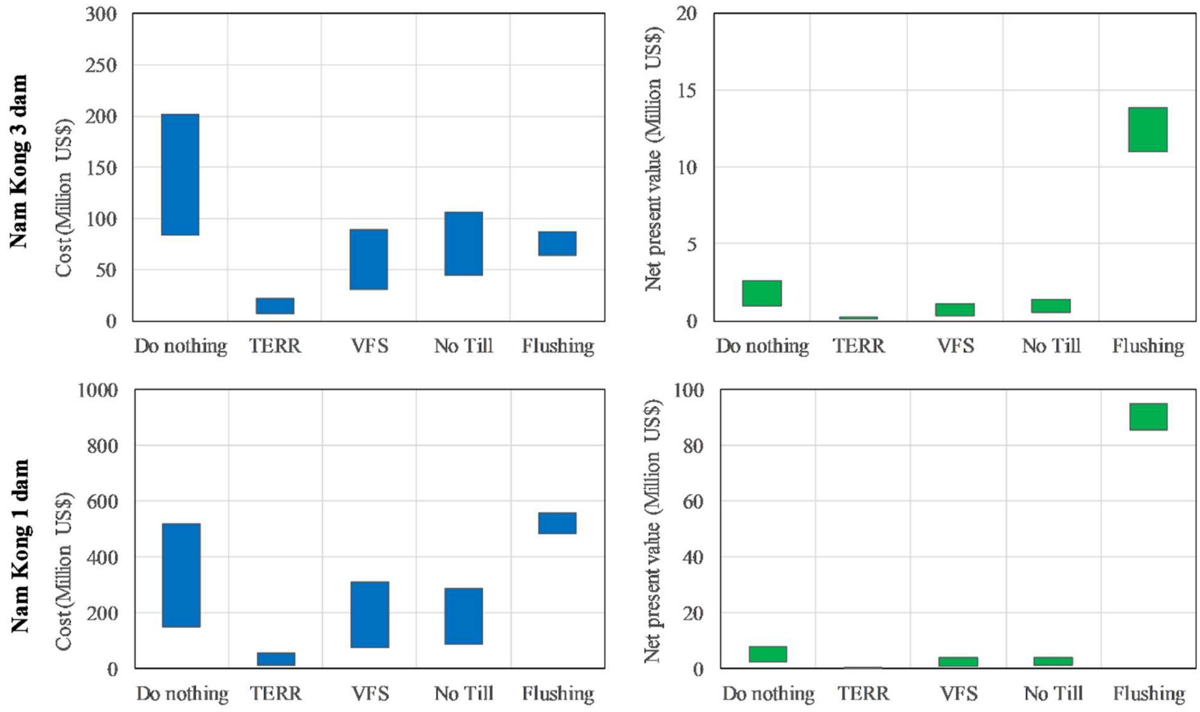

Figure 9. Costs and net present value of no sediment management and sediment management options over 100 years of reservoir operation. TERR = Terracing, VFS = Vegetative Filter Strips and No Till = No Tillage. Note: Cost presented in this figure refers to cost of reservoir sediment removal plus total cost of loss in hydropower production, and net present value is the sum of net present value of cost of reservoir sediment removal and net present value of cost of loss in hydropower production. There is a range for each bar which is due to the LULC change scenario differences.

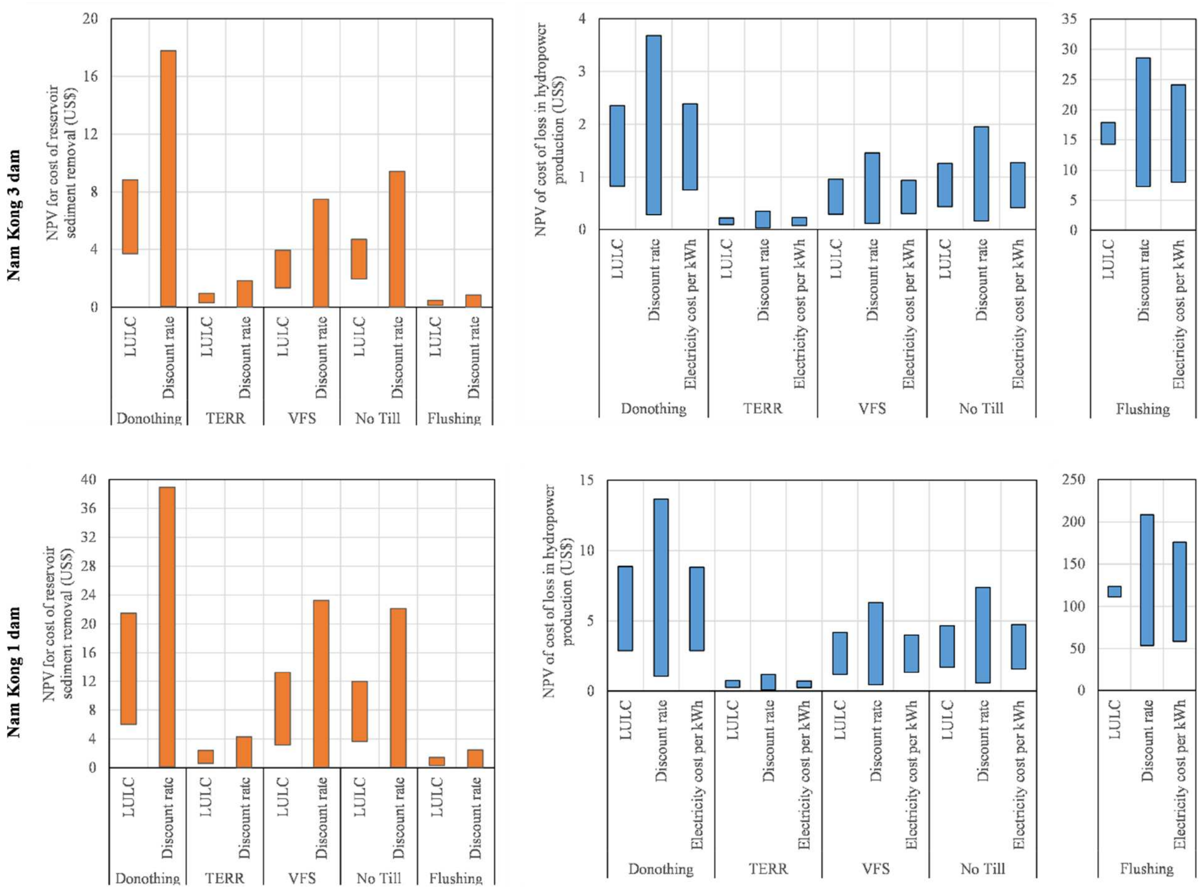

Figure 10. Plots of range of net present value (NPV) for cost of sediment management under three sources of uncertainty namely, land use land cover (LULC) change, discount rate and electricity price.