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Reservoir sedimentation management with upstream sediment remanipulated

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ABSTRACT: Despite studies showing that dams have significant effects on the sediment dynamics and evolution of a river upstream of a dam, the knowledge on relationships between river topography and sediment transport in the dam's backwater zone has been poorly applied in reservoir sedimentation management. Therefore, this study evaluated the benefits that topographic control might have on reservoir sedimentation. To do this, three test scenarios were applied to explore the hydraulic and sediment transport regimes in the Middle Yuba River. A two-dimensional hydrodynamic model was employed to simulate the stream hydraulic response to topographic controls. The results indicate that adding a topographic constrictions and expansion sequence can change a river's capability of entraining sediment and control the spatial distribution of sediment transport regimes by either accelerating sediment flushing near the dam or ponding the sediment farther upstream from dam. Topographic controls perform best for the low and medium flow.

1 INTRODUCTION

Damming a mountain river interrupts the continuity of sediment transport and raises the base level for the upstream reach, causing sediment to accumulate not only within the reservoir but farther upstream as well. As a result, reservoir sedimentation reduces reservoir water storage capacity and degrades flow regulation crucial for assuring reservoir functions of water supply, energy production, navigation, and flood control (ICOLD, 2012; Morris & Fan, 1998). The situation has been exacerbated for many mountain river dams by mining, logging, grazing, and urbanization because these activities dramatically increase sediment loadings to dams. Moreover, many mountain dams in the United States are nearing or have exceeded their design physical life spans for sedimentation. Managers are now facing the situation of what to do about the increasing costs and risks associated with aging dams (Ho et al., 2017).

The reservoir management strategy for sedimentation has been divided into three categories: (1) reduce sediment yield from the contributing watershed; (2) minimize sediment deposition in the reservoir; and (3) increase or recover reservoir volume (Kondolf et al., 2014). Under the volume recovery category which requires removing deposited sediment, mechanical and hydraulic excavation are two volume recovery strategies that have been widely used (Annandale et al., 2018, Schleiss et al., 2016). Hydraulic excavation has been applied mostly as a sustainable strategy of recovering reservoir storage, due to its efficiency and low cost (White, 2001). However, its complications such as outlet clogging and downstream ecological impacts stop the hydraulic excavation being used for some circumstances. Mechanical excavation is applied to where the hydraulic excavation cannot function. But the disposal of waste material and the relevant environmental impacts are always its major concerns (Wenger et al., 2017).

In this study, we developed a novel supplementary strategy to the above two excavation strategies for reservoir sedimentation management in smaller mountain reservoirs to take advantage of California’s summer dry season to drain a reservoir and re-contour deposited gravel sediment upstream of a reservoir as well as potentially add hydraulic structures. Mechanistically, we hypothesize that artificially established topographic steering of flow can induce flow convergence routing (Macwilliams et al., 2006) and backwater effects (Liro, 2017). These processes can then manipulate the spatial distribution of active sediment transport regimes to yield deposition where it can more easily be removed, rather than spread throughout a reservoir. In particular, we hypothesize that re-contouring deposited reservoir sediment to form a topographic constriction and expansion sequence will promote deposition farther upstream away from the dam during low flow and potentially stimulate high-energy sediment transport near the dam to pass sediment through sufficiently-sized open valves.

2 METHODOLOGY

2.1 *Experimental design*

Two designed scenario and one reference scenario were used to test the functioning of different artificially designed topographic constrictions and expansion relative to that of the existing baseline channel topography (Table 1).

Table 1. Exploratory modelling scenarios-Topographic control.

Scenario ID	Scenario name	Design conceptualization
S1	Original topography	S1 is the reference scenario
S2	Topographic constriction	The topographic control is a combination of two topographic constrictions (TPC1 & TPC2) built to accelerate the flow velocity and increase the backwater effect separately and a topographic expansion built as a buffer zone between constrictions. Ideally, during low flows, TPC2 accelerates flow velocity and carries more sediment to the pool below it. TPC1 increases the backwater effect to stop sediment further entering the reservoir. During high flow, TPC2 will be inundated and malfunction, TPC1 will play as an accelerator to flush more sediment through the dam (Fig. 2).
S3	Positioning of the topographic constriction	Two types of backwater stages (stage1 & stage2) were designed to estimate the position of TPC1. Stage 1 and stage 2 has the water stage 0.6 m lower and 0.3 m higher than that of the S2 separately. Stage 1 refers to the situation that TPC1 is close to the dam while stage 2 is farther upstream.

2.2 *Study reach*

Our House Dam (OHD) is a 40-m-radius double curvature concrete arch dam located on the Middle Yuba River (MYR) 19 km upstream of its confluence with the North Yuba River in the Sierra mountains. The Middle Yuba River was a major hydraulic mining area during the California Gold Rush. Large volumes of loose sediment have been washed down the channel. The dam is 21 m high with a crest length of 112 m, crest elevation of 625 m, and a drainage area of 376 km^2. This study focused on the 1-km backwater zone (Fig. 1), identified on the basis of sediment deposition and geomorphic indicators of the upstream extent of the backwater effect.

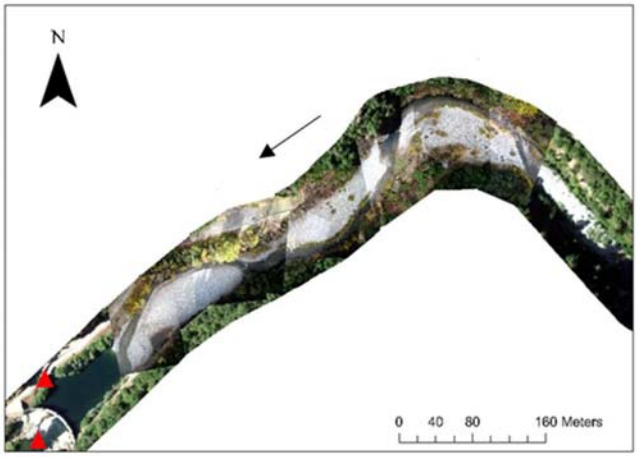

Figure 1. Aerial view of the upstream reach of the Our House Dam. Red triangles indicate the location of USGS gauge stations. Black arrow is the upstream flow.

2.3 *Data collection and topographic configuration*

2.3.1 *Hydrologic data*

Input flows (Table 2) were obtained from the USGS (https://waterdata.usgs.gov/nwis) gauge stations (Fig. 1). The upstream inflow was back-calculated based on the outflows. Reservoir stages were measured by Yuba Water Agency (YWA).

Table 2. Hydrologic data of Our House Dam.

Name	Source	Date
MYR upstream inflow	--	--
MYR downstream outflow	USGS 11408880	2016-01-01 to 2018-09-30
Lohman Ridge Tunnel	USGS 11408870	
Water stage	YWA	

2.3.2 *Topographic data*

River corridor topography and bathymetry were collected to make a digital elevation model (DEM) using a combination of airborne near-infrared Light Detection and Ranging (LiDAR) point cloud data from the OpenTopography.org website (2013 USFS Tahoe National Forest LiDAR dataset (11.61 pts/m^2)) and survey points mapped in October to November 2018 using a Leica TPS1100 robotic total station and Trimble R8 Real-Time Kinematic Global Positioning System (RTK-GPS) unit (point density: ~1pt/9m^2 for areas already covered by LiDAR or without many morphologic units changes, 1-1.5 pts/m^2 for the other areas). The unwadable reservoir was mapped by boat using a single-beam echosounder. Low-altitude kite-blimp imagery data collection was performed to enable visual examination of morphologic units and substrate facies.

2.3.3 *Topographic configuration*

Two DEMs with 1-m resolution were created from the collected topographic data. One is the original topography (Fig. 2A) while the other is the artificial topography (Fig. 2B). As for the artificially designed DEM, two topographic controls (TPC) were built. One is near the dam (TPC1). The other location is where the first natural topographic constriction occurs upstream of the near dam area (TPC2). The width of TPC1 was reduced to be 30% of the original wetted width of the highest flows (407 m^3/s) during the simulation period. The height of TPC1 is set to be the highest flow depth (407 m^3/s) to allow it to flush sediment through the dam. The width of the riverbed at TPC2 was reduced to 40% of the original riverbed. The elevation on the right bank was increased by 3 m while the left bank was slightly elevated (1 m) due to the feature of topography. Between the two topographic constrictions, a natural topographic expansion exists. Its bed elevation was reduced by 3 m to mimic the condition when the deposited sediment removed.

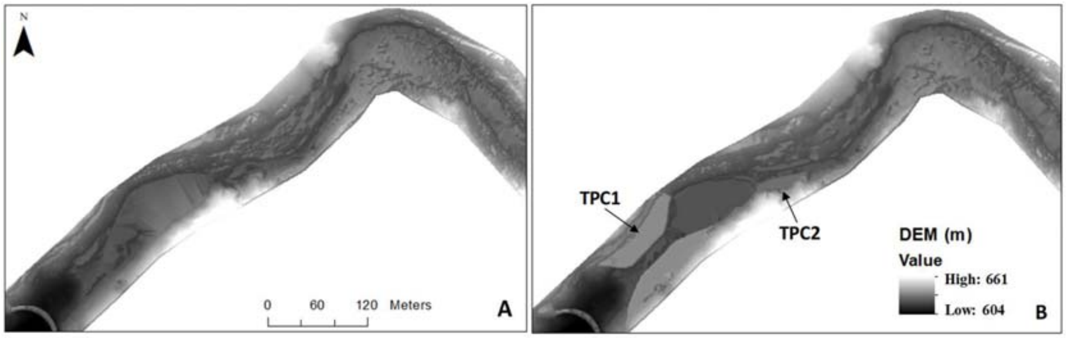

Figure 2. Digital Elevation Map (DEM) of original and topographic constriction applied study reach. (A is the original DEM. B is the study reach with topographic constriction applied.)

2.4 *Numerical Modelling*

Two-dimensional depth-averaged (2D) hydrodynamic model was applied to evaluate both the lateral and longitudinal positioning of sediment deposition and erosion under different scenarios. Even though the reservoir was included in the simulated zone, the reservoir itself is small and the major interest of this study is upstream of the reservoir. Besides, the proposed topographic controls was designed for the low and medium flow since it is impractical to build topographic controls for high flow whose flow depth is so large that a three-dimensional (3D) model is needed. All these made the 2D model a reasonable and economic choice over 3D model which would add significant uncertainty and computational power. Morphodynamic models are not used in this study because the physical processes of sediment transport are extremely complex and thus far numerical modelling to directly simulate sediment transport is still under development. Besides, model-predicted sediment transport rates are still markedly different from measured ones (Yager et al., 2019), questioning the viability of morphodynamic modelling for management use. In addition, the scenarios studied here are exploratory, which makes it difficult to validate the results given the remote setting and flood flows. Therefore, A 2D hydrodynamic model is best suited to the OHD study of reservoir sediment management using artificial constrictions and expansions in a narrow canyon.

Two-dimensional Unsteady Flow (TUFLOW) with the built-in powerful solver, Heavily Parallelised Compute (HPC), was used to simulate the lateral and longitudinal hydraulic field (Huxley and Syme, 2016). TUFLOW HPC is an explicit solver for the full 2D Shallow Water Equations, including a sub-grid scale eddy viscosity model. Discretizing the model into explicit finite volumes makes the scheme is both volume and momentum conserving. The scheme is 2nd order in space and 4th order in time. The adaptive time-stepping makes the model unconditionally stable (WBM, 2018). Eighteen flows spanning from 1 m^3/s to 407 m^3/s were selected to represent all the types of flows that happened to the study reach annually. Among the 18 flows, four (3, 9, 17, and 83 m^3/s) were selected as representatives for S3 to evaluate the position of TPC1. Two types of backwater stages were selected based on the maximum, mean and minimum reservoir level.

2.5 *Test metric*

Four reference values of the non-dimensional shear stress were used to differentiate the intensity and size selectivity of bedload transport (Lisle et al., 2000), patterns of erosion and deposition (Sawyer et al., 2010). To do so, bed shear stress output was used to calculate the non-dimensional shear stress with Equations 1 and 2 as follows:

$$\tau_b = \rho g V^2 n^2 \Big/ h^{1/3} \tag{1}$$

$$\tau^* = \tau_b \Big/ (\rho_s - \rho_w) g d \tag{2}$$

where ρ_w is water density, ρ_s is bed particle bulk density, d is the representative grain size (d: 8 mm). The local Shields stress (τ^*) values were categorized based on transport regimes defined by (Lisle et al., 2000) where values of $\tau^* < 0.01$ correspond to negligible transport, $0.01 < \tau^* < 0.03$ correspond to intermittent entrainment, $0.03 < \tau^* < 0.06$ corresponds to partial transport (Wilcock et al., 1996), $0.06 < \tau^* < 0.15$ corresponds to full transport, and $\tau^* > 0.15$ corresponds to channel alteration. The areal percentage of each sediment transport regime was used as a test metric to evaluate the sediment transport capacity of the river. There are higher thresholds at the transition from bedload transport to a regime of systemic channel change and for the associated with the onset of the suspended-load regime, but those are beyond the scope of what is commonly modeled. This approach evaluates sediment transport capacity, so it is independent of sediment supply. It is reporting the potential for what could happen to sediment throughout the river system.

3 RESULTS

Across all flow simulated, average areal percentage of all the sediment transport regimes in S1 was similar to those of S2. As for each flow, the study reach responded differently to the topographic controls in different flow ranges (Fig. 3). When the upstream flow was smaller than 9 m^3/s, the areal percentage of negligible transportation started to decrease while that of intermittent transportation increased and reached the peak of change (60%). As the upstream flow kept increasing, changes in partial and full transportation dominated. The variation of the areal percentage of partial transportation reached its peak of change (60%). As the upstream flow went up to 57 m^3/s, change in the areal percentage of channel alteration (20%) dominated the whole processes as the consequence of the reduction of the other four sediment transport regimes.

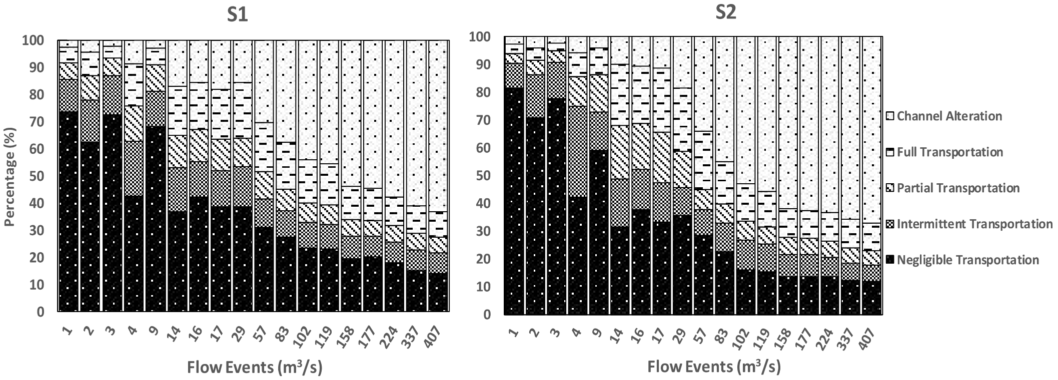

Figure 3. Areal percentage of sediment transport regimes of each flow for S1 and S2.

Spatially, having topographic constrictions significantly changed the spatial pattern of the sediment transport regime (Fig. 4). During low flow (< 29 m^3/s), the area around TPC2 had a higher capability of entraining sediment due to the increased areal percentage of higher levels of sediment transport regimes (partial, full and channel alteration). Meanwhile, the expanding area between TPC1 and TPC2 acted as a pool to stop sediment further entering TPC1. As the discharge increased, the river's capacity of entraining sediment in TPC1 was activated. At a flow of 83 m^3/s, TPC1 was fully activated (Figure 4D). As the discharge kept increasing, the whole channel was active with channel alteration dominated which caused the two topographic constrictions malfunction.

Within S3, the positioning of the TPC1 was explored. Among the four flows simulated, flows with stage 1 significantly activated the whole river's capability of entraining sediment (Fig. 5). Compared with S1, the areal percentage of full and partial transportation with stage 1 was increased by 41% and 110% separately. As for flows with stage 2, the areal percentage of intermittent and partial transportation increased by 18% and 9% compared with S1. Spatially, flows with stage 1 performed better in entraining sediment while flows with stage 2 performed better in ponding sediment in the area between TPC1 and TPC2. In addition, upstream reach of TPC2 was fully activated by channel alteration in stage 2.

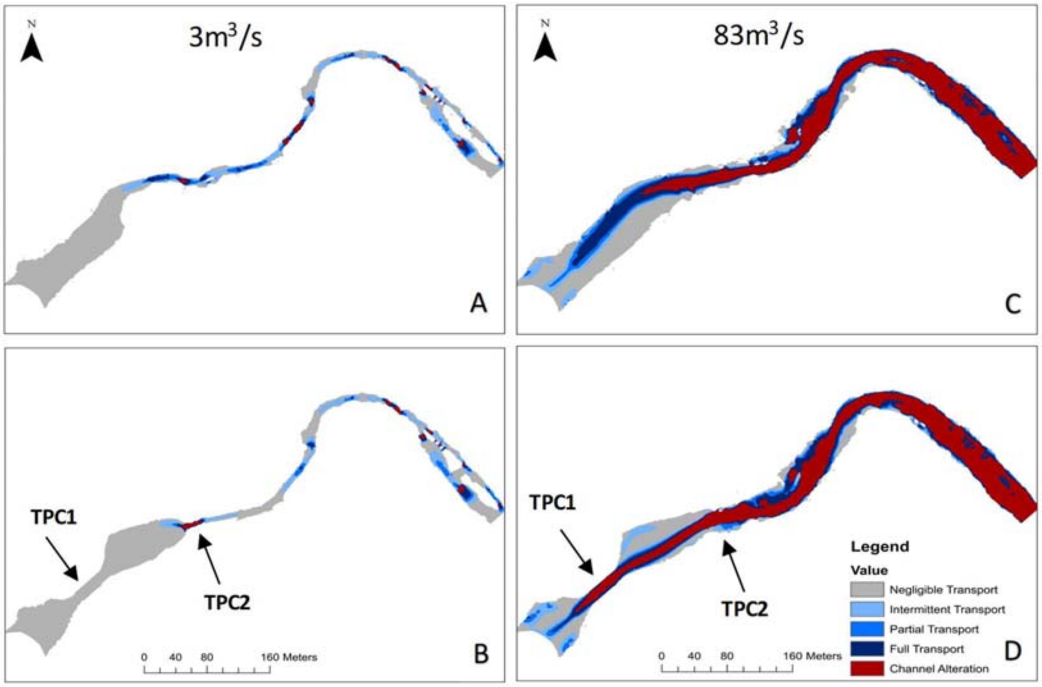

Figure 4. Sediment transport regime of S1 (A, B) and S2 (C, D).

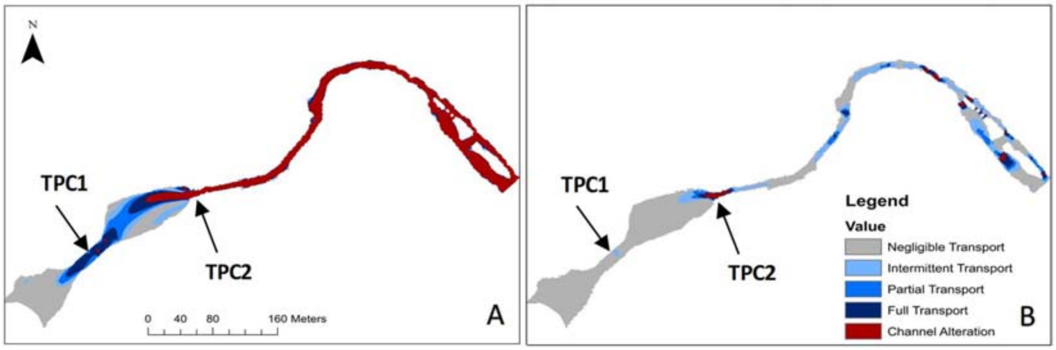

Figure 5. Sediment transport regime of scenario 3 with two stages applied (3 m^3/s, stage 1-A, stage 2-B).

4 CONCLUSION

This study experimentally tested the performance of topographic controls in assisting the sedimentation management of mid-sized gravel bedload at the upstream end of the reservoir. The mechanisms of backwater effects and flow convergence routing known to govern the formation and maintenance of riffle-pool sequences were theories imbedded into the topographic configuration. Based on the results, topographic controls were found to perform best during the low and medium flows. During these flows, the pattern and areal percentage of the partial and full transportation have been largely increased in the area of interest which implied that most of the particles of the given size on the bed surface are active while only a small amount of others of the same size are immobile. Based on the results, the location of TPC1 plays an important role in deciding the spatial distribution of the active sediment transport zone. Having TPC1 close to the dam can enhance water's capacity of transporting sediment which can cause more sediment enter the reservoir or pass through it, while far from the reservoir can enhance the backwater effect so that more sediment tends to stay in the pool between TPC1 and TPC2. However, topographic controls proposed here cannot be a standalone strategy in managing sedimentation at the upstream of dam. Instead, it is proposed as a supplementary strategy for hydraulic and mechanic dredging.

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