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Water Transfer Redistributes Sediment in Small Mountain Reservoirs

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Abstract
Reservoir sedimentation management has become an important topic for large dams in the United States due to their historical design, current age, and increased environmental regulation. Less attention has been paid to small dams (hydraulic size < 0.01) in remote mountains with urgent sedimentation problems. In drier climates, such reservoirs may be frequently drained and trans-catchment flows routed over their sediment deposits heading from one mountain tunnel to another. This study asked an unexplored scientific question focusing on this special setting: how do different amounts of water transfers interact with different reservoir stages to affect sediment erosion and its redistribution in the backwater zone? Mindful timing and magnitude adjustment of water transfer, involving water diverted across watersheds by tunnels, through a reservoir were hypothesized to strategically redistribute sediment erosion for sites with water transfer/diversion facilities in the main channel. For a study site in the north-central Sierra Mountains of California, 2D hydrodynamic modeling revealed that sediment erosion within the backwater zone increased by > 100% when water transfer was maximized, involving a flow 12 times higher than mean annual discharge. With reservoir stage drawdown, the increment of sediment erosion was further increased by > 50% compared with water-transfer-only scenarios. The natural upstream inflow with daily flow occurrence of 5–25% was the optimal water transfer to avoid disturbing sediment. These results indicated that water transfer and stage drawdown optimization is a promising strategy to promote or abate redistribution of deposited sediment through a smaller reservoir.

Keywords Reservoir sedimentation · Small dams · Water transfers · Backwater effects · Sediment management

1 Introduction

Mountain rivers are defined as rivers located in a high-relief, high-elevation physiographic region with a slope ≥ 0.002 m/m (Jarrett 1992) and a mean elevation above sea level ≥ 1000 m (Viviroli et al. 2003). Many dams have been built in these regions due to

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the rich water resources and high potential for energy (Person 2013). Nowadays, water and sediment transfers by rivers are impeded by 91,457 dams in the United States alone (NID 2021). About 93% of the dams are small dams, defined as a collection of low-head dams, run-of-the-river dams and any other dam whose height does not exceed 15 m (AASHTO 2005). Many small dams were placed in rivers to aid transfer waters for irrigation, municipal water supply and electricity generation (Csiki and Rhoads 2010). Consequently, flow regulation has changed the dynamic intertwining of hydrologic, ecologic, and geomorphic river functions, including upstream and downstream effects (Schleiss 2018; Li and Pasternack 2020).

The mechanism for reservoir sedimentation has been ascribed to the backwater effect, which is the impact of the newly formed hydraulic base level on the upstream reach, including reduced flow velocity and increased water depth (Julien 2010; Paschalidis et al. 2021). In fluvial geomorphology, backwater is defined as the water profile with flow depth higher than the average flow depth in the reservoir because the normal and critical flow depths of a natural river are difficult to calculate (Liro 2019). Due to the reduced flow velocity, more incoming coarse sediment tends to deposit at the reservoir head and then the focal point of coarse-sediment deposition migrates upstream (Hotchkiss 1990), while finer sediment deposits downstream. The primary sedimentation impact is storage loss that impairs water supply, hydropower and flood control (Molino et al. 2001; Garcia 2008). In drier climates reservoirs behind small dams may be empty or partially filled, exposing sediment fill. This results in a secondary effect associated with low-level valves and diversion tunnels that need to be kept free of sediment to maintain environmental flow regimes below dams and to provide water transfers among different reservoirs, regardless of reservoir stage.

Hydraulic and mechanical excavation are two strategies widely used to reduce deposited sediment (Annandale 2018). Hydraulic excavation involves adjusting flow operation based on the natural flow regime to maximize sediment transport, including flushing of deposited sediment with stage drawdown. Flushing is the management strategy applied to small mountain reservoirs with hydraulic size (ratio of reservoir storage capacity to mean annual discharge) less than 0.02 (Atkinson 1996). Nevertheless, its impact on the downstream ecosystem and the resizing and clogging of low-level outlets limits its implementation. Mechanical excavation removes accumulated sediments by heavy equipment or hydraulic pumps on barges with intakes. This strategy requires expensive hauling and storage of removed material, which can also raise further challenges and constraints.

While small dams are facing more critical challenges caused by reservoir sedimentation given their small total volume, relatively little is known about the status and consequences of small dams because the cost to study them can be higher than the cost of removing the dam (Fripp et al. 2020). The situation is even more complex in drier climates and where climate change will turn more small reservoirs dry for part of the year. In this setting, small dams often play an important role in trans-basin water transfers, with little water stored in a reservoir. When the reservoir is empty, diverting water through a reservoir from one mountain tunnel to another might significantly erode and redistribute deposited sediment compared to conditions when the reservoir is full. For any given discharge above baseflow, water transfers function differently than natural inflows. They are free of bed material sediment transport, they function independently from reservoir stage, they enter the channel perpendicular to it, and they are adjustable by managers. These differences merit investigation for their relevance to reservoir sediment management as a mindful management strategy could better protect key dam functions.

This study proposes water transfer optimization as a novel sediment management strategy for diversion dams. Compared to the reservoir sedimentation literature, this study is novel in four aspects: (i) a focus on small reservoirs in dry climates, (ii) analysis of water transfers on reservoir sediment redistribution, and (iii) use of spatially explicit sediment regime metrics to (iv) guide optimization of a water transfer regime. This work is valuable because it explored the possibility of extending the life of small dams through sediment redistribution, which may avoid exorbitant costs of dam removal/retrofitting, reservoir sediment excavation, and/or sediment flushing. Water transfer design involves a complex balance of many engineering, environmental, economic, and/or institutional competing factors, and now sediment management can be considered among those.

1.1 Scientific Questions and Hypotheses

For small dams having a hydraulic size below 0.01 (Kibler 2017), this study asks how different water transfer quantities interact with different reservoir stages to affect sediment erosion and redistribution in the backwater zone? This was divided into three tractable questions: (Qt1) how is sediment erosion affected by water transfer? (Qt2) how is sediment erosion affected by the interplay of water transfer and water surface elevation? (Qt3) what are the optimal hydrologic conditions for water transfer to maximize sediment erosion and redistribution? The first two questions analyze impacts of water transfer alone and joint impacts of water transfer and stage drawdown on the sediment erosion, respectively. The third question sought the optimal range of hydrologic conditions. Finally, taken together, results elucidated the hydro-sedimentary mechanism triggered by a range of operations and flow regimes.

Water transfer optimization is hypothesized to be a novel potential strategy that can increase or decrease sediment erosion in a small reservoir, and it can be used to direct transported sediment to a designated area, such as to an ideal excavation area or away from outflow valves. Stage drawdown is hypothesized to aid efficient water transfer, because for a given discharge and width, a lower stage yields a higher bed shear stress. Under natural flows, upstream inflow and a reservoir's water surface elevation (WSE) are correlated, so the joint effect on sediment erosion of adding a water transfer and imposing a stage drawdown is hypothesized to be limited to an optimal range of hydrologic conditions for which an ideal management strategy was conjectured to exist. Additionally, backwater effects are hypothesized to be a critical underlying governing mechanism of reservoir sediment dynamism. It is hypothesized that eroded areas will increase and shift downstream if the length of the backwater zone shrinks.

2 Material and Methods

2.1 Study Site

Log Cabin Dam (LCD) is a concrete arch diversion dam (32-m radius, 12-m height) in a remote mountain canyon. It is located on Oregon Creek 6.4 km upstream of the Middle Yuba River confluence in north-central California, USA. Oregon Creek's mean annual flow is 2 m^3/s. A majority of the time (69%), Oregon Creek has zero flow (summer and fall). Atmospheric rivers drive winter floods that regularly flow over the dam with a strong downstream current. Two diversion tunnels are operated near LCD. Lohman Ridge Diversion Tunnel (T1) conveys a maximum flow of 24.4 m^3/s from Middle Yuba River to Oregon Creek and can transfer as much as 12 times Oregon Creek's mean annual discharge. Camptonville Tunnel (T2) conveys up to 31 m^3/s of water from

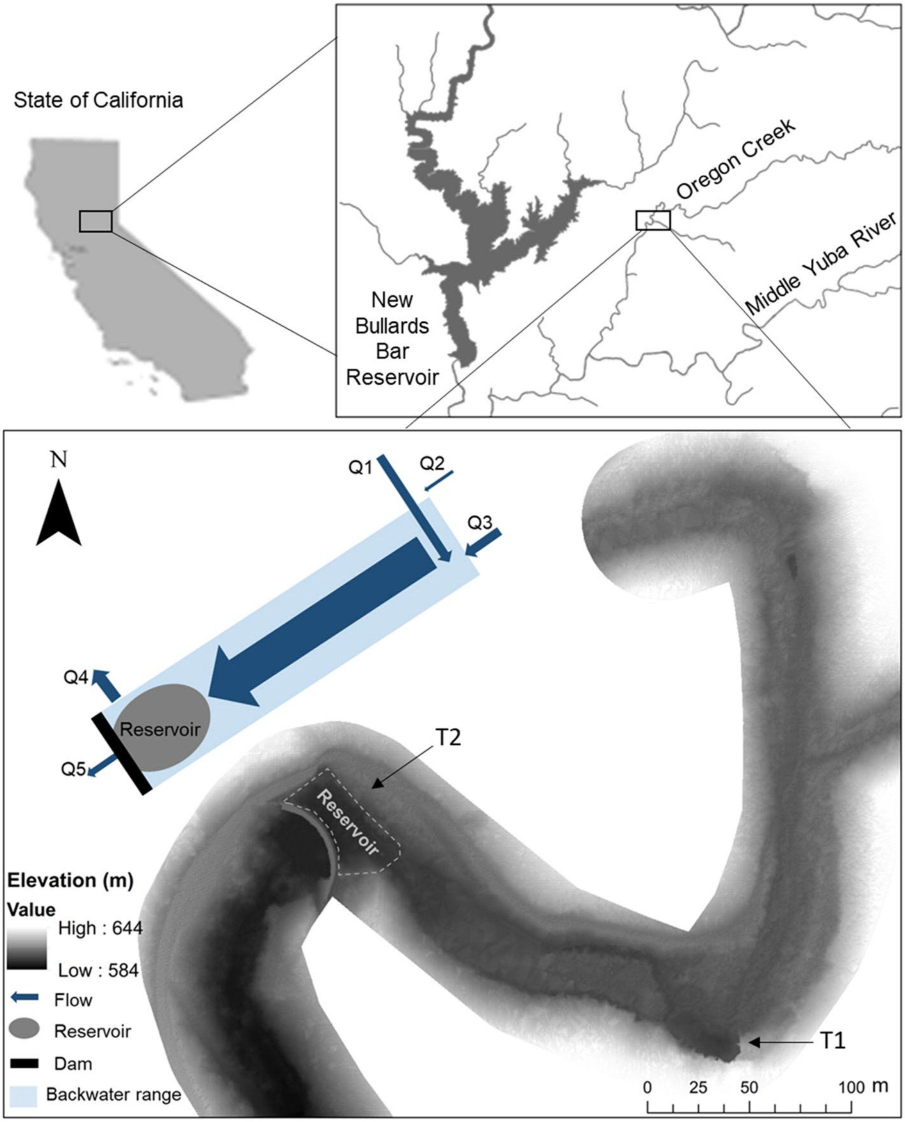

Fig. 1 Yuba River location, stream network map, study reach topography, and simplified schematic showing locations of the reservoir, backwater range, inflows (Q1, Q2, and Q3), and outflows (Q4, Q5)

Oregon Creek to New Bullards Bar Reservoir (YCWA 2012). Inflow to LCD comes from Oregon Creek, Grizzly Creek, and T1. The study reach length affected by the dam (~0.5 km) was selected based on the distribution of subaerial gravel-bar deposition (Fig. 1). From upstream to downstream, the extent of the backwater zone was evident in a channel boundary transition from bedrock to the onset of bar deposition. Therefore, upstream where bar deposition transitioned to bedrock was deemed to be free of significant backwatering.

2.2 Experimental Design

To answer scientific questions using hypothesis testing, five experimental scenarios were designed (Table 1). First, three flow events (base, medium and high flow regime), each with five representative grain sizes (1, 3, 8, 32, and 64 mm), were simulated to characterize the sediment erosion and transport regime in a regular reservoir operation (scenario S1). Then, four other scenarios (S2-S5) were run to test different conditions. For each scenario, one representative grain size was selected to answer questions based on a sensitivity analysis. Comparisons among S1, S2 and S3 answered Qt1. Comparisons among S3, S4, and S5 answered Qt2 and Qt3.

2.3 2D Hydrodynamic Modelling

The LCD study area is in a forested, confined canyon well-protected from wind fetch. Its maximum pool volume is 111,013 m^3 (hydraulic size of 0.005). Density currents and other three-dimensional, macro-scale limnological processes were negligible given the low depth and small reservoir size. Tunnel inflow and outflow structures are perpendicular to the channel on opposite sides of the river, potentially setting up cross-channel sediment transport. Given these physical conditions, a two-dimensional depth-averaged (2D) hydrodynamic model was used to evaluate the lateral and longitudinal positioning of sediment erosion under different scenarios.

2.3.1 Digital Elevation Model

A combination of airborne near-infrared Light Detection and Ranging (LiDAR) point cloud data from the OpenTopography website (2014 USFS Tahoe National Forest LiDAR dataset (8.9 pts/m^2)) and survey points mapped from October to November 2018 using a Leica TPS1100 robotic total station and Trimble R8 Real-Time Kinematic Global Positioning System unit was used to make a digital elevation model (DEM). The point density in areas already covered by LiDAR or with little morphologic variability was 1pt/9m^2. In other areas, the point density was 1–1.5 pts/m^2. The unwadable reservoir was mapped by boat using a single-beam echosounder. A one-meter resolution DEM was produced using

Table 1 Exploratory modeling scenarios

Scenario	Name of scenario	Design conceptualization
S1	Current flow operation	S1 is the reference scenario
S2	Low water transfer	Water transfer was reduced to 10% of the original tunnel flow
S3	High water transfer	Water transfer discharge was set to the maximum level (24.4 m^3/s)
S4	Water transfer and stage drawdown I	Adjusting water transfer discharge and WSE jointly WSE was reduced by one-third of the adjustable range of WSE (difference between the flood and minimum WSE)
S5	Water transfer and stage drawdown II	WSE was reduced by two-thirds of the adjustable range of WSE

published procedures and quality control/quality assurance measures (e.g., Barker et al. 2018).

2.3.2 Model Parameters

TUFLOW HPC (build 2018–03-AC-iDP-w64) was used to simulate steady-state lateral and longitudinal hydraulics. TUFLOW HPC is an explicit solver parallelized across multiple computational cores for the full 2D Shallow Water Equations, including a sub-grid scale eddy viscosity model (WBM 2018). A one-meter resolution computational grid was built for a computational domain beginning 0.5 km upstream and ending at LCD. The default TUFLOW Smagorinsky viscosity was used for turbulence closure with a coefficient value of 0.5 and a constant value of 0.005 m^2/s. Oregon Creek has little aquatic vegetation but its banks are heavily covered (> 50%) by riparian vegetation, especially willows (Fig. S1 in SI). Therefore, vegetated surface roughness was assigned to riparian land cover using a Manning's n of 0.24 based on Abu-Aly et al. (2014). As for the unvegetated surface roughness, due to the L-shape channel geometry, Oregon Creek has an abrupt variation in grain size from gravel to sand/clay (Fig. S1 in SI). Thus, a spatially distributed Manning's n was used to represent flow resistance caused by gravel (0.04) or sand/clay (0.02) substrate.

2.3.3 Steady-state Flow Simulations

Steady-state flow simulations of in-channel flows (not floods) were used to evaluate how sediment would respond to different water transfer schemes because water transfers tend to be operated over many days, holding relatively steady in all the flow regimes. Three representative flow events (base flow: 0.3 m^3/s, medium flow: 6.3 m^3/s and high flow 18 m^3/s) were selected with spearman correlation and flow frequency analysis (Tables S1–S5 in Supplement document: SI). Given the remote and extremely hazardous conditions in the river during even modest flows, most model validation was infeasible except for comparing modeled and observed water surface elevations at the dam crest, which was done. TUFLOW HPC has been extensively validated for use in mountain and valley sections of the Yuba River (e.g., Schwindt et al. 2019).

2.4 Test Metrics

2.4.1 Sediment Erosion Capability

To infer the capability of water to scour the deposited sediment, bed shear stress (Eq. (1)) was first converted into non-dimensional shear stress (Shields stress, Eq. (2) to make results comparable across all scenarios. Instead of calculating a specific sediment transport rate or a single threshold of mobilization, local Shields stress (τ^*) values were categorized into sediment 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 use of groupings significantly reduces uncertainty and simplifies the prediction target.

To further simplify erosion analysis and increase the likelihood of predictive success, partial, full and channel alteration transport regimes were grouped into a single active sediment transport regime (AST) mapped with polygons. The area covered by AST was referred to as an unstable riverbed. The normalized-areal coverage of AST (A_{st}, Eq. (3)) was used as the test metric to evaluate the scour capability of water. Meanwhile, area covered by negligible and intermittent transport regimes was assumed to be a stable riverbed.

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

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

$$A_{st} = \frac{(A_p + A_f + A_c)}{TA_{s1}} * 100\% \tag{3}$$

where ρ_w is water density, ρ_s is bed particle bulk density, g is gravity, d is the representative grain size, n is Manning's n, V is flow velocity and h is flow depth. A_p, A_f, A_c are the areal coverage of partial, full and channel alteration regimes respectively. A_{st} is the areal coverage of AST normalized by TA_{s1} (maximum total wet area in S1 (14,985 m^2)). $A_{st} = 100\%$ means that the whole channel is unstable while the minimum $A_{st} = 0\%$ means that the whole channel is stable.

2.4.2 Shortest Distance Between AST and T2

The second test metric, sediment transport distance, was defined as the shortest distance between the location of T2 and the location of the cross-section with an AST coverage $\leq 50\%$. The next step required dividing the river into cross-sectional rectangles and computing the AST coverage within each. For the length of the study site, 102 evenly spaced rectangles along the centerline of the corridor were created using River Bathymetry Toolkit (ESSA 2019). The percentage of AST coverage within each rectangle was calculated by dividing AST coverage by rectangle area.

2.4.3 Longitudinal Extent of Backwater Effect

The Pettit test allowed for automatic detection of the location of a change in river hydrodynamics along with the longitudinal river profile (Liro et al. 2020). This test previously detected homogeneous river sections with regard to active channel width, morphological channel changes and in-channel sedimentation (Liro 2016). It assumes a sequence of random values X_1, X_2, to X_T has a change point at θ if X_t for $t = 1, 2$, to θ has a common distribution function $F_1(x)$, X_t for $t = \theta + 1$ to T has a common distribution function $F_2(x)$ and $F_1(x) \neq F_2(x)$. The null hypothesis (H_0) is defined by the stationarity of the series, i.e. no change (or T=n). The H_0 is tested against the alternative hypothesis H_a defined by a change. Let t be the rank, $U_{t,T}$ be the test statistic and K_θ be the nonparametric statistic indicates the most probable change point:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sign(X_i - X_j) \tag{4}$$

$$K_\theta = \max_{1 \leq i \leq T} |U_{t,T}| \tag{5}$$

For a given scenario, the averaged flow depth of a given flow event was calculated for consecutive river cross-sections represented a data series which was analyzed with the test to identify the location of a change disrupting its homogeneity.

2.5 Data Analysis Framework

To evaluate sediment dynamism, spatially explicit bed shear stress and flow depth rasters were used to describe scour potential (independent of sediment supply), the location(s) where sediment erosion would happen relative to key infrastructure, and the longitudinal extent of backwater effects (Fig. 2). Three test metrics, the areal percentage of the unstable river bed, sediment transport distance, and longitudinal extent of backwater effects were computed and used to address the questions and hypotheses.

3 Results

3.1 Sediment Erosion in Regular Reservoir Operation

The areal percentage of AST of the five grain sizes simulated can be summarized into two groups with distinct dynamics. The threshold is eight mm (details in Supplement document: SII). When grain size was smaller than eight mm, around 50% of the study reach was occupied by unstable river bed. When grain size was larger than that, around 70% of the

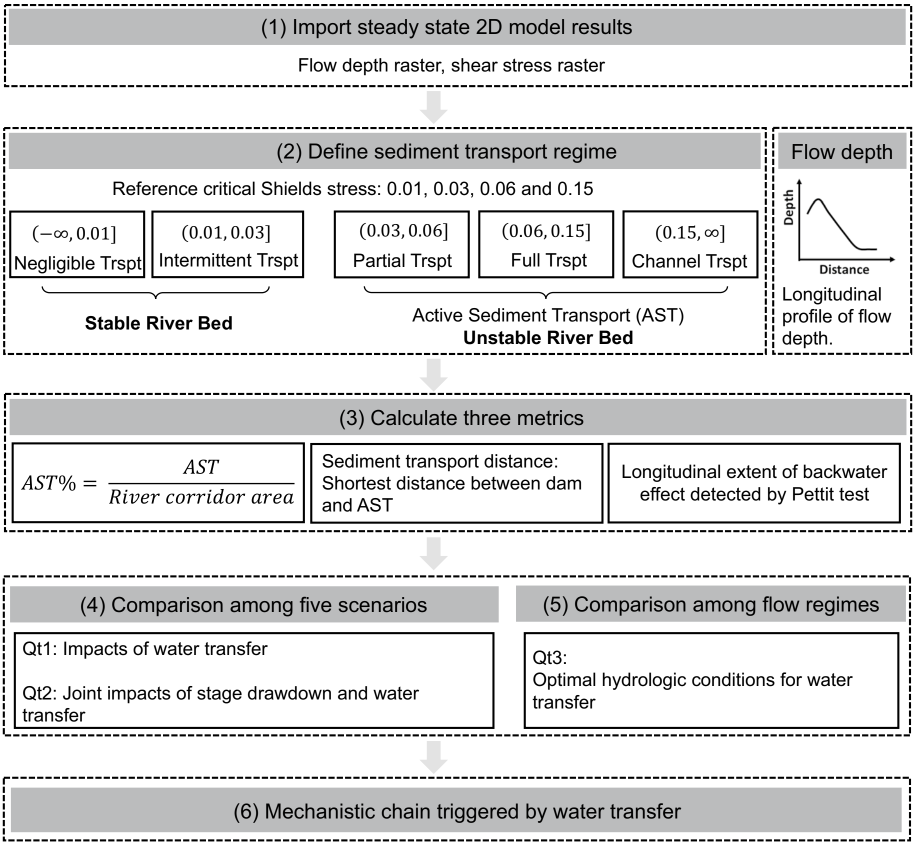

Fig. 2 Data analysis framework

river bed was stable. Spatially, the longitudinal A_{st} indicated grains smaller than eight mm passed through the backwater zone and entered the reservoir in all simulated flow events, while most of the large grains (> 8 mm) stopped near the river bend (T1), except for during the occurrence of relatively low WSE, which enabled higher velocities.

The spatial distribution of AST in the three flow regimes exhibited three modes (Fig. 3). In the base flow regime, even though water transfer was high, the whole channel was mostly covered by the non-AST transport regime due to the small upstream inflow and backwater effect. As the upstream inflow increased to the medium flow regime, AST both upstream and downstream of T1 increased significantly even though water transfer decreased

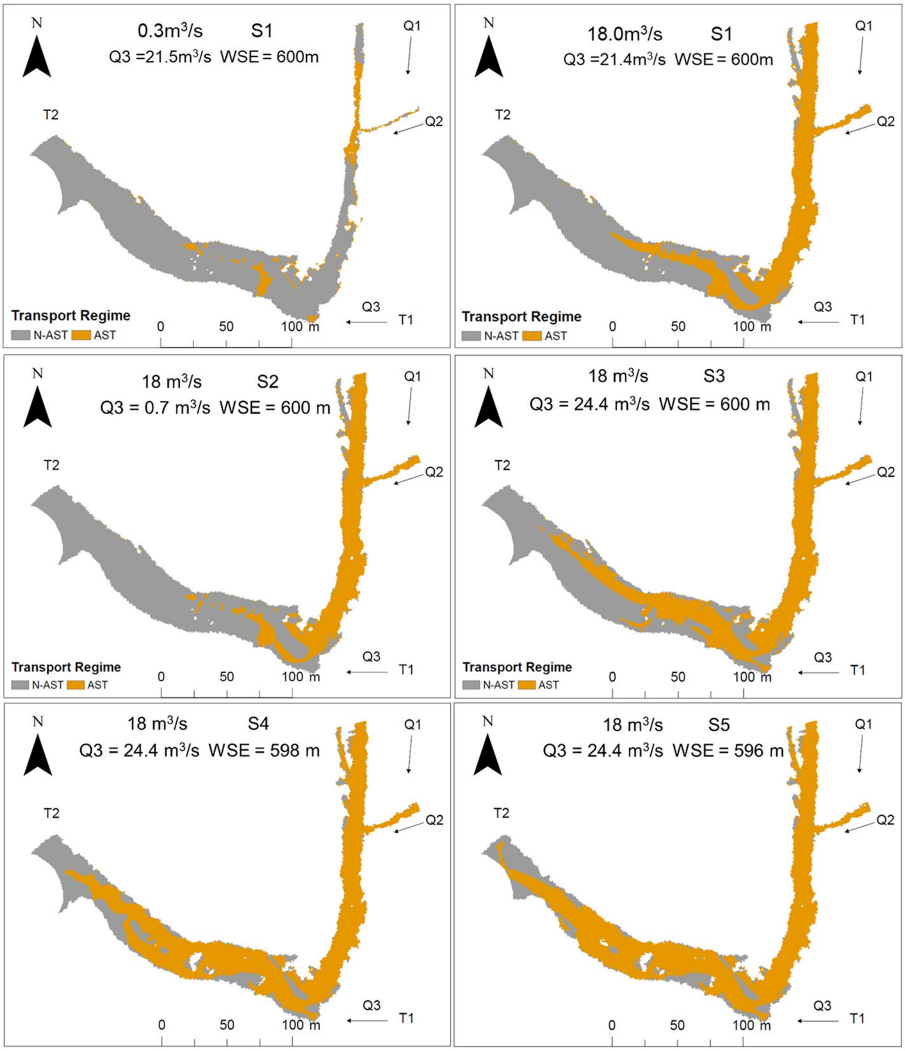

Fig. 3 Spatial distribution of the sediment transport regimes in S1-S5. Q1 is the Oregon Creek, Q2 is Grizzly Creek flow, Q3 is flow out of Lohman Ridge Tunnel (T1)

slightly. AST coverage continued to increase as the upstream flow increased. However, the incremental growth of AST was mild between medium and high flow regimes due to the significant decrease in water transfer.

3.2 Sediment Erosion Pattern in the Whole Channel

3.2.1 Water Transfer Through Tunnel T1

Adjusting tunnel operation had limited impacts on sediment erosion along the whole channel (Fig. 3). In water-transfer-only scenarios (S2 and S3), AST coverage increased along with upstream inflow. The highest A_{st} in both S2 and S3 occurred in high flow regime (S2: 23%; S3: 27%) and the lowest A_{st} was in the base flow regime (S2 and S3: 3%). In addition, the variation of A_{st} caused by water transfer was negatively related to upstream inflow. For example, compared with A_{st} in S1, reducing water transfer discharge by 10% of the original discharge caused negligible impacts on A_{st} in S2. The A_{st} was increased by less than 8% in S2 across all three flow events. Compare S3 with S2, turning on the tunnel water to its maximum level increased A_{st} by 14%, 24% and 18% in the three flow regimes respectively.

3.2.2 Water Transfer with Stage Drawdown

Different from water transfer, lowering WSE was found to yield high velocities that erode more deposited sediment across the whole channel and further increase A_{st} from water transfer scenarios (Fig. 3). A_{st} in both S4 and S5 ranked the top two among all scenarios. In S4, 17, 32 and 42% of the study reach was covered by AST in base, medium and high flow regimes respectively. In S5, 21, 36 and 46% of the study reach was covered by AST. Compared with S3 which has the maximum water transfer discharge, stage drawdown increased AST coverage by 419, 63 and 55% of A_{st} in S3 from base to high flow regimes. Continue to reduce WSE increased A_{st} by 29, 12 and 9% of A_{st} in S5 compared with that in S4.

3.3 Sediment Erosion Pattern within Backwater Zone

3.3.1 Water Transfer Through Tunnel T1

Adjusting water transfer through tunnel operations had a much stronger impact on sediment erosion in the backwater zone (downstream of T1) than in the whole channel modeled. In S2, AST coverage was reduced below 12% of the downstream area and ranked the lowest among all scenarios. As for the relative variance of A_{st} caused by water transfer, compared with S1, lowering water transfer discharge by 10% of its original condition reduced downstream A_{st} by 81, 70 and 31% in base, medium and high flow regimes respectively. Meanwhile, increasing water transfer discharge from a low point (S2) to the maximum tunnel capacity (S3) increased A_{st} by 840, 483 and 169% in base, medium and high flow regimes respectively.

As for the shortest distance between AST cross section and T2, adjusting water transfer discharge can change this distance. Specifically, increasing water transfer discharge reduced the shortest distance while decreasing water transfer discharge increased the distance. From the base to high flow regime, the shortest distance was 75 (343 m), 49 (224 m) and 32% (146 m) in S2 while 45 (206 m), 20 (91 m) and 13% (59 m) of the study reach in S3. Compared with S1, reducing water transfer discharge (S2) increased the shortest distance by 13% (58 m) of the length of study reach on average. Compare S3 with S2, increasing water transfer discharge from the low point to the maximum level decreased the shortest distance by 30, 29 and 19% of the study reach.

3.3.2 Water Transfer with Stage Drawdown

Compared with water transfer adjustment, reducing WSE significantly increased the areal coverage of unstable river bed. A_{st} in S4 and S5 ranked the top two among the five scenarios. The lowest and highest A_{st} was 31% and 39% in S4, and 37% and 46% in S5 respectively. Compared with that in S1, A_{st} was increased by 670% in base flow regime and 185% in high flow regime respectively in S4. Compared with S3, reducing WSE increased A_{st} by 343%, 80% and 53% from base to high flow regime respectively in S4. Compare S5 with S4, further lowering WSE one-third of the adjustable range increased A_{st} by 210%, 130% and 8% from the base to high flow regimes.

The joint adjustment also had a strong impact on the shortest distance compared to water transfer alone. For example, even in the base flow regime, reducing WSE reduced the shortest distance from 206 m (45% of the study reach) (S3) to 40 m (9% of the study reach) (S4). In the other two flow regimes, AST occurred in the vicinity of T2 in S4 (31 m, 7% of the study reach). Compared with S3, stage drawdown made the shortest distance in S4 160 m, 80 m and 48 m (35, 17 and 10% of study reach) shorter from base to a high flow regime, respectively. Further reducing WSE in S5 reduced the distance to zero in all flow regimes. Compared with S4, the shortest distance was shortened by 40 m, 12 m and 12 m (9, 7 and 7% of study reach).

3.4 Longitudinal Extent of Backwater Effect

In S1, S2 and S3, the extent of a backwater effect stopped 218 m upstream of T1 near where T2 locates in all three flow regimes (Fig. 4). These findings indicate that adjusting tunnel operation will not change the extent of the backwater effect. Specifically, even increasing water transfer discharge to its maximum level will not extend it. As for S4 and S5, the break point of a backwater effect also occurred in the vicinity of T1 in base and medium flow regimes. However, in the high flow regime of S4 and S5, the break point occurred farther upstream (S4: 355 m; S5: 373 m) of T1. This result was counterintuitive because the longitudinal extent of a backwater effect was expected to shrink due to the reduced WSE in both S4 and S5. One potential reason might be the backwater effect was too weak to be correctly identified due to the reduced downstream WSE and increased upstream WSE according to the increased upstream inflow (S4: 103 m; S5:87 m). Therefore, the break point was manually located where the variation of flow depth became relatively flat.

4 Discussion

This study is the first to investigate how water resource managers can jointly manipulate water transfers and reservoir stages to manage sediment behind small dams in a dry climate. Transfer tunnels operated during in-channel flows have negligible impact upstream of their outlet, because mountain channels are typically confined and already highly erosive

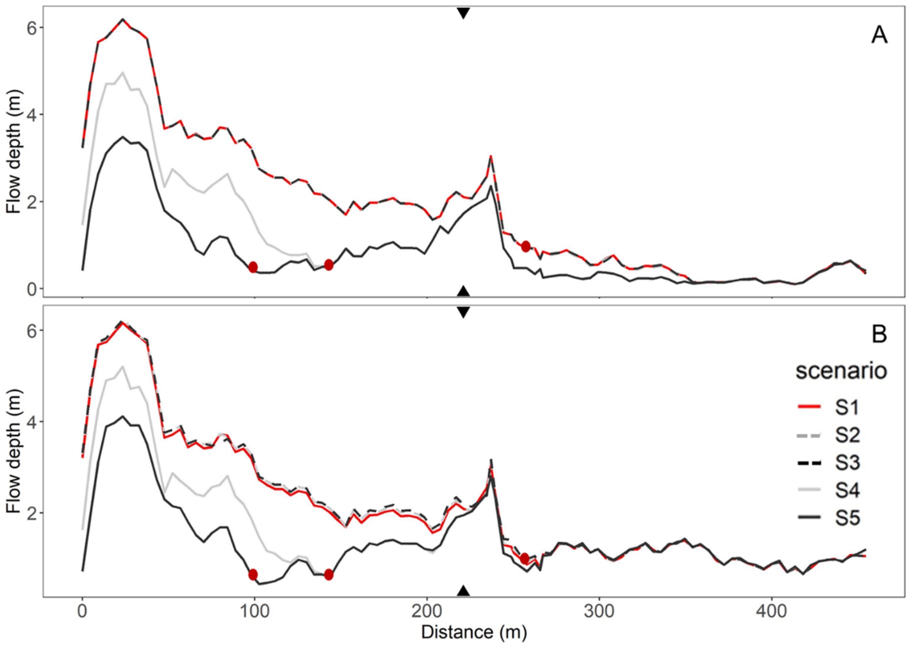

Fig. 4 Longitudinal profile of flow depth and bed elevation. Distance = 0 m indicates the location of T2. Distance = 457 m is upstream. The black triangle is the location of T1. Red circles are change points detected by Pettit test. A shows the base flow regime (0.3 m^3/s). B shows the high flow regime (18 m^3/s)

during in-channel flows, even with a backwater effect. Therefore, discussion focuses downstream of the tunnel outlet.

4.1 Question 1: Impacts of Water Transfer

Adjusting water transfer discharge had a significant impact on sediment erosion within the backwater zone. The coverage of unstable river bed is positively related to the water transfer discharge. Turning water transfer to its maximum capacity can increase the unstable river area by over 100%, while shutting down it reduced the unstable river bed to the least area. The range of variance of the unstable areal coverage was about 7% to 20% of the maximum wet area in S1. Besides mobilizing the deposited sediment, increasing water transfer discharge can erode sediment in the vicinity of a vital low-level dam outlet while turning off water transfer moves the active sediment erosion zone about 100 m (22% of the study reach) away from the low-level outlet. The range of variance in the distance was 20% to 30% of the study reach.

4.2 Question 2: Impacts of Water Transfer with Stage Drawdown

This study corroborated that stage drawdown was an important hydrologic factor affecting the sediment erosion effects of water transfers in a small reservoir in a dry climate. Compared to sediment erosion in the high water transfer scenario (S3), reducing WSE by one-third of the adjustable flow depth (2 m) increased the unstable riverbed area by at least

53% in S4. Compared with S4, further lowering WSE by another one-third of the adjustable flow depth (4 m) increased the unstable riverbed area in S5 by over 60%. Even though unstable riverbed areas in S5 ranked the highest, results did not necessarily mean reducing WSE to the lowest point can always increase sediment erosion efficiently. Comparing the two-stage drawdown scenarios (S4 vs S5), continuing to lower WSE in S5 increased the area of unstable riverbed by 21% on average. This variation (S4 vs S5) was relatively small compared with that caused (343%) by lowering WSE jointly with water transfer (S3 vs S4). These findings supported the study hypothesis that water transfer can act as a supplementary strategy to reduce the need of stage drawdown.

4.3 Question 3: Optimal Hydrologic Conditions for Water Transfer

An optimal range of hydrologic conditions identifies a water transfer strategy based on the relative variance of unstable river bed coverage, which was always found to be the highest in base flow events and lowest in high flow regimes. For example, comparing high and low water transfer scenarios, the highest variation (840%) occurred in base flow while the lowest occurred in high flow. This pattern existed in all comparisons among the five scenarios, indicating that the base flow regime is the best hydrologic condition for water transfer. However, considering the plot of ATS coverage versus discharge, the break point of unstable river bed coverage implied that the medium flow regime would be the optimal hydrologic condition instead. Specifically, the variance (slope of AST coverage) was steep between base (0.3 m^3/s) and medium (6.3 m^3/s) flow regime. Then it became relatively gentle between medium (6.3 m^3/s) and high (18 m^3/s) flow regime. Even though water transfers during the base flow regime can induce the highest variation of unstable river bed coverage, the incremental increase in the unstable area was small because the total inflow was not high enough to erode sediment. As the upstream inflow kept increasing, the threshold value of sediment erosion was reached and the unstable area increasing rate was enhanced. Thus, a medium flow regime is the optimal hydrologic condition for water transfer to mobilize sediment within the backwater zone.

4.4 Mechanistic Chain Triggered by Water Transfer

For managers globally, this study reveals the mechanistic chain triggered by water transfer and the underlying reasons governing these processes (Fig. 5). Specifically, increasing transfer discharge increases sediment erosion downstream of an inflow tunnel and transports sediment to the vicinity of dam. In addition, the extent of the backwater effect is not

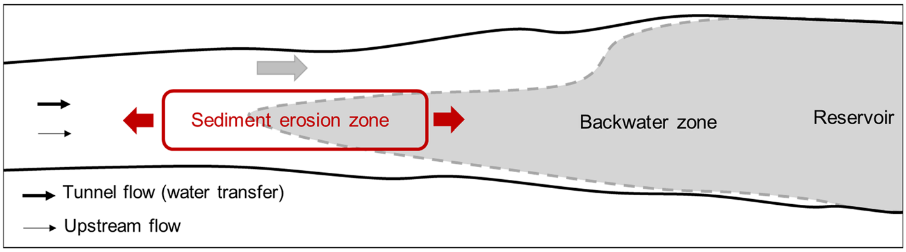

Fig. 5 Conceptualization of sediment transport and backwater extent with water transfer. Red and grey arrows indicate the extent of sediment erosion area and backwater zone, respectively

affected by a water transfer, which makes it a good supplementary strategy to assist sediment management.

WSE is a key factor impacting sediment erosion because it controls the extent of backwater. Lowering WSE can shrink the extent of backwater, and thus increase the erosion capability of water transfer and transport sediment to the dam. In addition, water transfer with stage drawdown can have similar erosion capability to sediment as reducing water surface elevation to the lowest point does. Therefore, water transfer with stage drawdown can reach the same amount of sediment erosion while reducing the pressure of giving up the stored water. As for the optimal flow regime for water transfer, the river's flood regime is not considered as a suitable hydrologic condition for water transfer since the high WSE can counteract the effect of water transfer. Operating in the medium flow regime is recommended as the optimal hydrologic condition for sediment redistribution due to the high variance and rate of change of unstable river bed coverage.

5 Conclusions

This study experimentally tested the effects of water transfers through a reservoir as a novel sedimentation management method for small reservoirs (hydraulic size <0.01) in remote mountains in a dry climate. The areal coverage and location of unstable river bed, as determined with 2D hydrodynamic modeling, were analyzed to evaluate the redistribution of deposited sediment triggered by water transfer. The extent of backwater effect was detected by the Pettit test to infer the mechanistic chain triggered by water transfer. The results found that a large water transfer can redistribute deposited sediment by increasing unstable area by over 100% compared with a small water transfer. WSE is the key factor affecting water-transfer effects. With stage drawdown, water transfer can further increase the area of sediment erosion, and the two can be tuned together to yield an optimal management outcome, depending on the goals for each reservoir. For example, water transfer through tunnels was found to be able to flush reservoir sediment to a safe designated area upstream of the dam, keeping low-level outlets free of sediment. Having the deposited sediment gathered in one area can reduce the cost of excavation or can aid sediment flushing. Instead of conducting mechanical excavation in the whole upstream, a hydraulic pump can be installed upon that area to constantly remove sediment with less labor work.

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Availability of Data and Material The authors confrm that some data and codes are available from the corresponding author on request.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

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Competing Interests Not applicable.

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