Basin-Scale Sediment Transport for Sustainable Sand Mining – A Case Study in Punatshangchhu Basin, Bhutan

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Abstract

This case study evaluated sediment dynamics in the Punatshangchhu basin in Bhutan. Sand mining operations in the basin commenced in 2007, with an average annual extraction rate of 0.3×10^6 m^3, accounting for approximately 65% of the country's sand demand. However, sand mining has been conducted without a comprehensive understanding of the basin's sediment budget. Therefore, this study examines the sediment budget at the basin scale using numerical modeling. Two numerical models were developed: the Rainfall-Runoff-Inundation (RRI) model simulated the 2017 flood event, while the Rainfall-Sediment-Runoff (RSR) model computed daily sediment yields during the monsoon season (May–September). The RSR model was simulated for two cases: Case 1 considered sediment supply from the river channel only, while Case 2 considered sediment supply from the river channel and slopes. The model results were evaluated against daily observed stream-flow data, suspended sediment load, and particle-size distribution. The model achieved NSE, PBAIS, and R^2 values of 0.9, -0.12, and 0.9, respectively, in calibration. The validation achieved similar NSE and PBAIS values, with an improved R^2 of 0.94. The total sediment yield in Case 2 was 34% higher than in Case 1. The model results showed balanced sediment inflow and outflow in the basin. However, sediment extraction at the current rate is unsustainable, with riverbed degradation at a rate of 0.26 m/year. Nevertheless, a downstream hydropower dam is expected to create an opportunity for sustainable mining.

Key Words: *Rainfall-Sediment-Runoff, Basin-scale sediment transport, sediment budget*

1. INTRODUCTION

Sand and gravel are vital materials in the construction industry (Padmalal & Maya, 2014). Villioth (2014) argues that sand has become the second most used natural resource after water, with demand escalating significantly over the last two centuries. However, continued and unregulated sediment mining activities pose a severe threat to river ecosystems. The global demand for sand reached 50 billion tonnes annually in 2019, outpacing the natural replenishment rates by geological processes, which has raised concerns about sustainability (UNEP, 2019). Extensive mining disrupts the sediment mass balance in the basin, leading to river adjustments, such as riverbed incisions that extend beyond the mining site (Hackney et al., 2020; Jose et al., 2014). Therefore, understanding basin-scale sediment transport processes is crucial for determining how sediment is generated, transported, and deposited in river channels and floodplain areas.

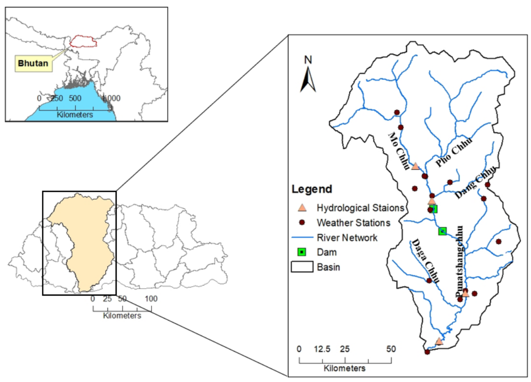

Fig. 1: *Punatshangchhu River Basin*

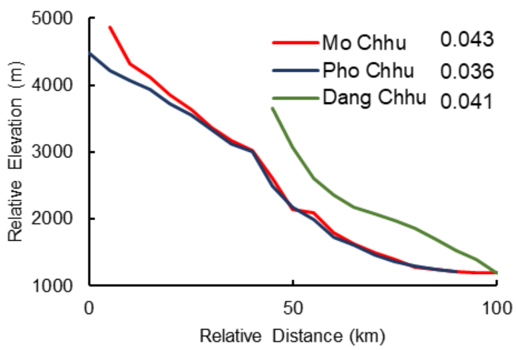

Fig. 2: *Longitudinal profiles*

The Punatshangchhu River Basin in Bhutan faces similar pressures as the global sand demand continues to rise, threatening its long-term sustainability. The Punatshangchhu basin (Fig. 1) is one of Bhutan's four primary drainage basins, originating in the Himalayan range and flowing through the western central part of Bhutan. As illustrated in Fig. 2, the basin is characterized by diverse morphology, and the longitudinal profiles of its main tributaries – Mo Chhu, Pho Chhu, and Dang Chhu exhibit steep slopes of 0.043, 0.036, and 0.041, respectively. The watershed covers 9547 km^2 and is home to 221 glacial lakes, 17 of which are classified as potentially dangerous glacial lakes (NCHM, 2019).

Fig. 3: *Sand mining activities along the Punatshangchhu River*

At Wangdirapids station, the basin recorded its highest discharge of 2650.26 m³/s on May 25, 2009, and its lowest of 51.713 m³/s on September 3, 2015 (Namgyel & Tamang, 2022). The basin also houses two hydropower dams, Punatshangchhu-I and Punatshangchhu-II, with power-generating capacities of 1,200 and 1,020 megawatts (MW), respectively. The basin is one of nine sand mining regions in Bhutan, supplying approximately 65% of the country's total sand demand annually. Fig. 3 illustrates the mining activities in the basin. Despite its significance, no study has been conducted on the sediment budget in the basin, which is crucial for ensuring sustainable sand extraction. Therefore, this study investigates the sediment budget in the basin by numerical modeling. The study's findings will provide policymakers, researchers, and relevant stakeholders with critical information for developing sustainable sediment management strategies and regulatory frameworks that promote responsible sand extraction practices.

2. METHODOLOGY

The study developed two numerical models to analyze hydrological processes and sediment transport dynamics. The RRI model (Sayama et al., 2012) was used to simulate watershed hydrological response by employing (i) diffusion wave approximation for lateral surface flow routing, (ii) Green-Ampt method for vertical infiltration of the plain area, and (iii) Darcy's equation for the subsurface lateral flow in steep terrain.

The RSR model integrated these hydrological outputs with sediment mass balance equations, enabling a quantitative assessment of erosion-deposition dynamics in the basin. This approach, developed by Egashira et al. (2000), predicts temporal and spatial changes in sediment influx, deposition patterns, and particle-size distributions in response to rainfall inputs (Fig. 4). The sensitivity of the RSR model was examined using different combinations of grain-size distributions for the river channel and slopes. The study applied the bedload formula from Egashira et al. (1997), the suspended load formula from Harada and Egashira (2020), and the hillslope sediment load formula from Qin et al. (2023).

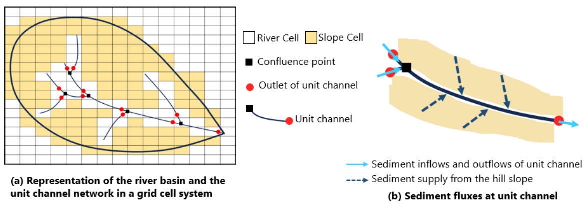

Fig. 4: *The concept of slope erosion process in the rainfall and sediment runoff model*

2.1. Governing equations for the numerical model

To quantify sediment influx in the catchment, we have applied the principles of mass conservation. The riverbed elevation change is computed by mass balance:

$$\frac{z_b}{\partial t} = \frac{1}{(1-\lambda)B(r1_{i+1})L(r1_{i+1})} + \frac{1}{(1-\lambda)}\sum_j ((D_{sj}(r1_{i+1}) - E_{sj}(r1_{i+1})) \qquad (1)$$

where:

- $\frac{z_b}{\partial t}$ = rate of riverbed elevation change [m/s],
- λ = porosity of bed sediment,
- $B(r1_{i+1})$ = width of the channel [m],
- $L(r1_{i+1})$ = length of the channel [m],
- $Q_{bj}(r1_i)$ and $Q_{bj}(r2_i)$ = bedload

sediment discharges (size class-j) from $r1i$ and $r2i$ [m^3/s],

- $Q_{bj}(r1_{i+1})$ = bedload sediment discharge (size class-j) transported to $r1_{i+1}$ [m^3/s],
- $D_{sj}(r1_{i+1})$ = Deposition rate of suspended sediment (size class j) [kg/m²]s],
- $E_{sj}(r1_{i+1})$ = erosion rate of suspended sediment (size class-j) [kg/m^2.s].

The depth-integrated suspended sediment concentration for size class-j in a unit channel is governed by:

$$\frac{\partial hc_{sj}(r1_{i+1})}{\partial t} = \frac{1}{B(r1_{i+1})L(r1_{i+1})} \begin{Bmatrix} C_{sj}(r1_i)Q(r1_i) + C_{sj}(r2_i)Q(r2_i) \\ + \sum_j Q_{psj}^{n}(r1_{i+1}) - C_{sj}(r1_i)Q(r1_i) \end{Bmatrix} - D_{sj}(r1_{i+1}) + E_{sj}(r1_{i+1}) \quad (2)$$

where:

- C_{sj} = depth-integrated suspended concentration (size class-j) into flow [kg/m^2],
- $\sum_j Q_{psj}^{n}(r1_{i+1})$ = total sediment (size class-j) inflow from hillslopes [kg/s],
- n = total lateral inflow inlets,
- Q_{psj} = discharge of inflow lateral sediments obtained from (Equation 5).
- The bedload transport rate for sediment (size class-j) is quantified by the non-dimensional formula proposed by Egashira et al. (1997).

$$q_{b*j} = \frac{4}{15}\frac{K_1K_2}{\sqrt{f_d+f_f}}\tau_{*j}^{5/2}F_{bj} \quad (3)$$

where:

- q_{b*j} = non-dimensional bedload transport rate,
- K_1, K_2 = empirical coefficients,
- F_{bj} = fraction of (size class-j) in the bed surface layer,
- f_d , f_f = Darcy-Weisbach friction factors,
- τ_{*j} = non-dimensional bed shear stress (Shields parameter) for (size class-j).

The balance between particle fall velocity and upward entrainment velocity in density-stratified flows governs the entrainment of fine sediment into suspension. Harada et al. (2020) quantified this through the entrainment velocity ratio:

$$\frac{w_e}{u} = \frac{K_e}{R_{i*}} \quad (4)$$

where:

- w_e = entrainment velocity [m/s],
- R_{i*} = Richardson number,
- u = flow velocity [m/s],
- $K_e = 0.0015$ (Egashira and Ashida, 1980).

The sediment contribution from the slope area is quantified through a conceptual sediment path (Qin et al., 2023), which is integrated into the RSR model. The sediment supply from the slope is calculated as follows:

$$Q_{psj} = q_pB_p \cdot c_{pj} \quad (5)$$

where:

- Q_{psj} = sediment discharge of (size class-j) [m^3/s],
- q_p = flow discharge of the sediment path in unit width [m^3/s],
- B_p = width of the sediment path [m],
- c_{pj} = concentration of (size class-j) in flow path [kg/m^3].

The erosion and deposition processes govern the suspended sediment dynamics:

$$E_{sj} = F_{bj}w_e\overline{c_b} \quad (6)$$

$$D_{sj} = w_{0j}c_{sj} \quad (7)$$

where:

- E_{sj} = erosion rate of (size class-j) [kg/(m^2.s)],
- D_{sj} = deposition rate of (size class-j) [kg/(m^2.s)],
- w_e = particle entrainment velocity [m/s],
- w_{0j} = particle falling velocity [m/s],
- F_{bj} = fraction of (size class-j) in the bed surface layer,
- $\overline{c_b}$ = average sediment concentration.

The sorting algorithm (Eqs. 8 – 10) dynamically adjusts particle size distributions during the bed evolution as follows:

$$\frac{\partial z_b}{\partial t} > 0, p_j = F_{bj} \quad (8)$$

$$p_j = F_{tj} \quad (\Delta z_b + \delta_t > 0) \quad (9)$$

$$\frac{\partial z_b}{\partial t} < 0 \quad \left\{ p_j = \frac{F_{tj}\delta_t - F_{dj}(\Delta z_b + \delta_t)}{-\Delta z_b} \right. (\Delta z_b + \delta_t < 0) \quad (10)$$

where:

- $\frac{\partial z_b}{\partial t}$ = rate of change of the riverbed elevation [m],
- p_j = proportion of (size class-j) in exchanged sediment,
- F_{bj} = fraction of (size class-j) in the bed surface layer,
- F_{tj} ,F_{dj} = fraction of (size class-j) in top/deeper bed layers,

- Δz_b = change in bed elevation [m],
- δ_t = thickness of top active layer [m].

3. DATA

The 15-arc-second resolution data from HydroSHEDS were used to represent the study area's topography. Meteorological and discharge data were collected from the National Centre for Hydrology and Meteorology (NCHM). The sediment concentration data were also collected from NCHM and used for evaluation and comparison with the RSR model results. Analysis of suspended load data from 1995 to 2021 indicates that 95% of the sediment in the basin is transported during the period from May to September. Land cover and land use data from the International Center for Integrated Mountain Development (ICIMOD, 2022) are used in this study. Particle size distributions of the riverbed material were collected from five different locations within the study area, shown in Fig. 5 (a). Sieve analysis was then conducted at the laboratory of the National Standards Bureau in Thimphu, Bhutan. Locations 1 and 2 exhibited a predominance of finer particles, whereas the other three displayed a uniformly graded particle size distribution, as shown in Fig. 5 (b).

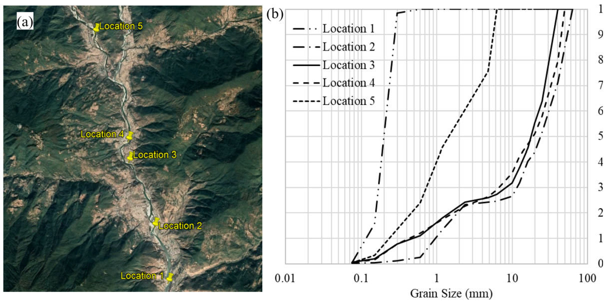

Fig. 5: *(a) Location of samples collected along the Punatshangchhu River (b) Particle-size distributions of samples*

Initially, the RRI model simulation was performed for the whole Punatshangchhu basin and calibrated and validated against the daily flow observed at Wangdirapids station. Next, the RSR model was developed for the Wangdirapids subbasin (Fig. 6). To analyze sediment transport processes, particle size distribution input files were prepared. The RSR model was then simulated under two cases: Case 1 considered sediment supply from the river channel only, while Case 2 considered sediment supply from both the river channel and slopes.

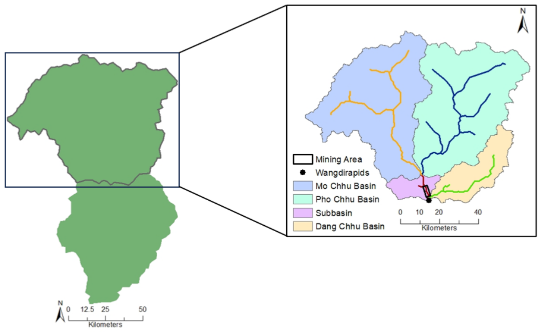

Fig. 6: *Wandirapids subbasin*

Finally, the total sediment volume transported through the outfall of the mining area and the sediment concentration at Wangdirapids station were compared.

4. RESULTS

4.1 Model calibration and validation

The hydrological model was calibrated and validated using daily stream-flow data from the Wangdirapids station for 2017 and 2019, respectively, as depicted in Fig.s 7 and 8. The simulation results showed a slight underestimation of low-flow conditions, while accurately capturing peak flow. Calibration was performed by iteratively adjusting input parameters until the simulated outputs were closely matched with the observed stream-flow data.

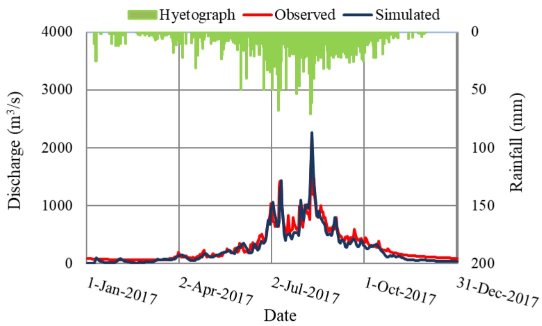

Fig. 7: *Model calibration for 2017 at Wangdirapids station*

Table 1: *Model performance indicators for calibration and validation*

Gauge Station	Calibration			Validation		
	NSE	PBAIS	R^2	NSE	PBAIS	R^2
Wangdirapids	0.9	-12	0.92	0.9	-12	0.94

Validation was then conducted using a calibrated model (Moriasi et al., 1983). The model's performance was evaluated against standard criteria (Moriasi et al., 2015): Nash-Sutcliffe Efficiency (NSE), percentage bias (PBIAS), and Root Mean Square Error (RMSE).

The model achieved acceptable values of NSE, PBIAS, and R^2 for calibration and validation (Table 1).

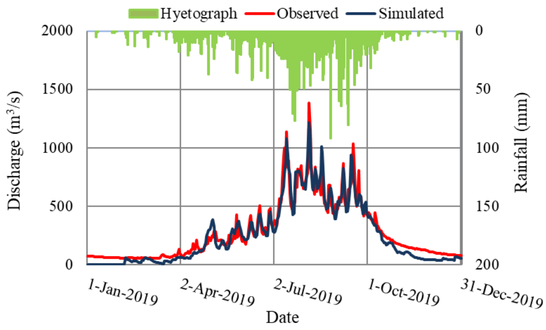

Fig. 8: *Model validation for 2019 at Wangdirapids station*

4.2 RSR model sensitivity analysis

Sensitivity analysis showed that initial particle size distributions have a significant impact on sediment transport processes. The sediment model was validated through an iterative calibration process using different combinations of particle size distributions for the river channel and slopes. Simulation results were compared against observed data, and the best particle size combination was selected for further analysis.

4.3 Suspended load discharge

The RSR model simulations using finalized particle size distributions exhibit good agreement with the observed suspended sediment discharge data at the Wangdirapids station, as shown in Fig. 9. When slope erosion processes were considered, the model improved significantly, demonstrating the substantial contribution of slope-derived sediments to the basin's sediment budget.

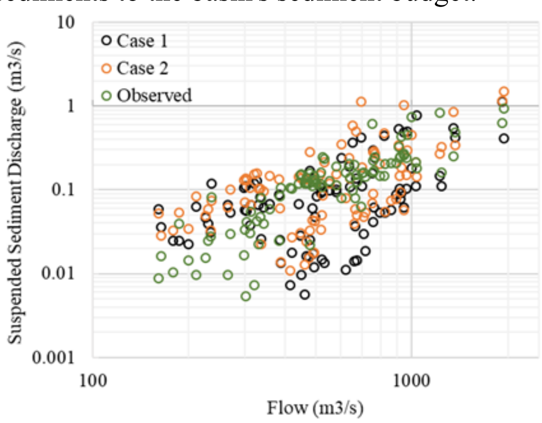

Fig. 9: *Comparison of suspended sediment discharge of Case 1, Case 2, and observed data*

5. DISCUSSIONS

5.1 Temporal sediment size distribution

A comparative analysis of simulated and field-measured sediment size distributions (Fig. 10a & b) showed distinct temporal patterns. During the initial 30-day period, the model results showed sand-dominated sediment (D_{50} = 0.9 mm). However, as time progressed, the median particle size increased by an order of magnitude to D_{50} = 10 mm by day 150, indicating that sand materials were gradually washed away, leaving behind coarser sediments. Case 2, which incorporated slope erosion processes, showed better agreement with field data compared to Case 1.

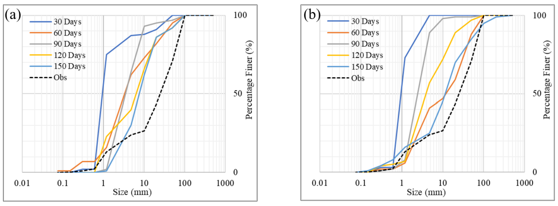

Fig. 10: *Comparison of riverbed sediment distributions of Case 1 (left) and Case 2 (right) with observed data*

5.2 Hysteresis in the sediment-runoff process

Fig. 11 (b) presents three hysteresis loops from three hydrological events. The basin exhibited a strong hysteresis pattern which indicates significant variation in sediment transport with changing flow conditions.

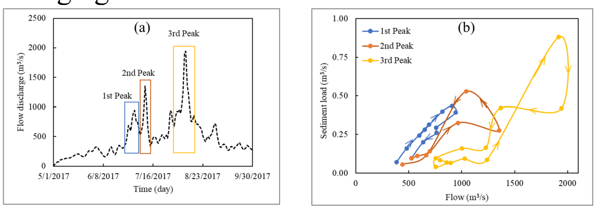

Fig. 11: *(a) Stream-flow discharge and (b) Hysteresis of three peaks*

Sediment discharge increased with stream-flow discharge until reaching a peak value, after which it began to decline. This pattern suggests that the river initially picks up and transports more sediment as the flow increases, but eventually reaches a point where the sediment supply becomes limited, or the river's transport capacity is exceeded.

5.3 Tributary contribution

The sediment contribution from the Mo Chhu and Pho Chhu tributaries was analyzed for both cases, as shown in Fig. 12. In both scenarios, the Pho Chhu tributary contributed 55% of the total sediment production, while the Mo Chhu contributed 45%. The model results indicate that the suspended load dominates, while bedload accounts for approximately 5%.

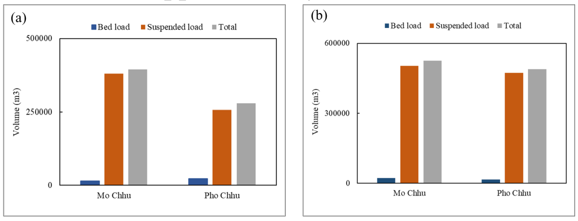

Fig. 12: *Sediment contribution of tributaries in Case 1 (left) and Case 2 (right)*

5.4 Sediment production

A comparative analysis of specific sediment yield in the Punatshangchhu basin with reference to a Japanese drainage basin. Fig. 13(b) illustrates the relationship between the annual average specific sediment production and catchment area.

The Punatshangchhu basin falls between zones 2 and 3 of the sediment production chart, which corresponds to large sediment discharge. This classification suggests that the basin has high natural erosion, sediment supply is amplified by human activities (mining, deforestation), and there is no major dam to trap sediment.

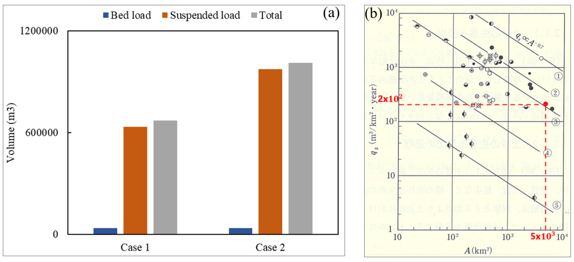

Fig. 13: *(a) Sediment production under Case 1 and Case 2, (b) Relationship between the annual average specific sediment production and the catchment area*

5.5 Sediment budget/balance

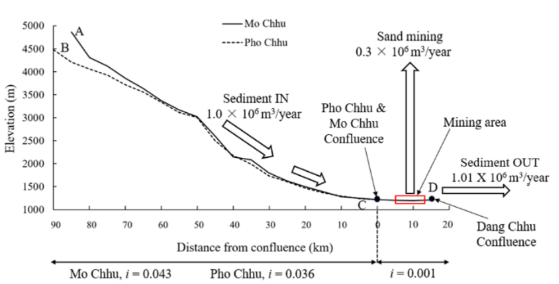

Fig. 14 *Sediment budget in the Punatshangchhu Basin*

The sediment budget of the Punatshangchhu River was assessed at the active sand mining reaches. Sediment inflow, derived from RSR simulations, yields an annual sediment discharge of 1.0×10^6 m³/year as depicted in Fig. 14.

Model results indicate that a similar quantity is being transported downstream. This balance between sediment inflow and outflow suggests that the system is in a state of equilibrium.

6. CONCLUSION

6.1 Scenario – I: Without downstream dam

In the current scenario, sand mining practices in the Punatshangchhu River basin are unsustainable, with approximately 0.3×10^6 m³ of sediment extracted annually—based on sand extraction data from the Natural Resources Development Cooperation Limited (NRDCL)—equivalent to 30% of the total sediment transport in the basin (1.0×10^6 m³/year). This extensive extraction has triggered the degradation of the riverbed at an estimated rate of 0.26 m/year, resulting in a sediment deficit in the river. This has led to changes in the river's flow dynamics, increasing the risk of flooding due to channel incision and bank destabilization. Furthermore, the loss of sediment disrupts the aquatic ecosystem. These results underscore the urgent need for stricter regulations and monitoring of sand mining activities to prevent further degradation.

6.2 Scenario II: With dam construction

The construction of a downstream dam is projected to significantly alter the fluvial hydrodynamics, with hydropower project feasibility studies indicating a 1-2 m water level rise 8 km upstream (Japan International Cooperation Agency & Electric Power Development Co., Ltd., 2001). This hydraulic modification will reduce flow velocities, decrease the sediment transport capacity, and promote sediment deposition in upstream reaches. The resulting aggregation creates an opportunity for sustainable sediment management, where controlled extraction can maintain channel equilibrium while reducing reservoir sedimentation. However, this approach requires proper monitoring and regulation, as well as effective sediment management strategies, to ensure long-term sustainability.

Future research should consider:

- Climate change impacts on sediment yield and transport capacity.
- Change in sediment dynamics in the basin due to the downstream dam.

7. LIMITATION

The sediment contribution from the Dangchu tributary was not included in this study because its watershed area constitutes approximately 10% of the total catchment area upstream of the Wangdirapids station.

8. ACKNOWLEDGEMENT

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