BASIN-SCALE SEDIMENT TRANSPORT FOR SUSTAINABLE SAND MINING: A CASE STUDY IN PUNATSHANGCHHU BASIN, BHUTAN

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ABSTRACT

This study evaluated basin-scale sediment transport processes in the Punatshangchhu River basin in Bhutan, using the Rainfall-Sediment-Runoff model to investigate sustainable sand mining. The basin has provided 65% of the country's sand resources for infrastructure development since 2007; however, sand mining has been carried out without studying the basin's sediment budget. Numerical simulations were conducted for five with two cases: Case 1 considered only erosion from the riverbed, while Case 2 considered erosion from both the riverbed and hillslopes. Calculation results were compared with the observed discharge, suspended sediment concentration, and sediment size distribution. In Case 2, the total sediment runoff volume was 34 % more than that in Case 1. The study found that the sediment budget in the basin is in equilibrium. Therefore, sand mining is not sustainable in the present scenario, with riverbed degradation estimated at a considerable rate of 0.26 m/year due to mining activity. However, constructing a dam downstream could potentially allow for sustainable sand mining.

Keywords: *Rainfall-sediment runoff, Basin-scale sediment transport, Sediment budget, Suspended sediment, Punatshangchhu River.*

1. INTRODUCTION

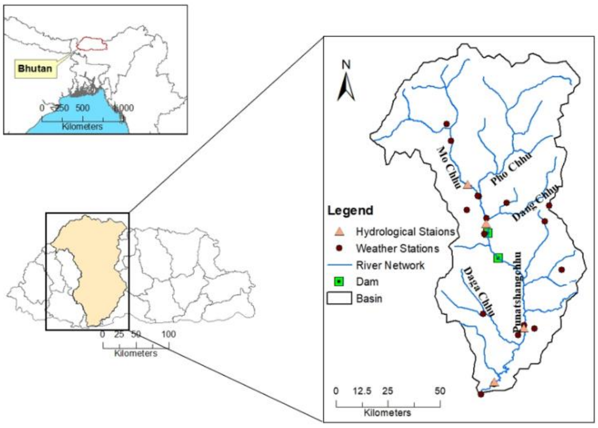

Figure 1: Punatshangchhu River basin

Towering mountains, deep valleys, and dense forests characterize the Punatshangchhu basin in Bhutan. The Punatshangchhu River originates from the Himalayan range and flows through western central Bhutan before reaching the Indian plains. The basin area is approximately 9547 km^2, and is home to 221 glacial lakes, with 17 of them classified as potentially dangerous glacial lakes (NCHM, 2019). The basin recorded the highest discharge of 2650.26 m^3/s on 25th May 2009 and the lowest of 51.713 m^3/s on 3rd September 2015 at Wangdirapids station. Additionally, the basin houses two hydropower dams: Punatshangchhu-I and Punatshangchhu-II with power-generating capacities of 1200 and 1020 megawatts, respectively. Rapid social development and construction growth in Bhutan have escalated the demand for sand to support infrastructure projects, resulting in widespread riverbed sand mining. Mining activities in the Punatshangchhu River basin began in 2007 with an average mining volume of 0.3 million m^3/year. However, sand mining is being carried out without studies on the basin's sediment budget. Therefore, this study aimed to evaluate basin-scale sediment transport processes for sustainable mining using a rainfall-sediment-runoff (RSR) model.

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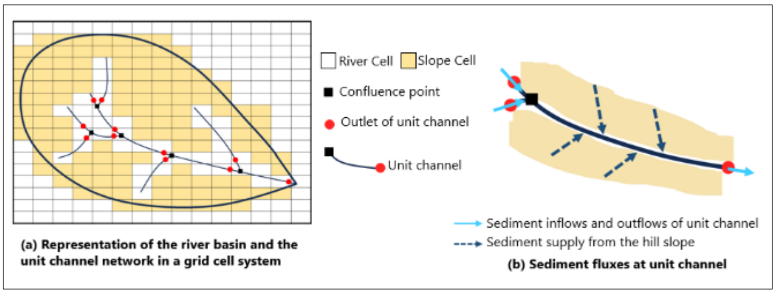
2. THEORY AND METHODOLOGY



(a) Representation of the river basin and the unit channel network in a grid cell system

(b) Sediment fluxes at unit channel

Figure 2: Channel network and unit channel concept in the RSR model

To evaluate the sediment transport processes in the Punatshangchhu River basin, the RSR model was developed by adapting the rainfall-runoff-inundation (RRI) model. In the rainfall-runoff analysis, the lateral surface flow is computed by the diffusion wave approximation, the vertical infiltration in the plain area by the Green-Ampt equation, and the lateral infiltration flow in a mountainous area by Darcy's equation (Sayama et al., 2012). A basin channel network is formed by a series of unit channels having two inflow points and one outflow, as shown in Figure 2 (a) & (b). Egashira et al. (2000) describe the concept of channel networks in the basin scale, which facilitates temporal and spatial change estimations in sediment discharge, storage, and size when provided with rainfall data as inputs. The bedload formula from Egashira et al. (1997), the suspended load formula from Harada & Egashira (2020), and the hillslope sediment load formula from Qin et al. (2023) were employed here.

Governing equations for sediment

The following equation describes the mass conservation of riverbed sediment transport:

$$\frac{z_b}{\partial t} = \frac{1}{(1-\lambda)B(r1_{i+1})L(r1_{i+1})}$$

$$\{(Q_{bj}(r1_i) + Q_{bj}(r2_i) - Q_{bj}(r1_{i+1}))\}$$

$$+ \frac{1}{(1-\lambda)}\sum_j((D_{sj}(r1_{i+1}) - E_{sj}(r1_{i+1})) \quad [1]$$

where z_b is the river bed elevation; λ the porosity of bed sediment; $B(r1_{i+1})$ the width of the unit channel; $L(r1_{i+1})$ the length of the unit channel; $Q_{bj}(r1_i)$ and $Q_{bj}(r2_i)$ are bedload discharges of size class-j sediment from $r1i$ and $r2i$ transported to the unit channel $(r1_{i+1})$ (refer to Figure 2[b]); $Q_{bj}(r1_{i+1})$ the bedload discharge of size class-j sediment flowing from the unit channel; $D_{sj}(r1_{i+1})$ the deposition rate of size class-j suspended sediment (see equation [6]); and $E_{sj}(r1_{i+1})$ is the erosion rate of size class-j suspended sediment (see equation [7]).

The suspended sediment concentration in a unit channel was calculated by:

$$\frac{\partial hc_{sj}(r1_{i+1})}{\partial t} = \frac{1}{B(r1_{i+1})L(r1_{i+1})}$$

$$\left\{\begin{matrix} C_{sj}(r1_i)Q(r1_i) + C_{sj}(r2_i)Q(r2_i) \\ +\sum_j Q_{psj}^{n}(r1_{i+1}) - C_{sj}(r1_i)Q(r1_i) \end{matrix}\right\}$$

$$- D_{sj}(r1_{i+1}) + E_{sj}(r1_{i+1}) \quad [2]$$

where C_{sj} is the average concentration of the size class-j suspended sediment in the flow; $\sum_j Q_{psj}^{n}(r1_{i+1})$ the total size class-j sediment discharge supplied from the adjacent hillslope area on both sides of the $(r1_{i+1})$ unit channel; n the total number of lateral inflow inlets of each unit channel; and Q_{psj} the discharge of inflow lateral sediments obtained from equation [5].

The bedload sediment transport is described by the non-dimensional critical bed shear stress and non-dimensional critical shear velocity in which the bedload transport rate is proportional to ${\tau_*}^{5/2}$ (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 K_1, K_2, f_d, and f_f are parameters referred to by Egashira et al. (1997); q_{b*j} the non-dimensional bedload transport rate; and τ_{*j} the non-dimensional bed shear stress.

Harada et al., 2020 proposed the erosion rates of suspended sediment from the concept of entrainment velocity in density-stratified flow as represented below:

$$\frac{w_e}{u} = \frac{K_e}{R_{i*}} \qquad [4]$$

where w_e is the entrainment velocity; R_{i*} the Richardson number; and u the flow velocity.

A conceptual sediment path along the hillslope gradient is proposed by Qin et al. (2023) which is integrated into the RSR model. The sediment supply from the hillslope is calculated as follows:

$$Q_{psj} = q_p B_p \cdot c_{pj} \qquad [5]$$

where q_p is the flow discharge of the sediment path in unit width; B_p the width of the sediment path; and c_{pj} the size class-j sediment concentration of the flow in the sediment path.

The erosion and deposition rate for suspended sediment is calculated as follows:

$$E_{sj} = F_{bj} w_e \overline{c_b} \qquad [6]$$

$$D_{sj} = w_{0j} c_{sj} \qquad [7]$$

where w_e is the entrainment velocity of the particle; w_{0j} the falling velocity of size class-j sediment; F_{bj} the fraction of size class-j in the bedload layer; $\overline{c_b}$ is the average sediment concentration ($\overline{c_b} = {c*}/{2}$) ; and c_* is the sediment concentration of the stationary layer.

The sorting algorithm of the sorting process in the multilayer model is as follows:

$$\frac{\partial z_b}{\partial t} > 0, p_j = F_{bj} \qquad [8]$$

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

$$\frac{\partial z_b}{\partial t} < 0 \begin{cases} p_j = \dfrac{F_{tj}\delta_t - F_{dj}(\Delta z_b + \delta_t)}{-\Delta z_b} \quad (\Delta z_b + \delta_t < 0) \end{cases} \qquad [10]$$

where δ_t is the depth of the transition layer; δ_d the depth of the deposited layer (a fixed value often given as D_{max} or D_{90}); Δz_b the bed elevation difference in the time step; F_{tj} the fraction of sediment size class-j in the transition layer; and F_{dj} the fraction of sediment size class-j in the deposited layer.

3. DATA

The 15-arc-second Digital Elevation Model (DEM) data from HydroSHEDS was used to represent the study area topography, and the daily ground rainfall data for 2017 was used for the simulation. Initially, the RRI model simulation was performed for the whole Punatshangchhu basin and calibrated and validated against the daily discharge observed at Wangdirapids station. Next, the RSR model was developed for the Wangdirapids subbasin. In addition to the RRI model, a sediment input file was prepared to simulate the RSR model. For that, non-uniform sediment distribution files were prepared to account for sediment supply from the riverbed and hillslopes. Six different initial grain size distributions (GSDs) were used for the trial, and the total sediment volume transported through the outfall of the mining area and sediment concentration at Wangdirapids station was checked. Based on the results, GSDs for the riverbed and slope were chosen, as shown in Figure 3. Finally, further analysis of sediment transport processes in the basin was conducted by simulating the RSR model under two cases: Case 1 considered only erosion from the riverbed, while Case 2 considered erosion from both the riverbed and hillslopes.

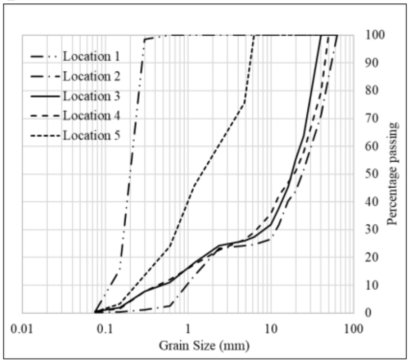


Figure 3: Grain Size Distribution

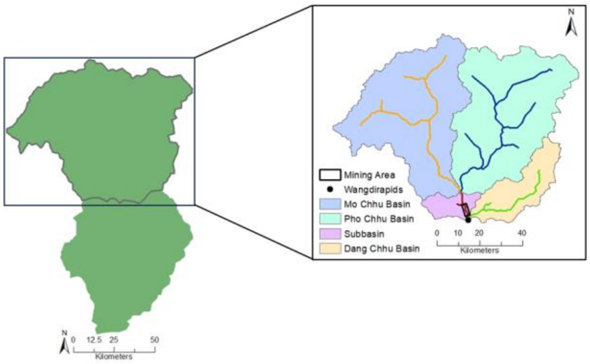


Figure 4: Wangdirapids station

4. RESULTS AND DISCUSSION

a) RRI model

The calibration and validation results are shown in Figures 5 and 6. The RRI model showed good performance in assessing basin hydrological responses. The model slightly underestimates the low flows, but the peak flows matched well. Acceptable values of NSE = 0.9, PBIAS = -12, and R^2 = 0.92 were obtained for the calibration process. The model provided better validation results for the 2019 flood discharge with NSE, PBIAS, and R^2 values of 0.9, -12, and 0.94, respectively.

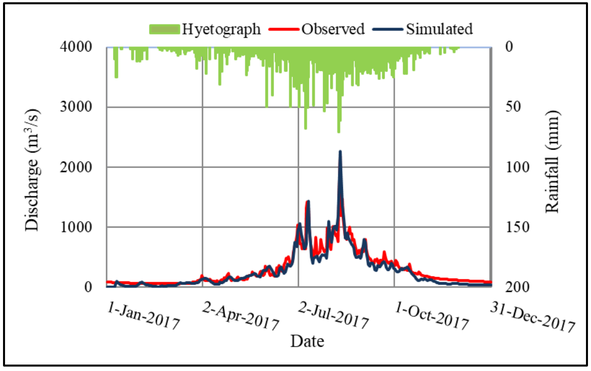


Figure 5: RRI model calibration

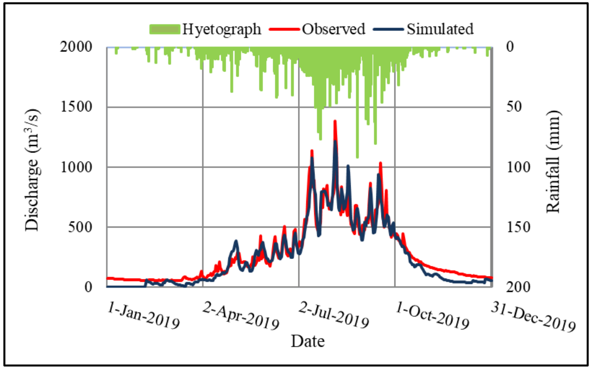


Figure 6: RRI model calibration

b) RSR model

(1) Model validation in terms of suspended sediment discharge

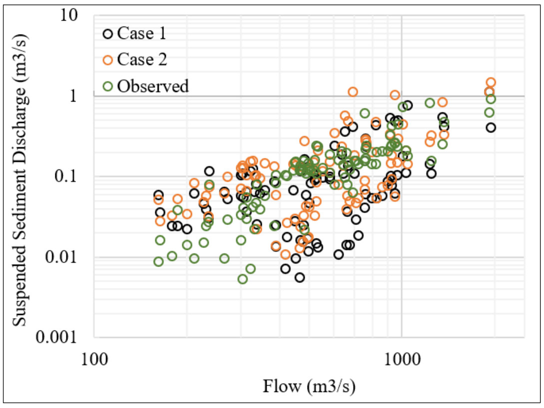


Figure 7: Comparison of suspended sediment discharge of Case 1, Case 2, and measured data

Figure 7 shows the simulated suspended sediment discharge for both Case 1 and Case 2, conducted from May to September 2017, together with the measured data at Wangdirapids station. The model's predictions show reasonably good agreement with the observed field data. When comparing the sediment discharge between Case 1 and Case 2, it became evident that the sediment discharge in Case 2 was well simulated, effectively capturing the hillslope erosion process in the calculation.

(2) Temporal change of sediment particle size

Figure 8 shows the temporal variation of sediment size distribution compared with measured field data in Case 1 and Case 2. The computed results for the first 30 days indicate the dominance of fine materials, signifying that a large volume of fine materials is initially transported from the upstream area. However, as time progressed, the sediment size distribution shifted, and by the 150th day, the sediment became coarser. When comparing the GSDs of Cases 1 and 2, Case 2 was simulated closer to the field-measured data.

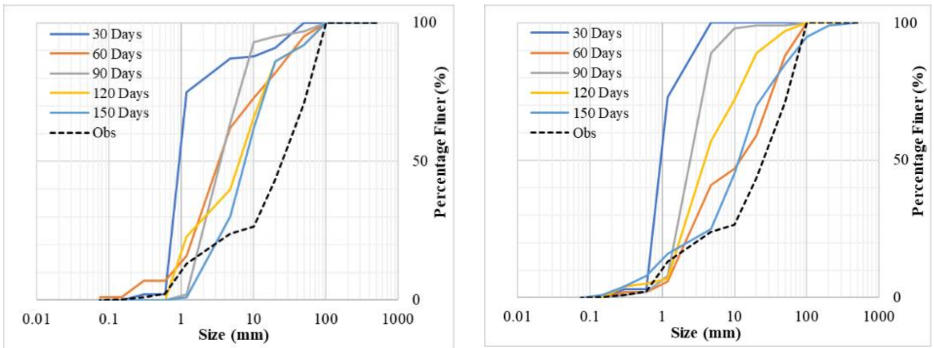


Figure 8: Comparison of riverbed sediment size distributions of Case 1 (left) and Case 2 (right), and observed data.

(3) Tributary contribution

Figure 9 represents the sediment contribution of two main tributaries. The analysis results show that the Pho Chhu tributary contributes about 55% of the total sediment transported, while the Mo Chhu tributary contributes 45% in both cases. It was also observed that about 5% of the total sediment transport was in the form of bedload, while the remaining 95% was in the form of suspended sediment

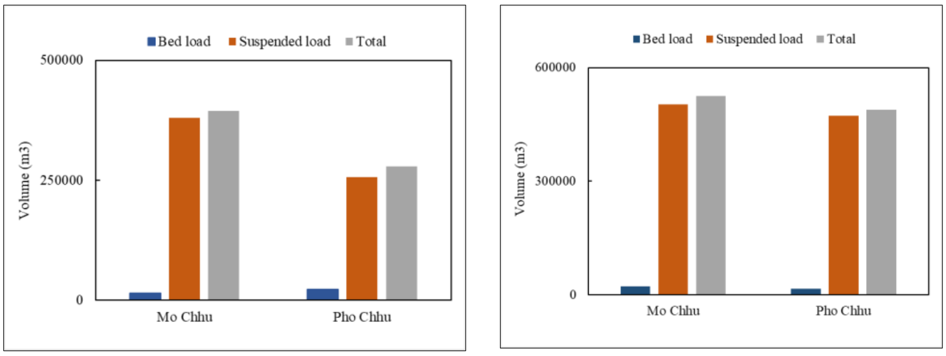


Figure 9: Sediment contribution of tributaries under Case 1 (left) and Case 2 (right)

(4) Sediment production

Figure 10 shows the sediment production in two cases. Sediment production increased by approximately 34 % in Case 2 compared to that in Case 1. This difference is attributed to the hillslope erosion process, considered during the Case 2 calculation. The sediment production in the basin is compared with the Japanese Drainage basin chart, which shows the relationship between the annual average specific sediment production and catchment area. Punatshangchhu basin falls within zones 2 and 3, corresponding to 'Large sediment discharge.' This underscores the high activity of the sediment transport process within the Punatshangchhu basin.

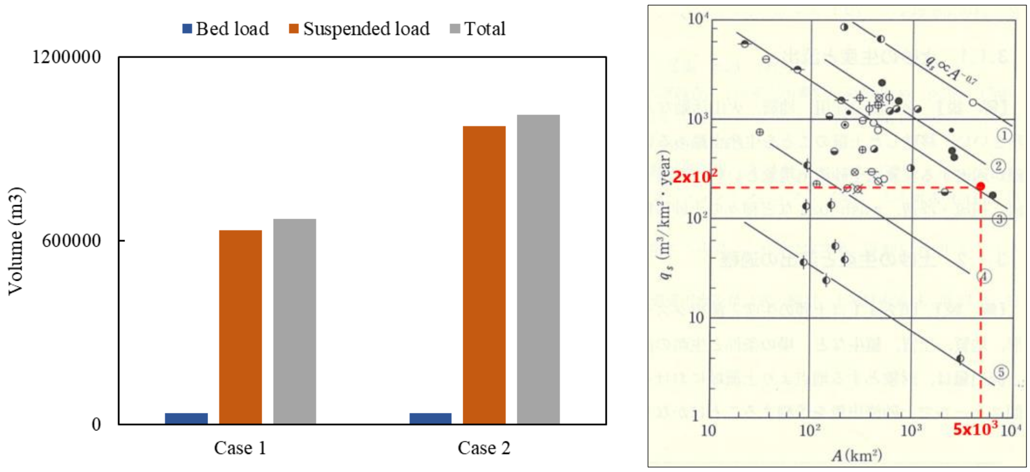


Figure 10: Sediment production in the basin (left). Relationship between annual average specific sediment production and catchment area (right).

(5) Sediment budget/balance

Figure 11 illustrates the sediment budget in the sand-mining stretch. The model shows that the sediment discharge in the Punatshangchhu River basin is approximately 1.0×10^6 m^3/year, and nearly the same amount of sediment is transported downstream, signifying a balance between sediment inflow and outflow. Here, riverbed degradation was estimated to be 0.26 m/year due to mining, computed by dividing the volume of sediment transported in a year by the riverbed area. We concluded the findings under two scenarios. Scenario – I: considering the present situation with no dam downstream, sand mining resulted in an imbalance in the sediment budget within the basin. Approximately 0.3 million m^3 of sediment is extracted annually, accounting for 30 % of the total sediment transported in the basin. This raises concerns about the sustainability of sand mining, as the replenishment rate may remain insufficient, leading to riverbed degradation at a rate of 0.26 m/year. As a result, sand mining is considered not sustainable. Scenario – II: with the construction of a dam downstream, sand mining may become a potentially beneficial and sustainable solution. This construction may alter the natural flow of river water and may lead to the deposition of sand in the river's upstream reaches. This could allow for sustainable sand extraction, providing a continuous supply of fine-grained material for construction and industrial purposes.

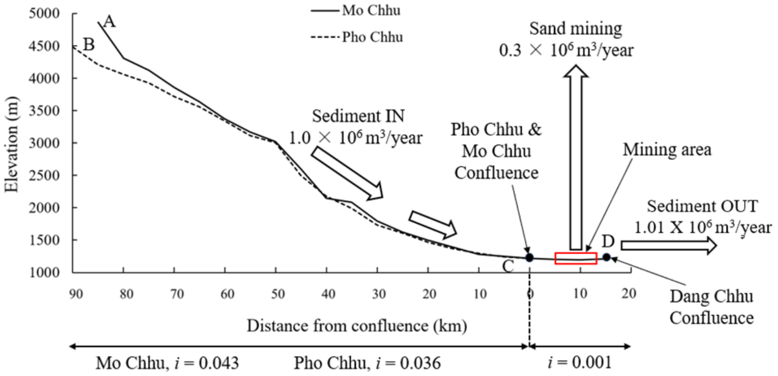


Figure 11: Sediment balance in the basin

5. CONCLUSIONS AND RECOMMENDATIONS

This study evaluated basin-scale sediment transport processes in the Punatshangchhu River basin in Bhutan to understand sustainable sand mining practices. The key findings and conclusions are: (I) the sediment budget in the basin is in equilibrium. However, riverbed degradation is occurring at a considerable rate of 0.26 m/year due to mining. (II) In Case 2, where erosion was considered from both the riverbed and hillslopes, the total sediment runoff volume was 34 % more than that in Case 1. (III) Sand mining is not sustainable in the present scenario; however, construction of a dam downstream could potentially render this sustainable. Based on the study findings, the following recommendations are proposed for sustainable sand mining in the Punatshangchhu River basin. (I) To maintain the basin's sediment balance and prevent riverbed degradation, it is essential to implement sediment management strategies. This could involve regulating sand mining activities to match the basin's natural replenishment capacity. (II) Regular monitoring of sediment transport, riverbed changes, and water quality parameters is crucial to assess the impact of sand mining on the basin's sediment dynamics. (II) Raising awareness about the importance of sustainable resource management and involving communities in decision-making processes can foster more responsible mining practices.

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