

Sediment-Inclusive Hydraulic Modelling Reveals Systematic Underestimation of Flood Hazard in Himalayan Rivers

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Research Article

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Abstract

Sediment–hydraulic coupling is an important but frequently neglected process in flood hazard assessment in the Himalayan River systems. The study evaluates sediment–hydraulic interactions for a 9.5 km reach of the Toorsa River (Amochhu) located in Phuentsholing, Bhutan, and the implications for 1D flood modelling using HEC-RAS. Sediment and flow velocity were collected at 38 systematically spaced sampling points, and discharge data (2006–2025) were compared with 1D HEC-RAS modeling, with and without sediment transport, using the Meyer-Peter and Müller transport function. Results revealed that the grain size distribution of the sediment was polymodal and spatially variable, with the dominant grain size being 4 mm gravel (24.51). Principal Component Analysis (PCA) accounted for 80.75% of the sediment variance along two axes: a coarse-to-fine gradient in hydraulic energy and medium sorting of sand. Spearman's correlation indicated a significant positive correlation between flow velocity and D50 ($\rho = 0.350$, $p = .031$) and no correlation between flow velocity and D10, indicating bimodal transport behavior. Channel slope was the better predictor of bedload transport rate ($R^2 = 0.455$) than flow velocity ($R^2 = 0.182$). The mobile-bed simulation with sediment resulted in a mean rise in water surface elevation of 1.083 m, a 53% increase in mean velocity, and a 2.41-fold increase in flow area compared to the fixed-bed simulation. All three parameters differed significantly from the no-sediment control case, with the Froude number not differing, indicating that the hydraulic regime remained stable under sediment-laden conditions, as confirmed by the Wilcoxon signed-rank tests ($p < .001$ for all three parameters; $p = .149$ for the Froude number). This result shows that hydraulic models with fixed beds systematically underestimate flood hazard in sediment-active Himalayan rivers and highlights the importance of sediment-inclusion modelling to support climate-resilient flood risk management and infrastructure planning in Phuentsholing City.

Introduction

Rivers in mountainous areas are among the most geomorphologically dynamic systems on Earth, with high transport of water, sediment, and nutrients in steep, frequently tectonically active environments (Wohl et al., 2015). Sediment transport is especially high in the Himalayan River systems, where monsoon runoff is high, channel gradients are steep, and mass wasting commonly occurs as landslides or glacial lake outburst floods (GLOFs). Sediment loads directly affect hydraulic processes by altering channel roughness, channel bed elevation, cross-sectional area, and flow conveyance, all of which can influence flood inundation in terms of spatial extent and depth (Hamidifar et al., 2024; Nones & Guo, 2023).

However, the documented relationship between sediment dynamics and flood behavior has not been incorporated into most operational flood assessments in Bhutan and across the Himalayan region, which still rely on fixed-bed hydraulic models and assume static channel geometry. These models are also incapable of incorporating changes in bed elevation caused by erosion and deposition, thereby underestimating flood risk in morphodynamically active reaches, as observed (Adhikari et al., 2023; Baniya et al., 2023). A significant example is the Melamchi flood in Nepal, which reached inundation

extents significantly higher than those predicted by the static-bed models (Baniya et al., 2023; Chen et al., 2025) due to channel aggradation of 5–20 m. Similar results have been reported for the Punatsangchhu Basin in Bhutan; sediment-including HEC-RAS modelling was found to be 15–25% more inundated than fixed-bed modelling (Choden & Dorji, 2025; Tenzin & Dorji, 2025).

Toorsa (Amochhu) in Phuentsholing Thromde is a critical case of sediment-induced flood amplification. The study reach can be characterized by a significant morphological gradient from a steep gorge in the Himalayan region to a low-gradient alluvial floodplain, which results in rapid deposition, channel aggradation, and bank instability along the river. According to historical trends, flood frequency has been increasing in Chukha Dzongkhag. In October 2025, a high-sediment-load flood displaced households and damaged critical infrastructure in Phuentsholing, highlighting the limitations of existing flood mitigation measures in coping with such events. (Dorji, 2025) Despite these hazards, no sediment-incorporating hydraulic model has been created for the Toorsa reach, and systematic characterization of the grain-size distribution of the study reach has never been attempted.

This study aims to address these gaps by using 1D HEC-RAS modelling, grain-size analysis, multivariate statistics, and field bedload sampling to: (1) characterize the spatial variability of sediment grain size distribution along the study reach of the Toorsa River; (2) evaluate relationships between the sediment characteristics and hydraulic parameters such as flow velocity, channel slope, and bedload transport rate; and (3) quantify the differences between fixed-bed and mobile-bed flood simulations (based on an average bed load transport rate of 12.5 kg/s) in terms of water surface elevation, flow velocity, flow area and Froude number. The results are the first sediment-integrated flood model for the Toorsa River and have implications for flood hazard assessment and climate-resilient planning in Phuentsholing.

Materials and Method Study Area

Study Area

The study was carried out in a 9.5 km reach of the Toorsa River (Amochhu) in the Phuentsholing Thromde of Chukha Dzongkhag, Bhutan (Figure 1). The Toorsa is a transboundary Himalayan River that originates in the Chumbi Valley, Tibet, with a catchment area of around 3304 km² at the Amochhu bridge hydrological station and flows through the Indian state of West Bengal via Phuentsholing. The study reach is located between about 160 and 293 masl and represents a transition from a steep, confined gorge to a low-gradient floodplain.

This morphological change creates high gradients in spatial sediment transport capacity. A humid subtropical climate is found in the lower catchment, with an average annual rainfall of ~4000 mm, with about 72% of the total rainfall occurring during the South Asian monsoon (June/September). About 98% of sediment transport occurs during the monsoon (Ghimire et al., 2024).

Sampling Design and Field Data Collection

A systematic sampling design was used to characterize the bedload sediment in the study reach. The 9.5 km reach was sampled at 38 plots spaced about 250 m apart, each assigned to one of three longitudinal zones: upstream (1–12), midstream (13–26), and downstream (27–38). To capture the natural hydromorphological variation due to differences in channel gradient, channel confinement, and tributary inputs, stratification was used (Bunte & Abt, 2001; Wolman, 1954). Coordinates and elevations of all sampling plots were recorded using the SW Maps mobile GIS application to ensure spatial precision and reproducibility.

Three replicate bedload samples were taken at each plot with a grab-type bed material sampler, two near-bank samples, and a sample at $\sim 1/4$ of the wetted channel width. Replicates were bulked for laboratory analysis in accordance with the standard bed-material sampling procedure (Bunte & Abt, 2001; Rice & Church, 1996). Flow velocity was measured at $\sim 1/4$ of the wetted channel width by using an area flow velocity meter. The river discharge data (2006–2025) were collected from Doyagang hydrological station.

Laboratory analysis

Grain size distribution of the collected bed load sediment samples was determined by dry sieve analysis, the standard method for characterizing particle-size distributions in coarse-grained fluvial sediments with a nested sieve stack ranging in mesh size from 4mm, 2mm, 1mm, 0.5mm, 0.25mm, 0.1mm, and <0.1 mm (Bunte & Abt, 2001; Rönnqvist, 2019).

Statistical analysis

The Shapiro–Wilk test was used to test data normality. Spatial variations in grain size fractions were assessed by using non-parametric Kruskal–Wallis tests, followed by Dunn's post hoc comparisons in the Bonferroni-corrected test. The data from grain-size fractions have been analyzed using Principal Component Analysis (PCA) to identify the main axes of sediment variation. Before PCA, Kaiser–Meyer–Olkin (KMO) sampling adequacy test and Bartlett's test of sphericity were conducted. Spearman's rank correlation was used to assess relationships between grain size parameters (D10, D50) and flow velocity. Simple linear regression models were used to assess the predictive ability of channel slope and flow velocity for bedload transport rate (TL). Seasonal discharge data were used for the Mann–Kendall trend test and Pearson's correlation. To compare hydraulic parameters (water surface elevation, velocity, flow area, Froude number) from the model between fixed-bed and mobile-bed conditions, Wilcoxon signed-rank tests and Pearson correlation were performed. Data were analyzed using SPSS and R.

1D HEC-RAS Sediment Transport Modelling

One-dimensional quasi-steady and unsteady flow HEC-RAS modelling (versions 6.6 and 6.7) was used to simulate sediment–hydraulic interactions along the study reach. Geometric data, including cross-sectional profiles, were derived from a digital elevation model (DEM) supplemented by field-surveyed cross-sections. A flow series was constructed from the 2006–2025 NCHM discharge record. Upstream and downstream boundary conditions were set to the observed flow hydrograph and the normal depth, respectively. Bed gradation curves derived from field samples were assigned to bed gradation curves within the stratified reaches.

The Meyer-Peter and Müller (MPM) bedload transport function was selected for the mobile-bed simulation, given its established applicability to coarse gravel-bed Himalayan rivers (Thapa et al., 2024; Choden & Dorji, 2025). Two scenarios were simulated: a fixed-bed (no sediment) baseline representing conventional hydraulic practice, and a mobile-bed (with sediment) scenario incorporating bed elevation changes driven by sediment transport. Key hydraulic output variables

- mean water surface elevation (WSE), mean flow velocity, mean flow area, and mean Froude number - were extracted at 74 cross-sections and compared statistically between scenarios.

Results and Discussion

Spatial Variability of Sediment Grain Size Distribution

The grain size distribution was polymodal and heterogeneous across the study area, reflecting a mixed-energy sediment transport regime. Gravel (4 mm) was the most dominant size across all zones (mean = 24.51%, SD = 21.65%), owing to the predominance of gravel-bed transport processes in the upper and middle reaches. The fine fractions (0.5 mm and <0.1 mm) had low mean values (8.63% and 3.48%) but high spatial variability (coefficients of variation >86%).

Statistically significant spatial differences were noted in the 0.5 mm fraction ($H(2) = 7.53, p = .023$) and in the <0.1 mm fraction ($H(2) = 9.14, p = .010$) as determined by Kruskal-Wallis tests, while Dunn's post-hoc comparisons showed significant differences between the upstream and midstream zones in both fractions. The dominant coarse fractions showed no statistically significant downstream fining trend, in contrast to the classic downstream fining trend (Knighton, 2014), and may be related to episodic mass wasting along the study reach, tributary sediment inputs, and local slope breaks.

PCA extracted two principal components that represent 80.75% of the total variance in grain size. PC1 was correlated with the coarse fractions (positive) and the fine fractions (negative), indicating a gradient in hydraulic energy (competence controls flow velocity and slope in sediment sorting). PC2 was most strongly correlated with medium sand size (1–0.25 mm), indicating an independent sorting mechanism that may be associated with secondary bar

formation or slack-water deposition. The results are consistent with those from other mixed-sediment mountain rivers in the Eastern Himalaya (Choden & Dorji, 2025; Tenzin & Dorji, 2025).

Relationships Between Sediment Characteristics and Hydraulic Parameters

Spearman's rank correlation test showed a significant positive correlation between flow velocity and D50 ($\rho = 0.350, p = .031$), suggesting that coarser median grain sizes were associated with higher-velocity reaches. However, there was no significant relationship between velocity and D10 ($p > .05$). This separation implies a bimodal transport regime, with competence-limited bedload transport shaping the transport of the coarse fractions (velocity – D50 coupling), and supply-limited wash load transport shaping the fine fractions, which are relatively insensitive to local velocity variations.

Simple linear regression showed that channel slope was a stronger predictor of bedload transport rate ($R^2 = 0.455, F(1,36) = 30.05, p < .001$) than flow velocity ($R^2 = 0.182, F(1,36) = 7.985, p = .008$). The regression equation for the slope model was $TL = -22.30 + 65,407.80 \times S_0$, and for the velocity model: $TL = -264.86 + 713.67 \times V$. The slope's better predictive ability is consistent with the shear stress theory, which states that the driving force for sediment entrainment is the gravitational component of shear stress (proportional to the bed slope) (Bagnold, 1980; Meyer-Peter & Müller, 1948). Overall, the relatively low R^2 for the velocity model is a reflection of the relatively high amount of unexplained variance in the bedload transport in these steep catchments, as the dynamics of bedload transport are complex and supply limited, with a large contribution from the macro-roughness elements, the bedform structures, and episodic sediment pulses (Recking, 2012; Yager et al., 2007).

Hydrological Analysis

The NCHM record from 2006 to 2025 was found to be strongly dominated by the monsoon, as indicated by seasonal discharge analysis. Mean monsoon discharge ($M = 291.55 \text{ m}^3/\text{s}, SD = 105.50$) was approximately 6.5 times greater than dry season discharge ($M = 44.94 \text{ m}^3/\text{s}, SD = 13.03$), and a paired t-test confirmed a highly significant seasonal difference (mean difference = $246.60 \text{ m}^3/\text{s}; t(18) = 10.414, p < .001$). Monsoon and dry season discharges were not significantly correlated by Pearson's correlation ($r = 0.235, p = .334$), implying different hydrological processes for the two seasons: monsoon dominated by rainfall, and dry season dominated by glacier and snowmelt. The Mann–Kendall trend tests did not show a significant long-term trend in either the monsoon discharge ($\tau = -0.216, p = .208$) or the dry season discharge ($\tau = -0.029, p = .889$) for the study period.

Simulated Riverbed Elevation Changes and Spatial Hydraulic Characteristics

The HEC-RAS mobile-bed simulations indicated a dominant net erosion pattern in the upstream and mid-reaches, with a near-equilibrium to net deposition pattern in the lower reach. The cumulative mass change values gradually decreased from the upstream boundary (~9,000 m) to near zero at the outlet, indicating abrupt, discontinuous changes in the mid-reach (6,000–5,000 m), where geomorphic features and changes in slope occur. This is similar to the sediment routing discontinuity that occurs in the lower, low-gradient portion of the channel, with episodic hillslope inputs and step-pool bedform dynamics (Benda & Dunne, 1997; Wohl, 2004).

The highest amplitude erosion-deposition oscillations were found in the mid-reach (7,500–4,000 m), which corresponds to a morphodynamically active zone, a local velocity maximum (6,000–5,500 m), and a minimum channel width (~5,000–3,500 m). This contracted portion of the gorge has a high concentration of stream power resulting in increased bed shear stress, incision potential, and sediment export. A decrease in velocity and a shift to a depositional regime were observed as the channel widened downstream from ~3,500 m to the outlet, which is in line with the behavior of piedmont channels in Himalayan foreland systems (Densmore et al., 2016; Gurnell et al., 2012).

Impact of Sediment Inclusion on Flood Hydraulic Parameters

Wilcoxon signed-rank tests revealed highly significant differences between fixed-bed and mobile-bed hydraulic outputs for water surface elevation ($W = 2764, Z = 7.416, p < .001$), flow velocity ($W = 2516.5, Z = 6.748, p < .001$), and flow area ($W = 2775, Z = 7.475, p < .001$) across 74 cross-sections. There was no statistically significant difference in the Froude number ($W = 1613, Z = 1.443, p = .149$).

The mobile-bed scenario resulted in a mean water surface elevation that was 1.083 m higher than in the fixed-bed scenario (Table 1). This increase is sufficient to breach low-lying embankments and flood peri-urban areas of Phuentsholing Thromde, which are not considered flood-prone in standard fixed-bed flood models. Sediment deposition can cause channel bed aggradation, leading to an increase in the longitudinal water surface profile, as observed in sediment-loaded Himalayan rivers (Ghinassi et al., 2016; Sinha et al., 2022). The simulated magnitude of the backwater effect is comparable with the water surface elevations and inundation area increases of 15–25% observed in sediment-inclusive simulations in comparison with fixed-bed simulations in the Punatsangchhu Basin (Choden & Dorji, 2025).

Table 1: Changes in Water Surface Elevation, Velocity, Flow Area, and Froude Number

Parameter	No Sediment	With Sediment	Change
Avg W.S Elev (m)	209.647297	210.730405	1.08310811
Avg Velocity (m/s)	1.72680556	2.64135135	0.9145458
Avg Flow Area (m ²)	365.242297	880.297162	515.054865
Avg Froude No.	0.60797297	0.66405405	0.05608108

The mean flow velocity rose by 53% with a mobile bed (from 1.727 to 2.641 m/s). The result is counterintuitive, as the increased velocity was associated with increased flow resistance due to the decreased cross-sectional area of the constricted mid-reach segments, where local aggradation caused flows to occur through smaller areas at higher velocity. This increase in peak velocity has implications for infrastructure vulnerability, as excess shear velocity (Wilcock et al., 2009) is raised to a power of 3 or higher when determining the rate of bedload transport. Similar velocity amplifications (40–70%) were reported by Battista et al. (2022) in alpine sediment supply modelling.

In the mobile-bed scenario, the mean flow area increased by 2.41-fold (from 365.24 to 880.30 m²), which corresponds to a significantly larger inundation envelope. Even minor bed aggradation allows lateral flooding in secondary channels and floodplain corridors in the lower, braided reach of the Toorsa floodplain (Hamidifar et al., 2024; Thapa et al., 2024). The Froude number ($Fr \approx 0.61$ - 0.66, subcritical) is the same in both scenarios, suggesting hydraulic self-regulation (proportional variations in velocity and depth in sediment-laden rivers (Buffington & Montgomery, 1999; Wohl & Wilcox, 2008). The practical significance of this finding is that flow regime classification can still be applied in hydraulic modelling practice when sediment processes significantly modify the absolute velocity and stage.

Conclusion

The results show that sediment–hydraulic coupling plays an important role in flood behavior along the Toorsa River at Phuentsholing, and that traditional fixed-bed hydraulic models consistently underestimate flood hazard in this sediment-dynamic Himalayan section. Polymodal and spatially variable bedload grain size distribution with a dominant (mean 24.51%) gravel fraction of 4 mm in size, and with significant spatial variation in fine fractions, rather than a classic downstream fining pattern. PCA accounted for 80.75% of sediment variance along two axes, one representing hydraulic energy gradients and the other medium sand sorting. Channel slope was the most important factor in the determination of bedload transport rate ($R^2 = 0.455$), thus supporting shear stress as the main entrainment control.

The water surface elevation rise, mean flow velocity, and flow area were found to be statistically different at $p < .001$, with a mean increase of 1.083 m, 53%, and 2.41, respectively. Despite significant changes in absolute flood parameters, the Froude number did not change significantly across the different scenarios ($p = .149$), suggesting hydraulic regime stability. These results support the failure of the fixed-

bed approach to delineate flood hazards in rivers with active sediment dynamics and the need to account for sediment dynamics in modelling to estimate flood stage, inundation extent, and infrastructure risk in Phuentsholing Thromde.

The study represents the first reach-scale bedload grain-size characterization and the first sediment-inclusive 1D flood model for the Toorsa River, establishing a fundamental baseline for climate-resilient flood risk management.

Declarations

Acknowledgement

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Figures

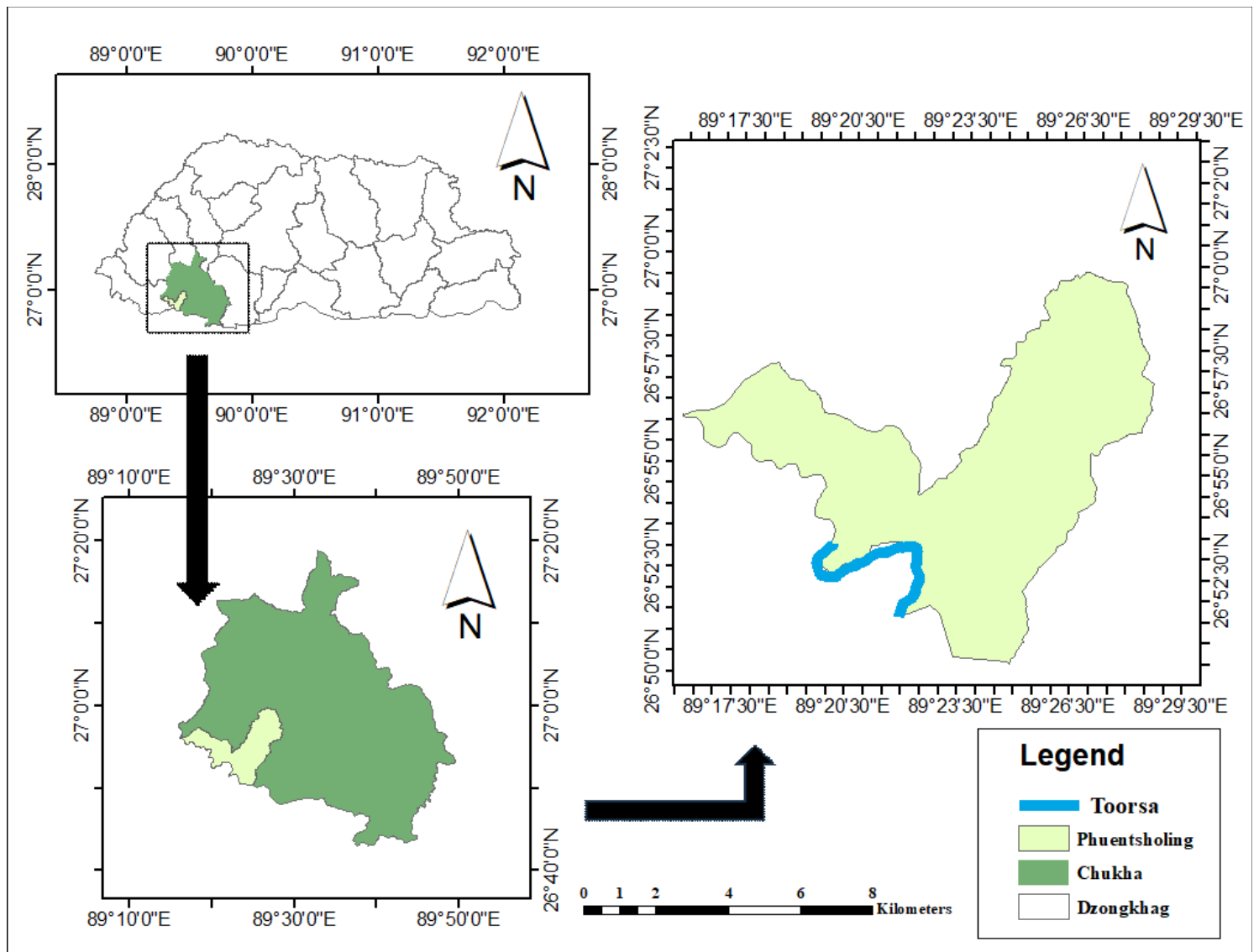


Figure 1

Study area along Amochu Basin, Toorsa River

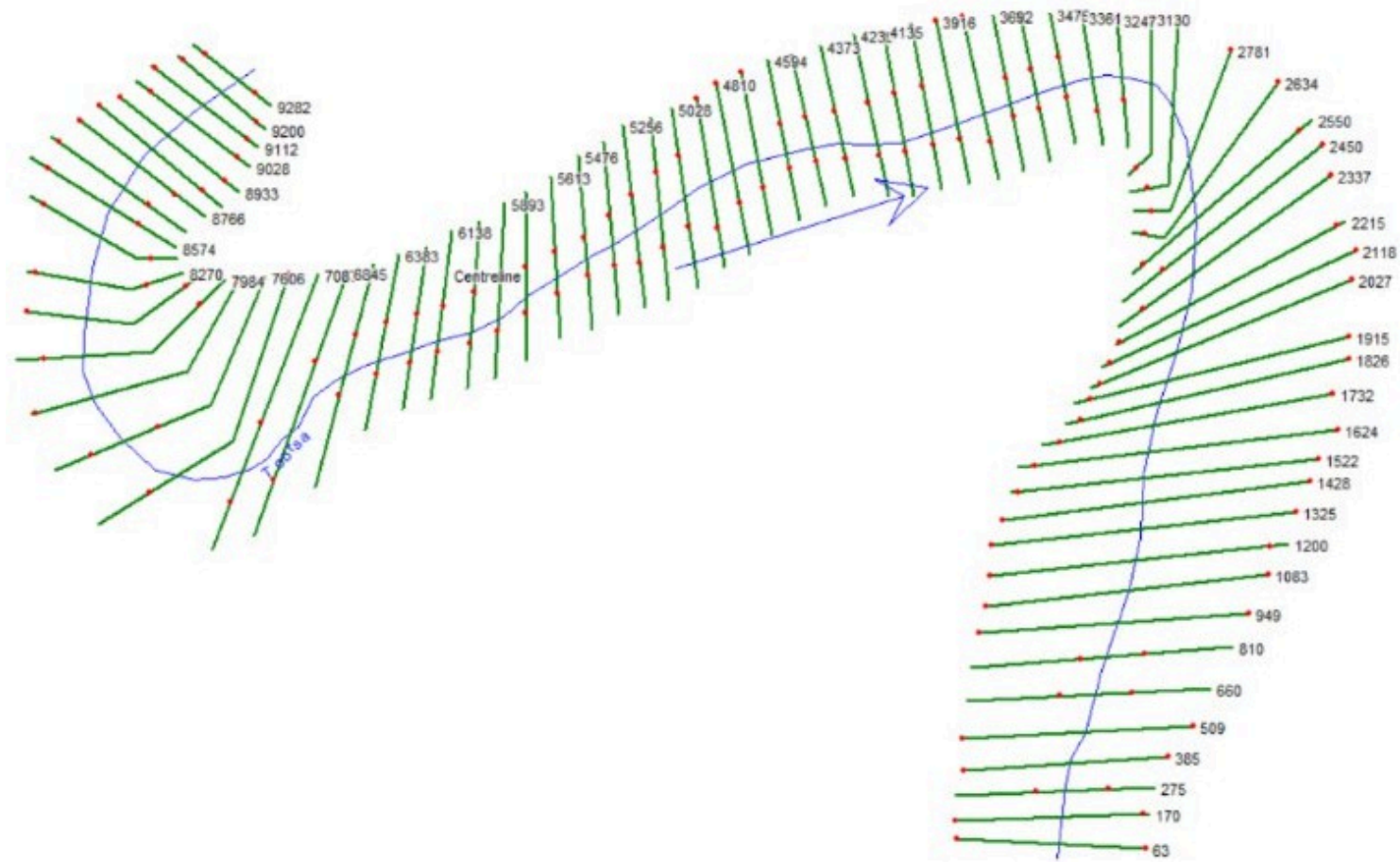


Figure 2
Geometric Data of the Study Area

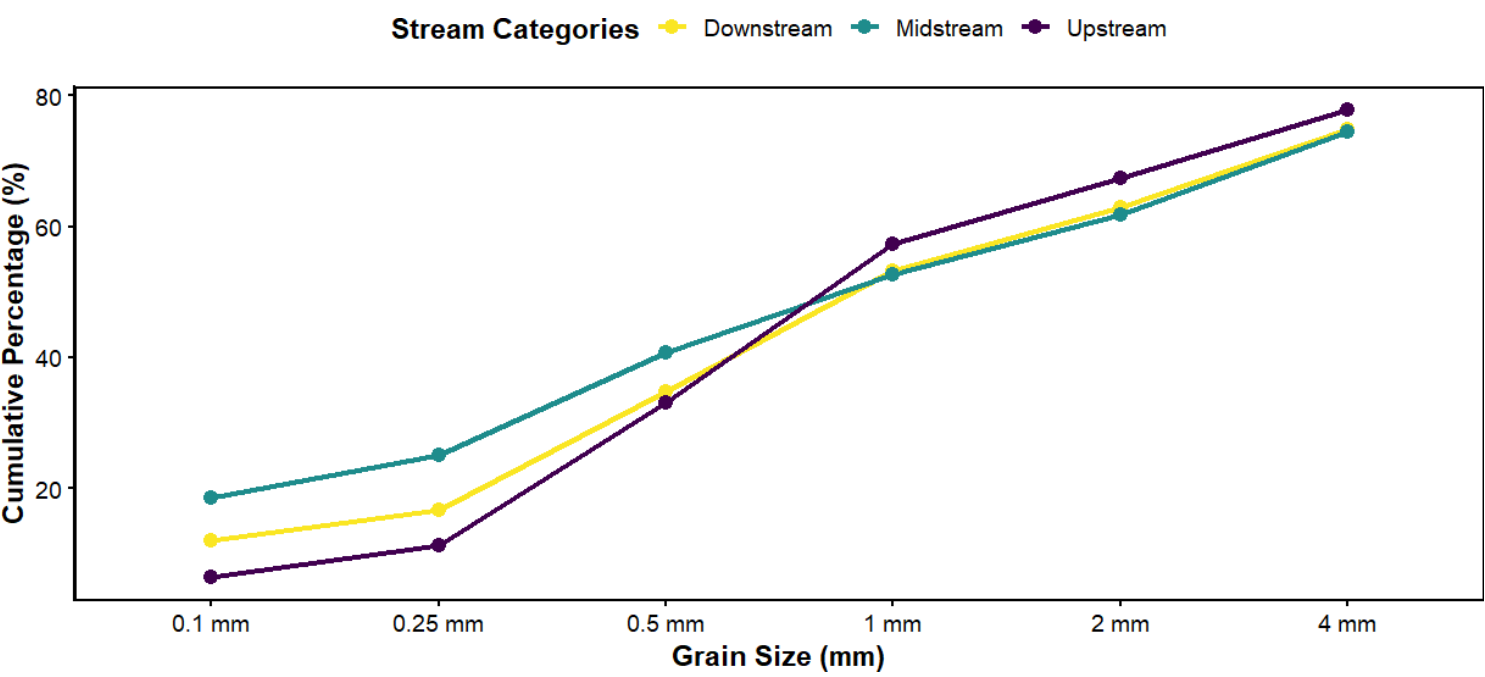


Figure 3

Grain Size Distribution Across Stream Categories

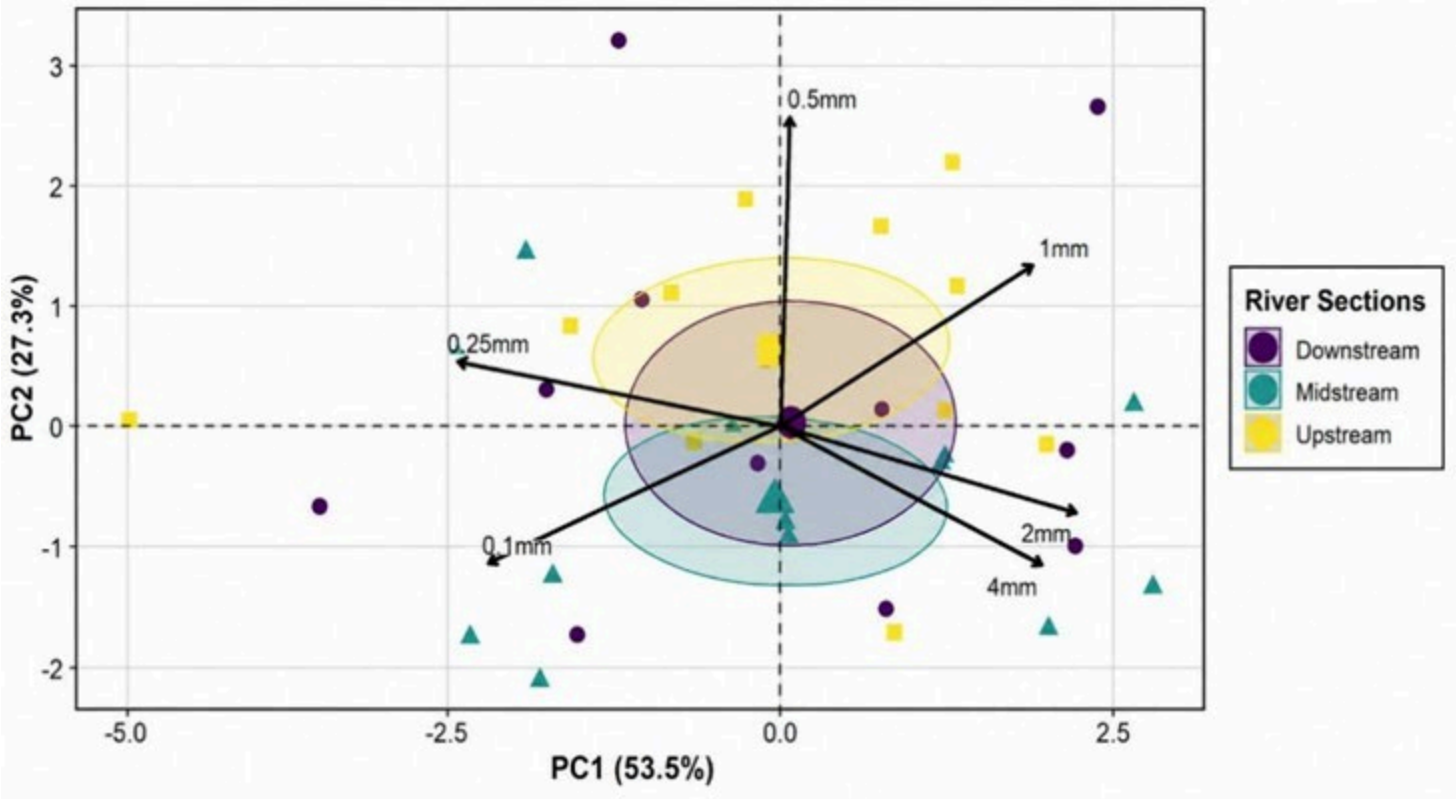


Figure 4

Loading graphs

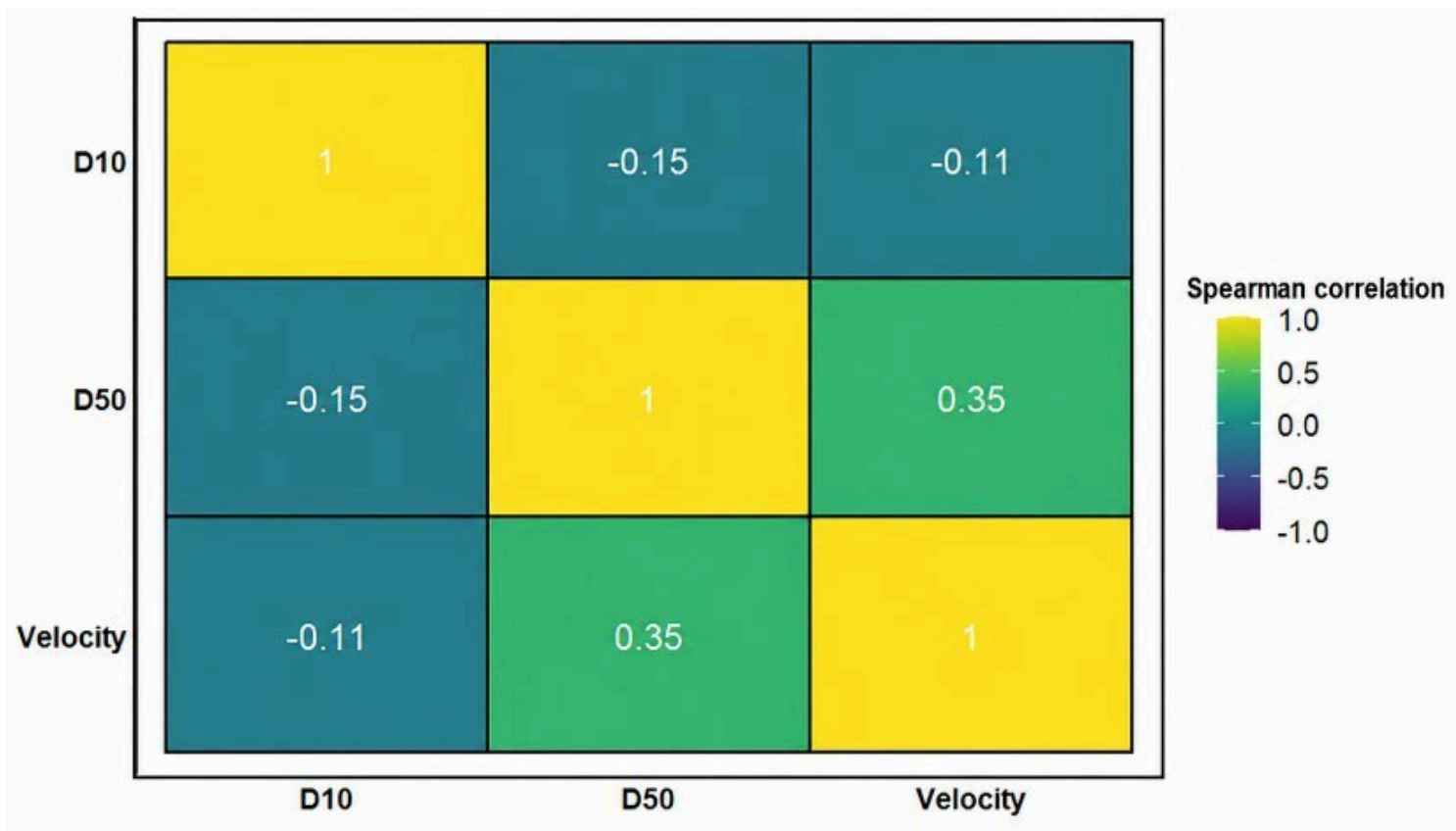


Figure 5

Spearman Matrix: Sediment Grain Size and Velocity

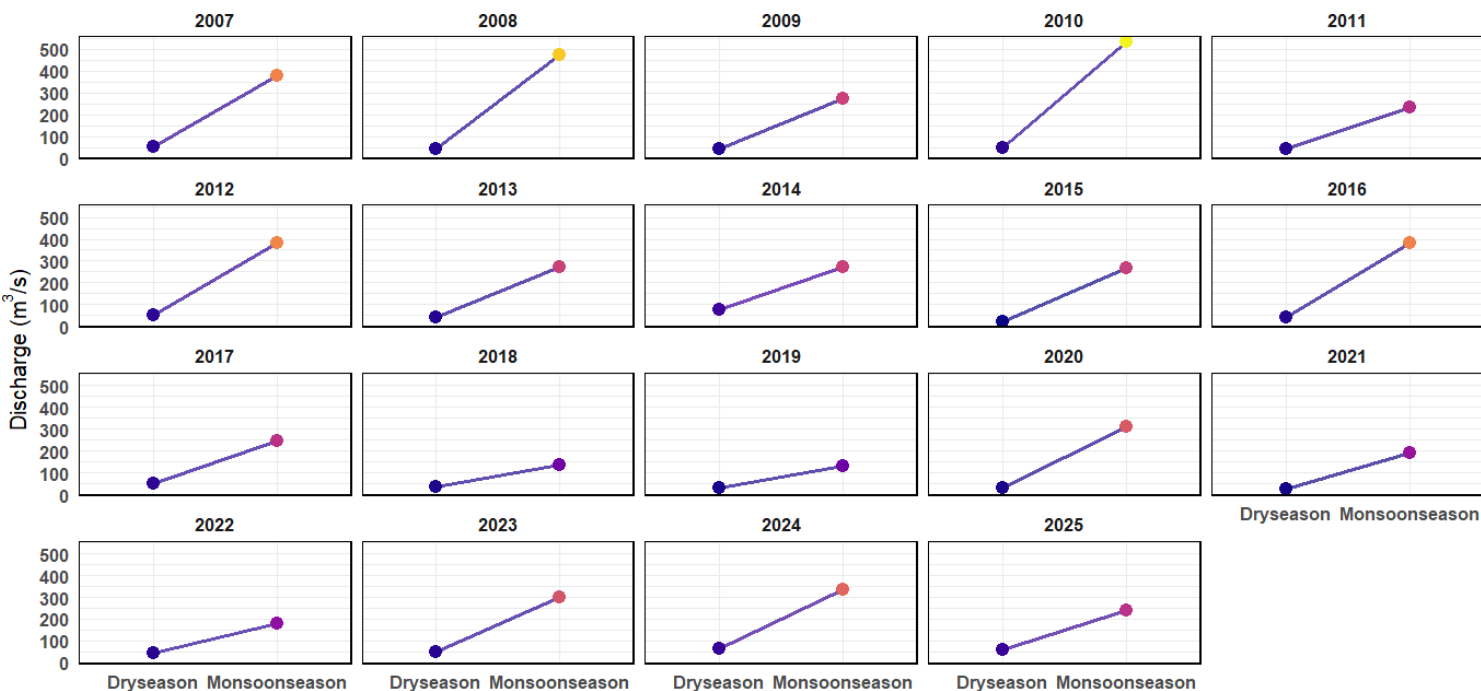


Figure 6

Dry vs Monsoon Discharge (Faceted by Year)

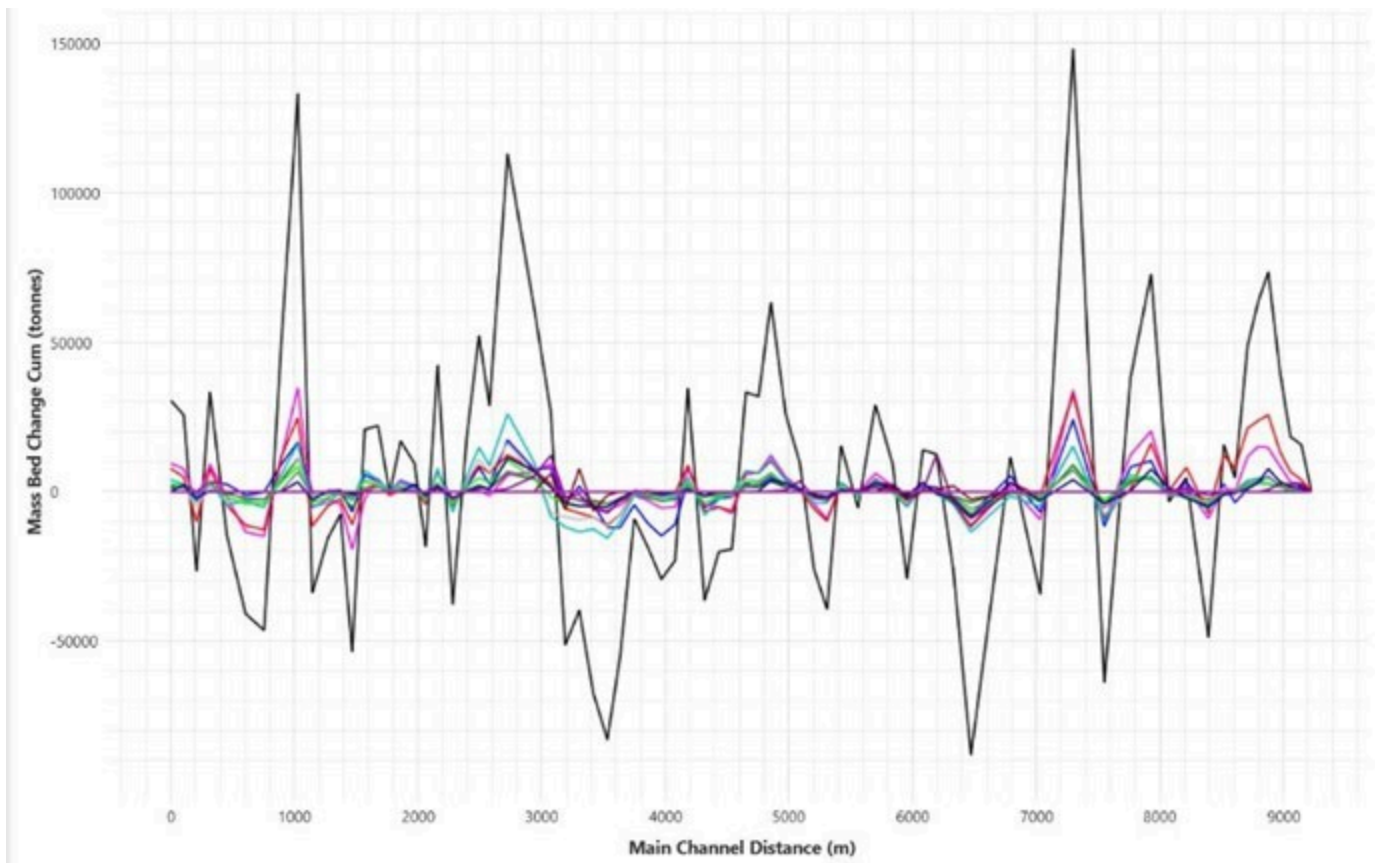


Figure 7

Instantaneous mass change along the channel showing erosion–deposition fluctuations

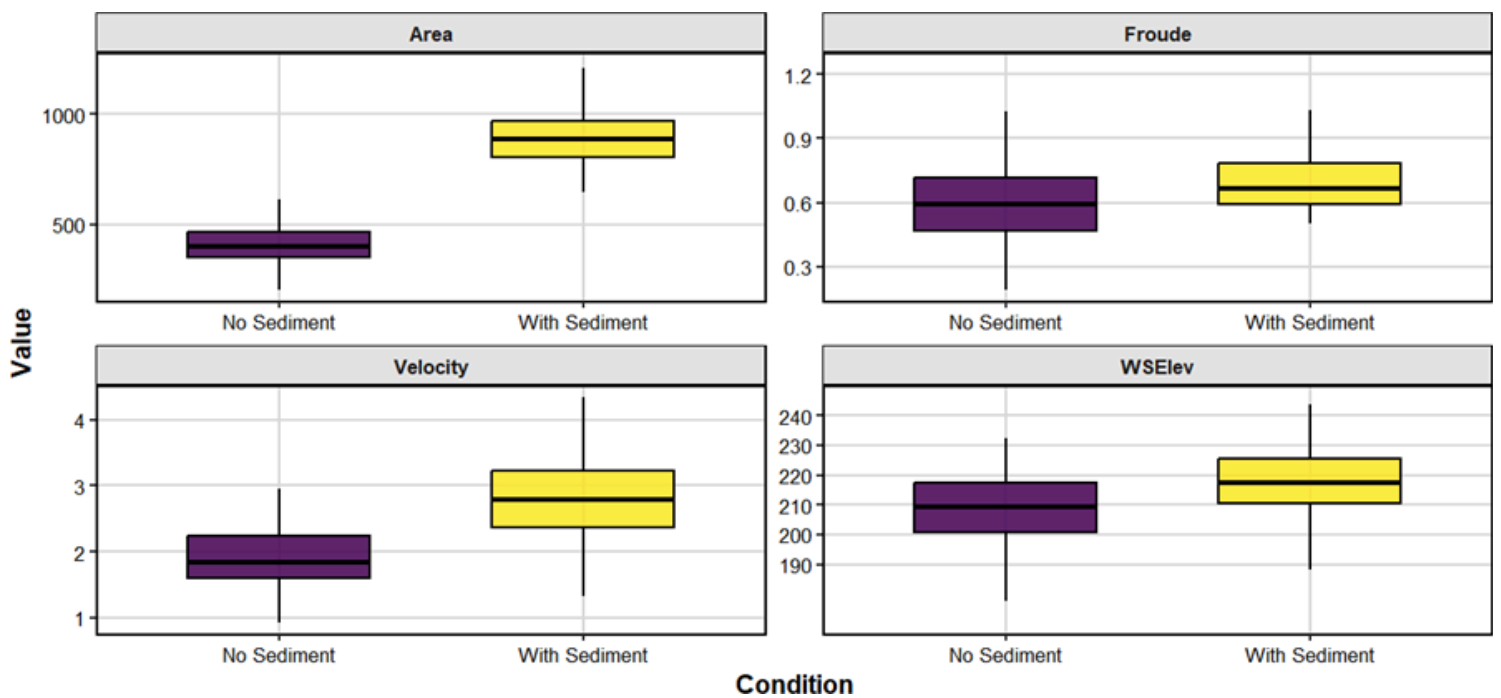


Figure 8

Impact of Sediment on Hydraulic Parameters

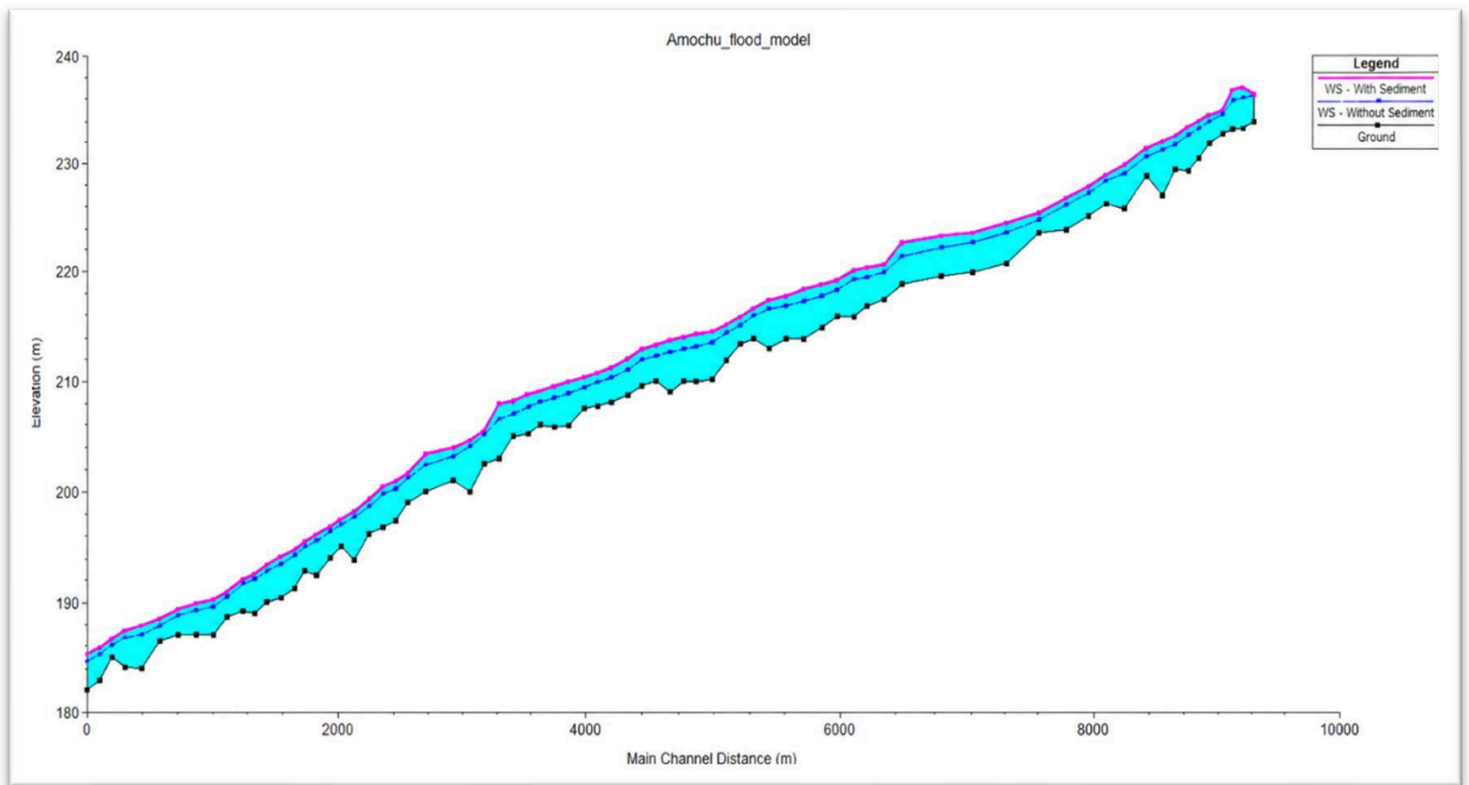


Figure 9

Water Profile Difference with and without Sediment