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River Bank Instability Detection and Monitoring Assessment

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Abstract

One principal cause of river bank collapse is the removal of more sediment from stream banks than the system can replenish. This study aims to assess the river bank erosion rate and erosion monitoring assessment for about 3 km of the Shelie River. The primary data (more than 20 river banks and 20 bed materials, as well as 104 river cross-sections) were collected using standard surveying equipment. Sieve and hydrometer analyses were implemented. Secondary (metrological) data were collected from an Ethiopian national metrological agency. The HEC-RAS model was used to compute the water surface profile and discharge-stage analysis. Additionally, the BSTEM model was used to depict the river bank migration rate and its stability analysis. BSTEM model result showed that left river banks are retreating laterally on average 0.012 m/hr for the considered reach, and the overall safety factor is greater than unity. Further, steady state flow simulation results confirmed that the conveyance capacity of the considered reach is not enough to carry a 50-year return period design discharge, and flood inundation raises a maximum of 1.2 m above normal flood level and extends 20 m laterally.

1. Introduction

River bank erosion is a natural phenomenon in stable rivers (Hasan et al., 2024). It is one of the most unpredictable and critical types of disasters that leads to loss of land, agricultural resources, settlement areas, communication, and forest (Mondal & Tripathy, 2020). Alluvial rivers in nature adjust their slope, plan form, and pattern to recover their former quasi-equilibrium (Alam & Singh, 2021). The lateral migration rate of river banks is related to rainfall quantity, soil structure, permeability, river meanders, river topography, and flood magnitude (J. Hasan et al., 2024). Flooding and landslide events in urban contexts worldwide have prompted further study and risk management (Yan et al., 2025). In recent years, rivers have undergone accelerated bank migration driven by both external factors and natural processes. Environmental degradation and disasters are widespread problems in Africa, driven by extreme floods and landslides (Hasan et al., 2024). In Ethiopia, more than 70 -90% of sediment comes from river bank erosions that lead to river bank mass failure (Hasan et al., 2024). In Woldia Town, people living along Shelie stream lose their properties, settlement areas, infrastructure, riparian, and agricultural lands due to lateral river bank migration and bank failure, land degradation, and flooding problems in the summer seasons. Every summer season, more than 350 people are affected by the Shellie river bank slide and flooding problems. Communities living along the Shelie River are still facing flooding and river bank sliding problems. Hence, understanding current, past, and future morphological trends and river dynamic changes is key to restoring damaged

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channels, managing rivers, monitoring human activity, and implementing sustainable mitigation measures. From the findings of the study, both structural and non-structural

Mitigation measures have been identified to address the severe riverbank erosion problem. Therefore, this study serves as an indispensable model for similar areas using HEC-RAS and BSTEM models to predict river bank migration rates and bank check stability.

2. Materials and Methods

2.1. Study Area

Shelie River rises from the Woldia University pond, flows northward, and debouches into Tikur Wuha at an elevation of 1726 m amsl. The catchment area covers 13.14 km2 and extends from an altitude of 1988 m to 1726 m amsl. The average annual maximum temperature in the Town is 27.48 0C while the minimum falls to 15.3 0C in December. The catchment is characterized by broad, very steep floodplains, old bench-forming terraces, and low- to high-relief basaltic hills with steep to flat slopes. In the lower reach of the river, especially around Gubalafto-enchet Tera, the channel has a very flat slope and discharges with a slow sediment load, leading to sediment deposition and bank overflow. The upper catchment is characterized by mountainous wedge-shaped and steep slopes

greater than 3.4 %), and the lower reach near the outlet is characterized by a flat slope less than 0.25%) due to excessive river bank migration and channel deposition. It has a high rainy season from June to 104.72 mm a mean annual rainfall of 104.72 mm recorded at Woldia meteorological station. In rainy months, the maximum temperature falls below 22 0C, the wind speed is 1.2 m/s, and the sunshine hours are 4.2 Hr. In contrast, during dry months, relative humidity is lower, reaching about 80% in the rainy months. It is located 521 km north of Ethiopia's capital city (Addis Ababa) and 360 km from the regional city (Bahir Dar).

2.1.1. Shielding Stream Banks from Erosion

The lack of comprehensive geotechnical and hydraulic protection measures leads to stream bank erosion and instability (Mondal & Tripathy, 2020). So, shielding stream banks from erosion is essential for maintaining river morphology change, preventing land degradation and preventing ecosystem damage along the channel (Ya net al., 2025). River bank erosion and instability may cause soil loss, upper-reach scouring, and channel sedimentation, destabilizing stream banks and harming fish habitats (Alam & Singh, 2021). Implementing strategies such as planting native vegetation and constructing retaining walls can effectively reduce the negative impact of water flow on the stream bed and banks. In addition, hydraulic protection measures are used to reduce the available boundary shear stress and increase shear resistance to particle detachment, thereby protecting the river bank from erosion (Sholtes & April, 2013). Toe armoring, vegetation, fiber chines, and bank face armoring, such as mattresses, vertical bundles, and geotextile protections, can improve bank stability and reduce toe erosion. (Mondal & Tripathy, 2020). These measures not only protect the land but also enhance biodiversity by providing habitats for various wildlife (Fubelli et al., 2013). By prioritizing the stabilization of stream banks,

Communities can safeguard their natural resources and promote a healthier environment for future generations. In the lower Shelie River reach, riparian vegetation, especially on the right river bank, is entirely out of shielding due to natural and external interventions (Fubelli et al., 2013).

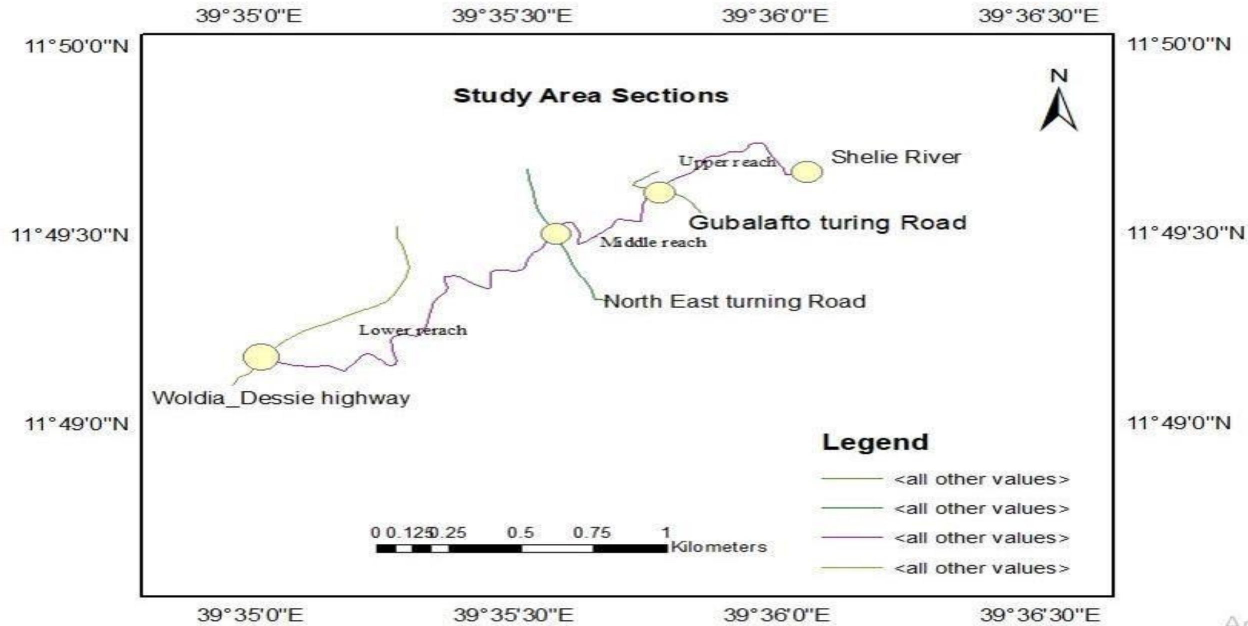


Figure 1. Study reach classification.

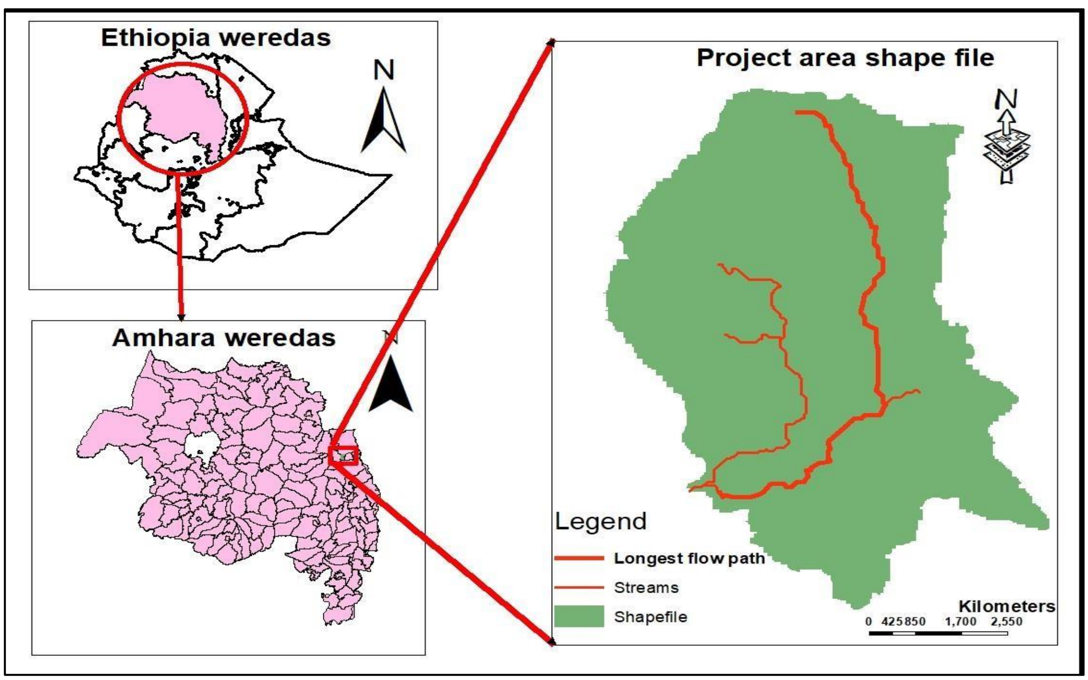


Figure 2. Study area.

2.2. Impacts of soil permeability on river morphology change

In alluvial rivers, flowing water can move materials when flow conditions exceed critical thresholds (Hekal, 2018). Soil permeability is the process of relating soil type to its permeability. It is one of the main influential factors that lead to altered stream morphology changes (Arora, 2003). It determines how easily water can infiltrate the river bank and causes mass failures. High soil permeability allows rapid water movement through the soil, reducing erosion and promoting sediment deposition along river banks. Conversely, low permeability can lead to increased surface runoff, resulting in higher river bank and bed erosion rates and significant changes in the river's channel shape (Srinivas et al., 2007). Understanding the relationship between soil permeability and morphological changes is vital for managing bank erosion and instability and predicting changes in river systems driven by natural events or anthropogenic activities.

2.3. Stream bed load and bank erosion dynamics

The rivers readjust by aggrading at one location and degrading at the other to maintain their equilibrium (Wynn et al., 2004). This aggradation and degradation process causes changes in the river course, flooding of nearby areas, and damage to hydraulic structures. Specifically; River bed erosion and bank instabilities are closely interrelated processes that significantly affect river habitats and their surrounding environments (Yan et al., 2025). Bed load materials are moved along the bed by the drag force between the fluid and individual particles. River bed erosion occurs when sediment at the bottom of a river is removed by the flow of water, which rolls, slides, and jumps it (Koehnken, 2018). This erosion can lead to channel scouring, deeper channels, altered river flow, and impacts on aquatic habitats (Knox & Latrubesse, 2016). As material is removed from the stream bed, it can destabilize the banks, making them more prone to collapse or failure (Kayyun & Dagher, 2018). Conversely, stream bank instability can further contribute to sediment supply to stream flow and cause lower-reach sediment deposition. This excess sediment can cloud the water, affecting fish and other aquatic organisms, and can cause flooding problems in the surrounding area (Simon et al., 2011).

2.4. HEC-RAS Model

HEC-RAS can compute networks of natural and man-made water surface profiles using 1D steady flow and the energy equation (equation 2) with an iterative procedure from one cross-section to the next (Joshi et al., 2019). Water-surface profile computation using various recurrence discharges is important for determining the maximum flood level at the reach before the construction of any hydraulic structures. HECRAS is the simplest, but the whole hydraulic model hypothesis using the energy equation is written as follows.

$$\mathbf{Z1} + \mathbf{Y1} + \boldsymbol{\alpha}1\,\frac{V1^2}{\mathbf{2g}} = \mathbf{Z2} + \mathbf{Y2} + \boldsymbol{\alpha}2\,\frac{\boldsymbol{V2^2}}{\mathbf{2g}} + \boldsymbol{he} \qquad (2)$$

Where Z1, Z2, and the bed elevation of the channel at sections 1 and 2, respectively (m), and Y1, Y2, and the water depth (m) at sections 1 and 2, respectively. V1 and V2 average velocity (m/s) at sections 1 and 2, respectively. α1, α2, velocity weighting coefficient at sections 1 and 2, energy head loss between section 1&2 (m), g, gravitational acceleration (m/s^2) comprises frictional loss and contraction/expansion losses.

In HEC–RAS model simulations, the roughness coefficient is a key hydraulic input parameter that varies with the physical characteristics of the channel, such as surface roughness, vegetation, channel plan form, and bank and bed materials (Chow, 1959). Therefore, n values for each segment -the main channel and the left and right floodplains of the study reaches - were estimated using Equation 1.

$$N = (n_0+n_1+n_2+n_3+n_4)\, m_5 \qquad (1)$$

where,
n_0: value due to river bed materials
n_1: value due to channel surface irregularities.
n_2: value for variation in shape and size of the channel cross-sections.
n_3: value for obstructions.
n_4: value for vegetation and flow conditions.
m_5, correction factor for meandering of a channel.
$n = 0.047 d_{50}^{1/6}$ (d_{50} in m); from the study geotechnical sample lab result, the average bed particle size of the study reach was, d_{50} = 0.047mm

2.5. Bank stability and toe erosion model

In recent years, BSTEM has been used iteratively to simulate the hydraulic erosion of the river toe and its stability during a series of flow events (Simon et al., 2011). This is the purpose of evaluating existing and potential change, failure frequency, and stream bank-derived sediment loads. Stream bank erosion is that part of channel erosion in which material is eroded from the stream bank and deposited at the base of the slope or channel (Lumpur, 2010). This bank-erosion and stability sub-model was selected to determine bank-stability and toe-erosion models based on stream characteristics such as reach meander, shear resistance, and channel width. The data required to run the BSTEM model are used to quantify driving and resisting forces that control hydraulic and geotechnical processes. These data are entered in separate worksheets (geometry data, material type, soil properties, bank vegetation cover, and bank erosion protection along the channel). The model supports up to 5 user-defined layers (Knox & Latrubesse, 2016). It is used to calculate the ratio of resisting force to driving force for multilayer stream banks. The resisting forces can be defined by the Mohr-Coulomb equation that describes the shear strength of saturated soil (Arora, 2003). The current version combines three limit equilibrium as horizontal layers, vertical slices with tension crack, and cantilever failures that calculate the factor of safety (Fs) for multilayer stream banks (U.S Army Corps of Engineers, 2016). The basic equations associated with the BSTEM model are listed below from equation 3:

$$Tf = c' + (\mu w) \tan\phi \quad (3)$$

Where: τf, shear stress at failure (kpa), c' effective cohesion (kpa), normal stress (kpa), μw, Pore Water pressure (kpa), and ϕ, effective angle of internal friction (degrees). However, negative pore-water pressure increases bank strength and soil weight (which is the driving/destabilizing force on the sloping soil mass, as given by Arora (2003).

$$Sd = W \sin \beta \quad (4)$$

Where Sd is the driving stress (kPa), W is the weight of the failure block per unit area of the failure plane (KN/m2), and β is the failure-plane angle in degrees. Therefore, from the above two equations the ratio of resisting to driving force gives bank stability factor of safety.

$$Fs = \frac{Resisting\ Forces}{Driving\ Forces} = \frac{c' + (\sigma - \mu w) \tan\phi y}{W \sin\beta} \quad (5)$$

If FS is less than 1, the bank is unstable; if it is between 1 and 1.3, the bank is conditionally stable. The relation between applied shear stress and the erodibility factor (k) is used to calculate the critical shear stress.

2.6. Data Formatting and Preparation

Primary and secondary data were collected through field surveys and the national meteorological agency. The study was limited to using ArcGIS, HEC-RAS, and the BSTEM model to quantify riverbank erosion rates and the influence of riverbank stability on river lateral migration. Separately, the BSTEM tool was used to show the bank and toe erosion rate and its stability.

2.7. Peak Discharge Determination

Shelie River is an ungauged river with a 13.14 km² watershed area located in North Wollo, in the Awash basin. For this study, more than 29 years of daily rainfall data were collected from the Ethiopian National Meteorological Office at Woldia Meteorological Station (near Woldia Town), covering the period from 1993 to 2022. Any absence of missing data was filled using the transposing weighted factor method for a given maximum daily rainfall data. Various point rainfall manipulation methods, like data quality and data consistency tests, mean annual, bank full, and design discharge computation, were done. For probable design flood computation, five different recurrence intervals of the study reach were used. To manipulate point rainfall, lognormal, log person, normal, Gumbel (I) and Gumbel (IV) methods were used as per needed. There are various methods to compute catchment runoff for ungauged streams. However complex, the hydrograph method is the most accurate for computing probable peak design discharge for ungauged streams. For this study, the complex hydrograph method is used to compute the incoming flood from the catchment. As shown in Fig. 3 below, the maximum incoming flood for a 50-year return period is 53.9 m^3/s; this is the design discharge of this study. The other corresponding result between the recurrence interval and probable peak discharge is located on the hydrograph below.

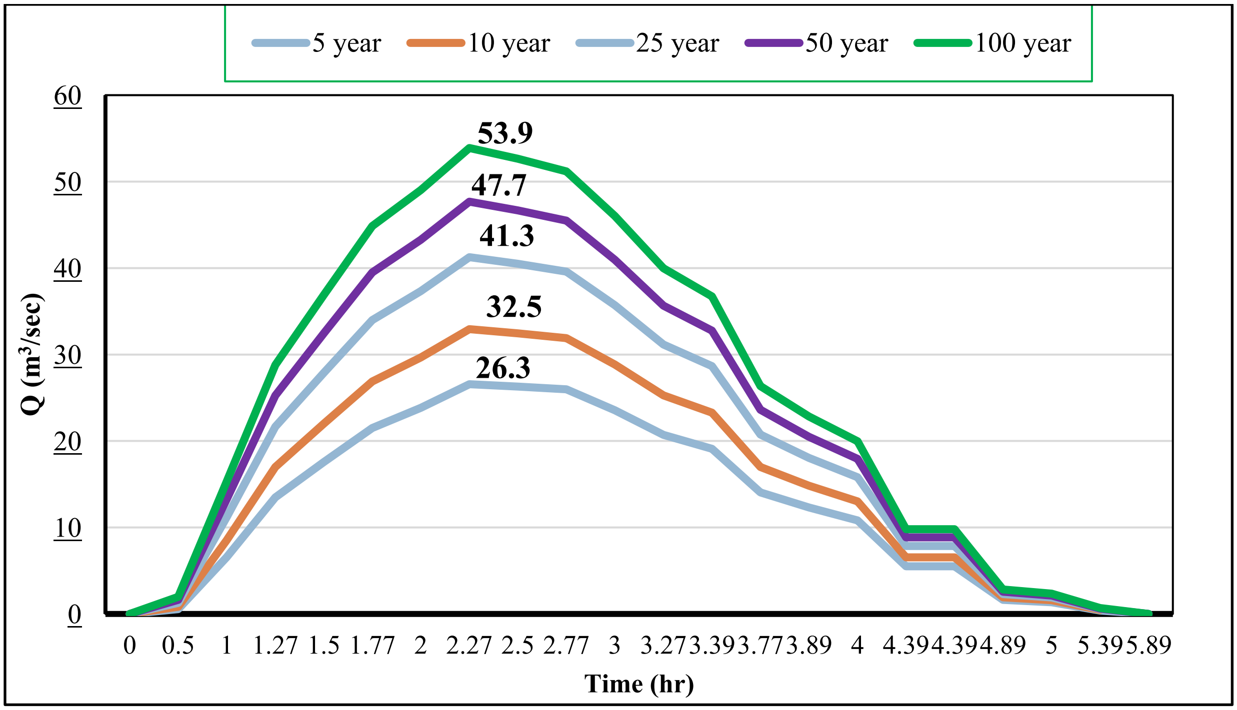


Figure 3. Complex hydrograph for five recurrence periods

2.8. River Cross-sections Collection

River cross-section data should be collected where discharge, slope, shape, roughness, and levees begin and end (Lumpur, 2010). As a rule of thumb, surveyed data was collected as a reference point on the left side of the river, with increasing elevation towards the right looking downstream, and the elevation of that point in meters. In the study, more than 104 river cross-section surveys were collected using standard equipment (total station, GPS) and laid out normal to the direction of flow at specified intervals measured along the center line of the main channel as shown (Fig. 4). The cross-section surveys were collected for a minimum of 20 m and a maximum of 30 m intervals between each cross-section for a 3 km reach length below.

Figure 4. River survey data collection March; 2024.

2.9. River Bank and Bed Material Templates

Rivers are constantly sorting their sediment loads. Hence, obtaining representative soil samples of riverbank and bed materials is difficult (Peixoto et al., 2009). To identify the grain size distribution of the study reach, the dominant soil type, sieve analysis, and hydrometric analysis method have been implemented in the laboratory. For the study, more than 40 soil samples for both bank and bed were collected from the upper, middle, and lower reaches for a 3 km reach length. Representative bed and bank samples were taken from the center, left, and proper channels and mixed (Figs. 5 & 6 below). Similarly, the representative bank materials were taken at the top, middle, and bottom and mixed. Both samples were collected in April 2024 and brought to the Woldia University soil laboratory, where sieving and hydrometric methods were used.

Figure. 5: Sample survey in April 2024

Figure 6. Sample survey in April 2024.

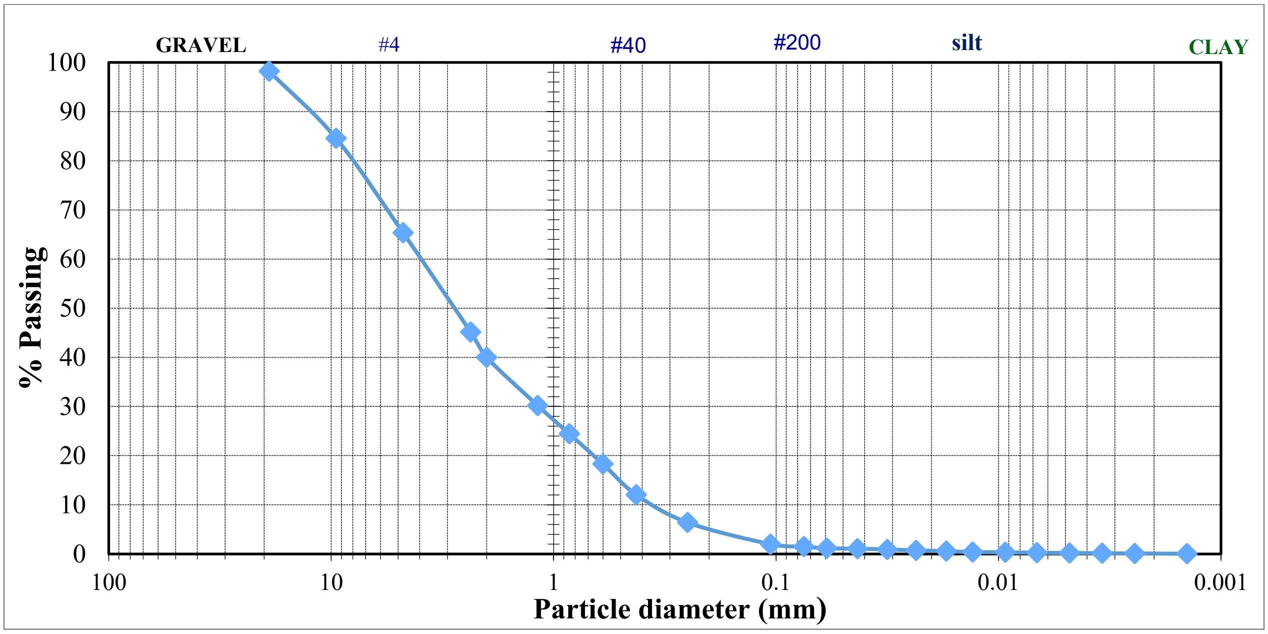


Figure 7. Grain Size distribution for the study reach

Table 1. Summary of primary and secondary input data and their sources

Data type	Period	Sources of data	Purpose
X-section	Apr-24	Field survey	Input for HEC-RAS and BSTEM model
Soil sample	Apr-24	Field survey	Input for HEC-RAS and BSTEM model
Metrological data	1993-20.	Metrological Agency.	To compute the design flood

3. Results and Discussion

3.1. Model Calibration for Manning Roughness (n)

The model calibration and validation were performed using recorded flow data from 2005 to 2014. To calibrate the model, maximum monthly flow data (Table 2) were compared with model-predicted discharges using the HEC-RAS model over a 10-year simulation period. From the best-fitting power-law equation (6), the study's rating curve was generally described by a power law, with a coefficient of determination (R^2) of 0.93.

$$H = 0.137Qw^{0.494} \quad (6)$$

Where: H: water surface elevation in for measured discharge (m): measured discharge in (m^3/s)

Table2. Measured stage-discharge validation.

Date of sampling	Measured discharge (m^3/s)	Simulated discharge (m^3/s)	Stage (m)
20Aug	0.4930	0.476	0.99
23May	7.2820	9.896	0.22
5-Sep	19.867	14.45	2.40
7-Sep	21.381	17.227	2.74
1-Aug	22.814	19.840	2.90

9-Aug	24.057	23.868	4.70

Similarly, the accuracy (validation) of the model can be quantified using root-mean-square error (RMSE) values. A lower RMSE indicates less residual variance and better model performance (Dewedar et al., 2019). For validation purposes in the study (2005-2014), the maximum monthly recorded flow was used. For the RMSE computation, the roughness coefficients were estimated (0.0361) for the main channel and 0.046 for both left and right banks, with a minimum RMSE value (0.507).

3.2. Steady Flow Result and Analysis

Water-surface profile computation for different return-period discharges is important for determining the maximum flood level reached before the construction of any hydraulic structures. According to the study's model simulation results, the reach for 5-, 10-, and 50-year return period discharges can be conveyed without bank overflow at all stations, except for some trenching sections. However, as shown in the results (Figs. 8 and 9 below), the flood rises from 0.5 to 1.2 m for the 100-year return period design discharge. According to the model results, the right reach can accommodate the incoming flood with overtopping because the terrain is situated at a relatively higher elevation on the right side of the floodplain. Overflooding on the left reach will affect the extent of the 100 m channel width with adjoining gently sloped land. In the upper reach, the flow depth is at a minimum due to the steep channel slope and deep bank depth. However, in the lower reach, flooding is more serious than in the upper reach due to lower flow velocity and a flatter channel slope.

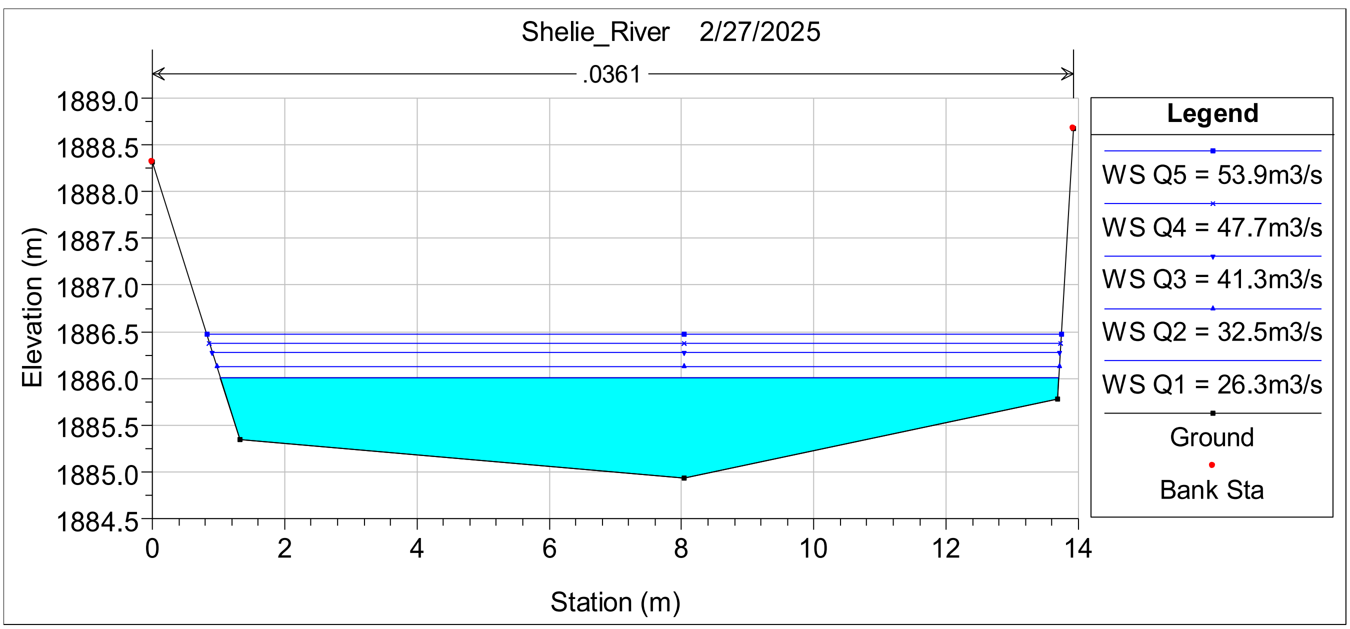


Figure 8. Plot of inundation cross-sections at station 5.

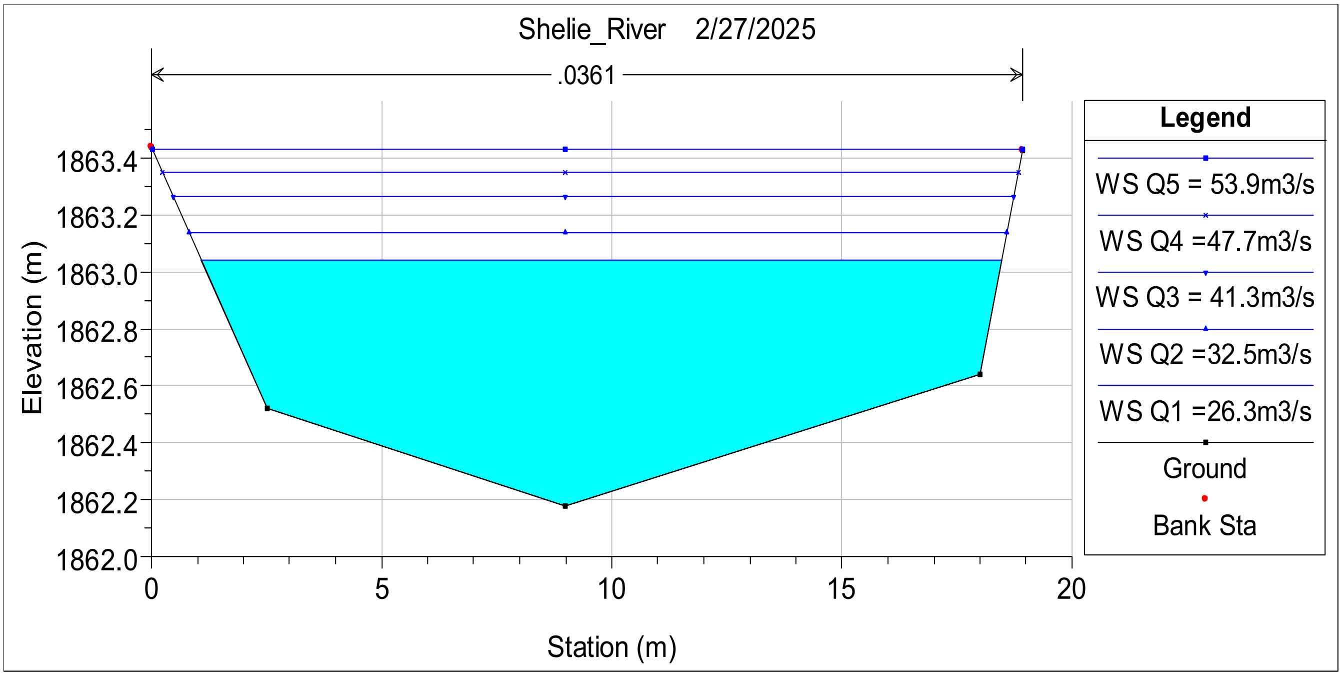


Figure 9. Plot of inundation cross-sections at station 20.

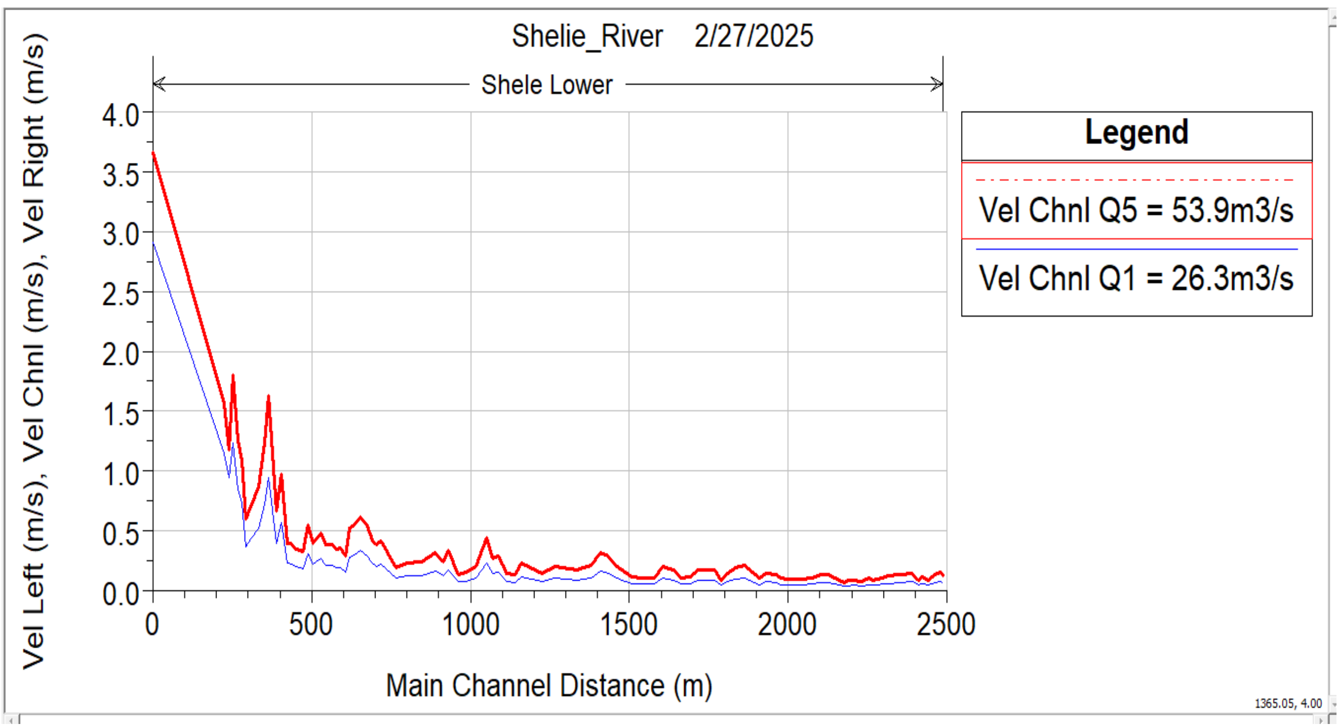


Figure 10. Plot of velocity profile for lower and higher discharge.

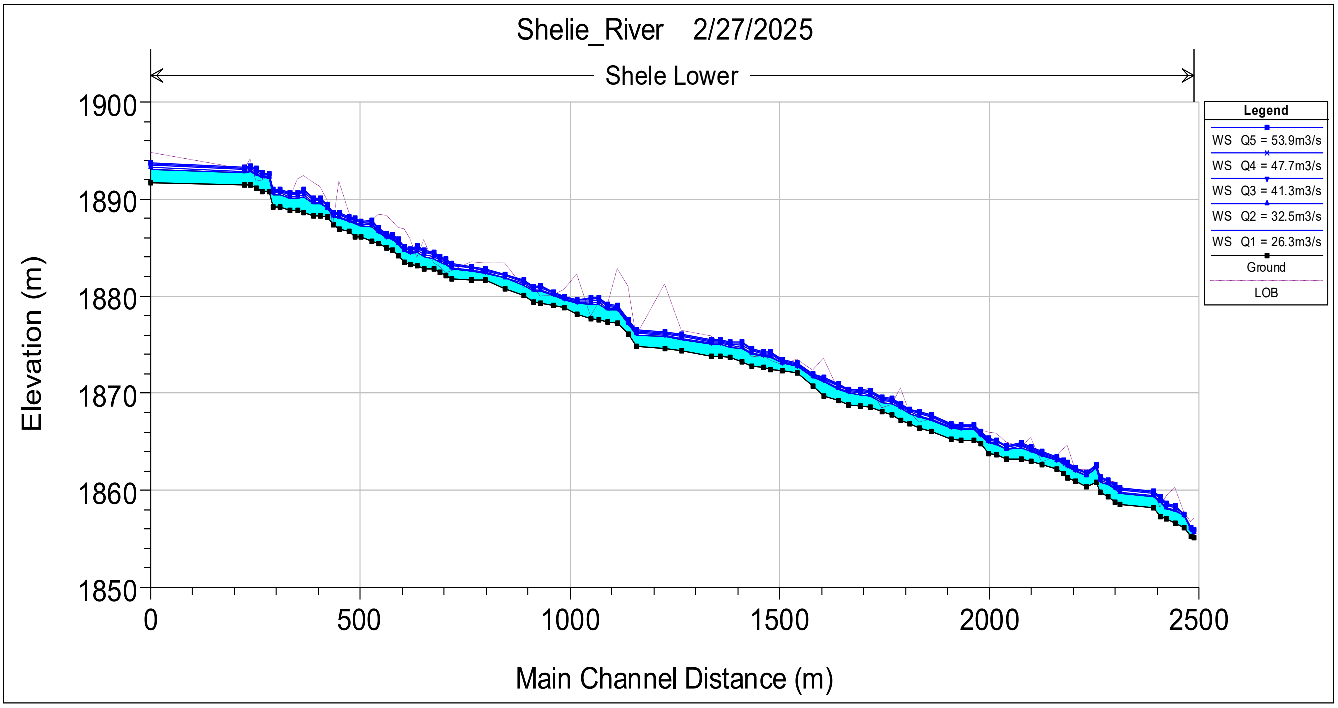


Figure 11. General water surface profile for 50-year return period discharge**.**

3.3. Rating Curve and Bank Full Discharge

The discharge-stage analysis is important for establishing and interpreting flood control structures and for understanding the channel characteristics at a particular station. It is important to determine the maximum flood level before constructing any hydraulic structures. These are various stream characteristics, such as cross-sectional area, channel slope, expansions and contractions, roughness coefficient, and vegetation cover, which are the main control factors for the discharge-stage relationship. From the study of the rating curve at chainage (0+00), the maximum bank full Discharge results (Fig. 12) are less than the probable design discharge. Contrary to the lower reach, it exceeds the probable design flood as shown, indicating a gentle slope and sediment deposition, and that the channel has inadequate capacity to overcome the incoming probable design flood, which is greater than the design flood. From the rating curves, the bank-full discharge capacity at three locations is 50 m^3/s at chainage (0+330) m, 54 m^3/s at chainage (0+620) m, and 54 m^3/s at chainage (1+790) m.

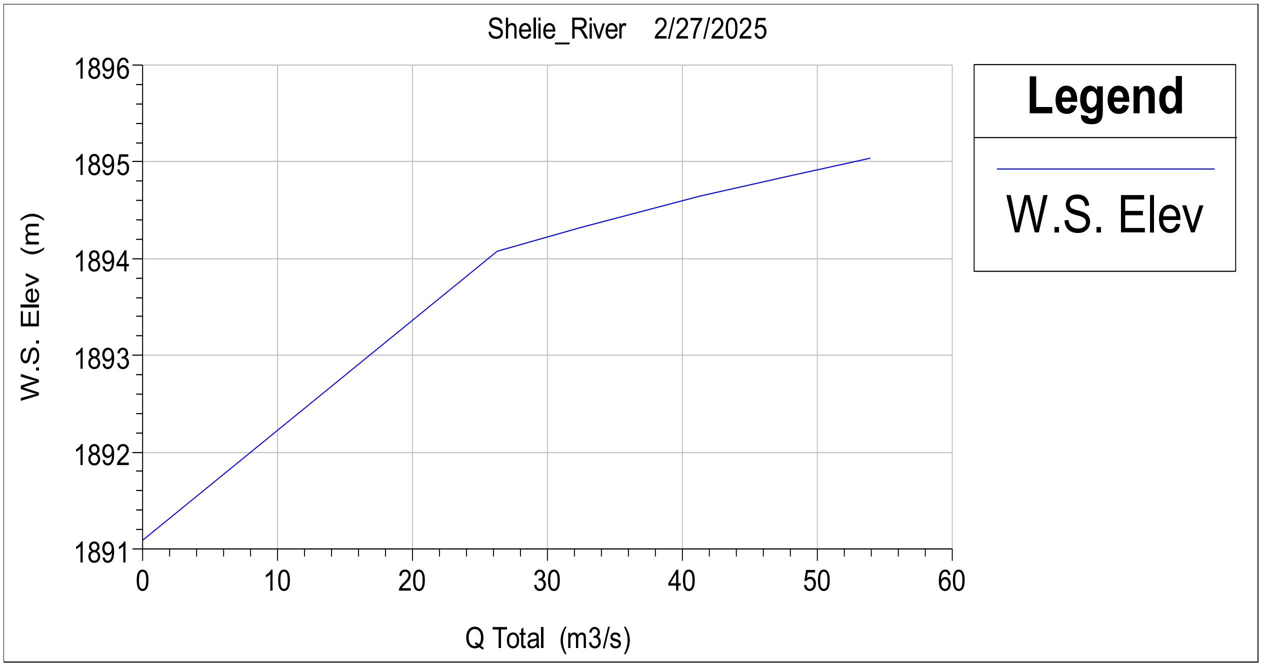


Figure 12. rating curve at chainage (0+00)

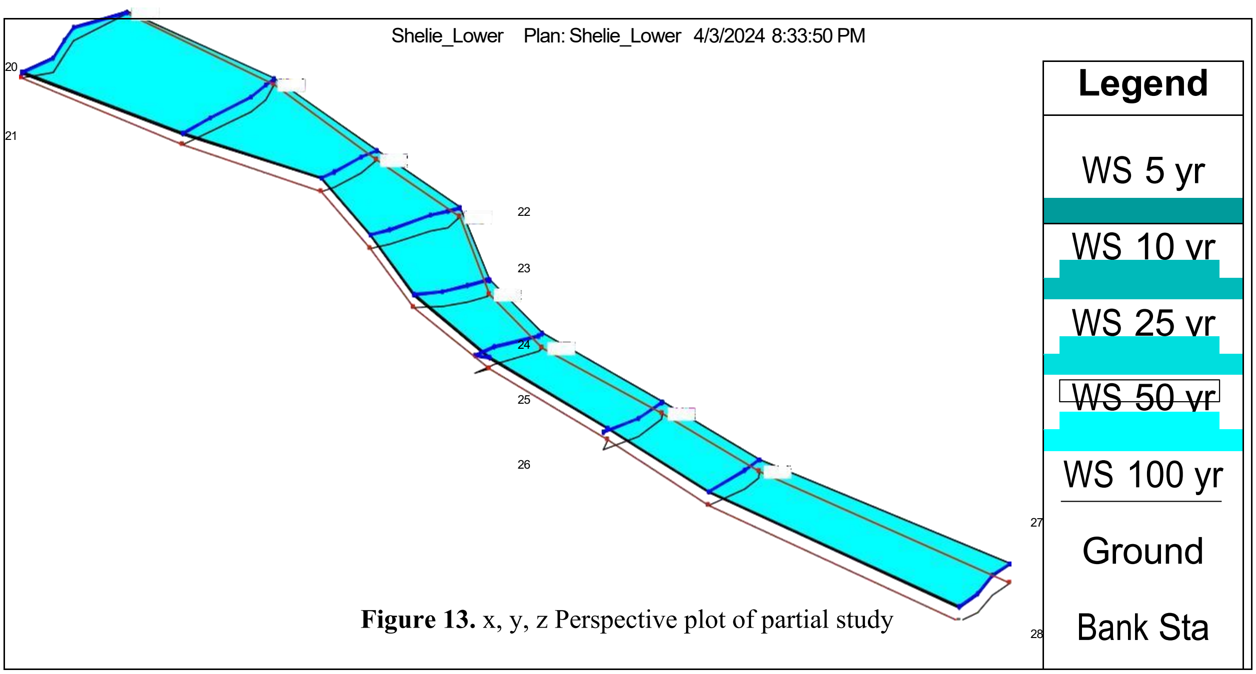
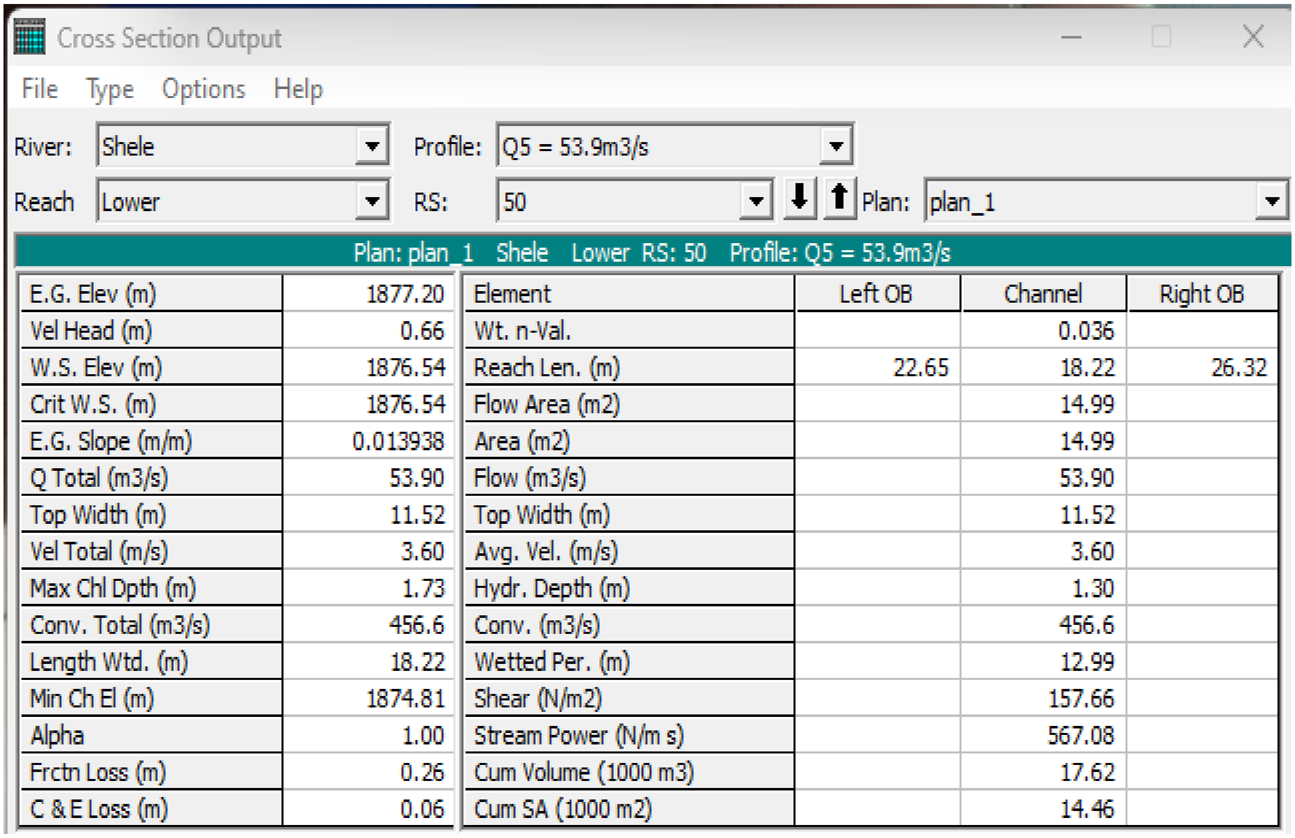


Figure 13. x, y, z Perspective plot of partial study

Table 3. General hydraulic properties.



E.G. Elev (m)	1877.20	Element	Left OB	Channel	Right OB
Vel Head (m)	0.66	Wt. n-Val.		0.036	
W.S. Elev (m)	1876.54	Reach Len. (m)	22.65	18.22	26.32
Crit W.S. (m)	1876.54	Flow Area (m2)		14.99	
E.G. Slope (m/m)	0.013938	Area (m2)		14.99	
Q Total (m3/s)	53.90	Flow (m3/s)		53.90	
Top Width (m)	11.52	Top Width (m)		11.52	
Vel Total (m/s)	3.60	Avg. Vel. (m/s)		3.60	
Max Chl Dpth (m)	1.73	Hydr. Depth (m)		1.30	
Conv. Total (m3/s)	456.6	Conv. (m3/s)		456.6	
Length Wtd. (m)	18.22	Wetted Per. (m)		12.99	
Min Ch El (m)	1874.81	Shear (N/m2)		157.66	
Alpha	1.00	Stream Power (N/m s)		567.08	
Frctn Loss (m)	0.26	Cum Volume (1000 m3)		17.62	
C & E Loss (m)	0.06	Cum SA (1000 m2)		14.46	

3.4. Comprehensive Analysis of the BSTEM Model Results

The riverbank erosion in alluvial streams occurs mainly due to hydraulic and geotechnical forces acting on the bed and bank surface. Most evidence shows that riverbanks are the dominant sources of sediment in river channels. Stream banks fail due to toe erosion by stream flow, bank undercutting, and the development of positive pore-water pressure. External interventions may destabilize stream banks. The model results showed that the stream bank lateral retreats at 1.18 cm/hr, 0.013 cm/hr, and 2.445 cm/hr in the upper, middle, and lower reaches, respectively. In addition, the upper and lower reaches are stable, with factors of safety of 4.41, 0.0, and 3.46, respectively. This stability is due to the strong geotechnical shear strength of bank material and density, and protective measures and adaptive management techniques are essential for predicting and responding to potential erosion events.

Riparian vegetation coverage along the reach. However, the middle and lower reaches are unstable, with a factor of safety less than unity, because the river system seeps through cracks in the soil, thereby wetting the stream bank materials and making them more prone to failure. As shown in Table 3 below, the total eroded area from the bank, bank toe, and bed was estimated to be 0.383 m², 2.644 m², and 2.448 m², respectively. The findings suggest. Overall, this analysis not only provides critical insights into the dynamics of river bank stability but also serves as a foundation for targeted interventions to preserve valuable river ecosystems and protect adjacent properties from erosion.

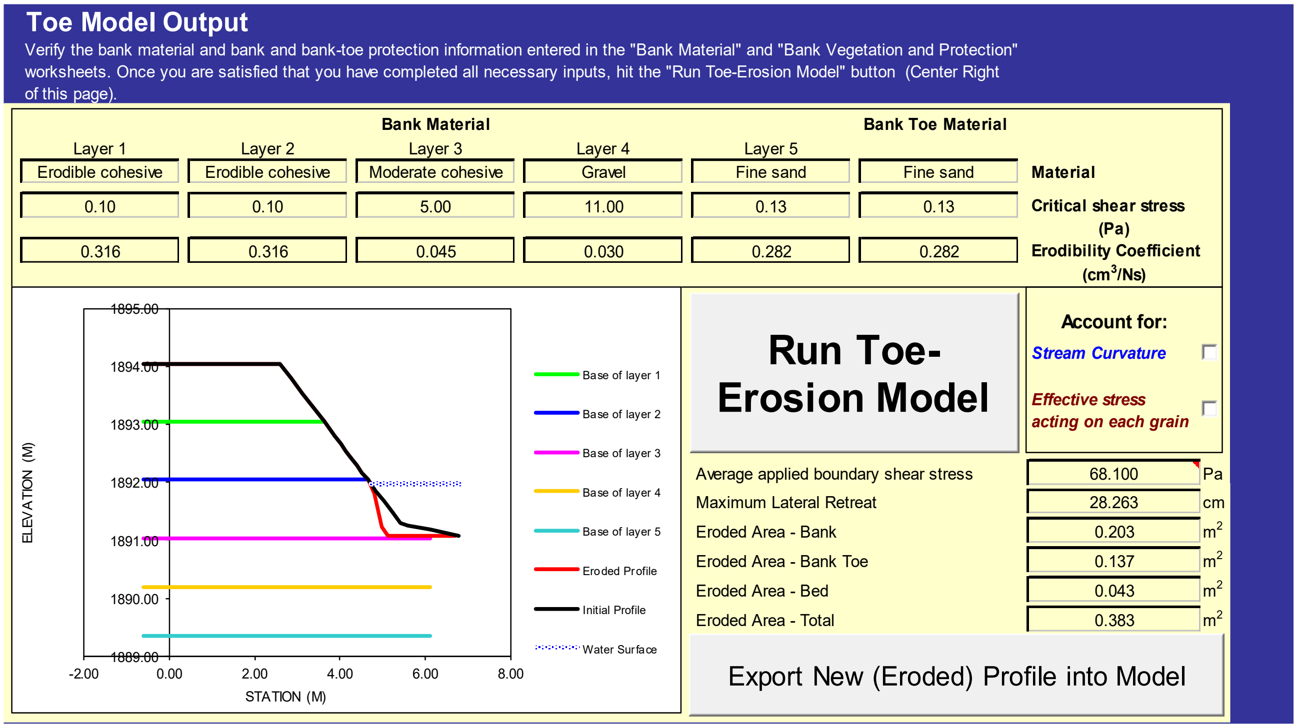


Figure 14. Toe erosion model.

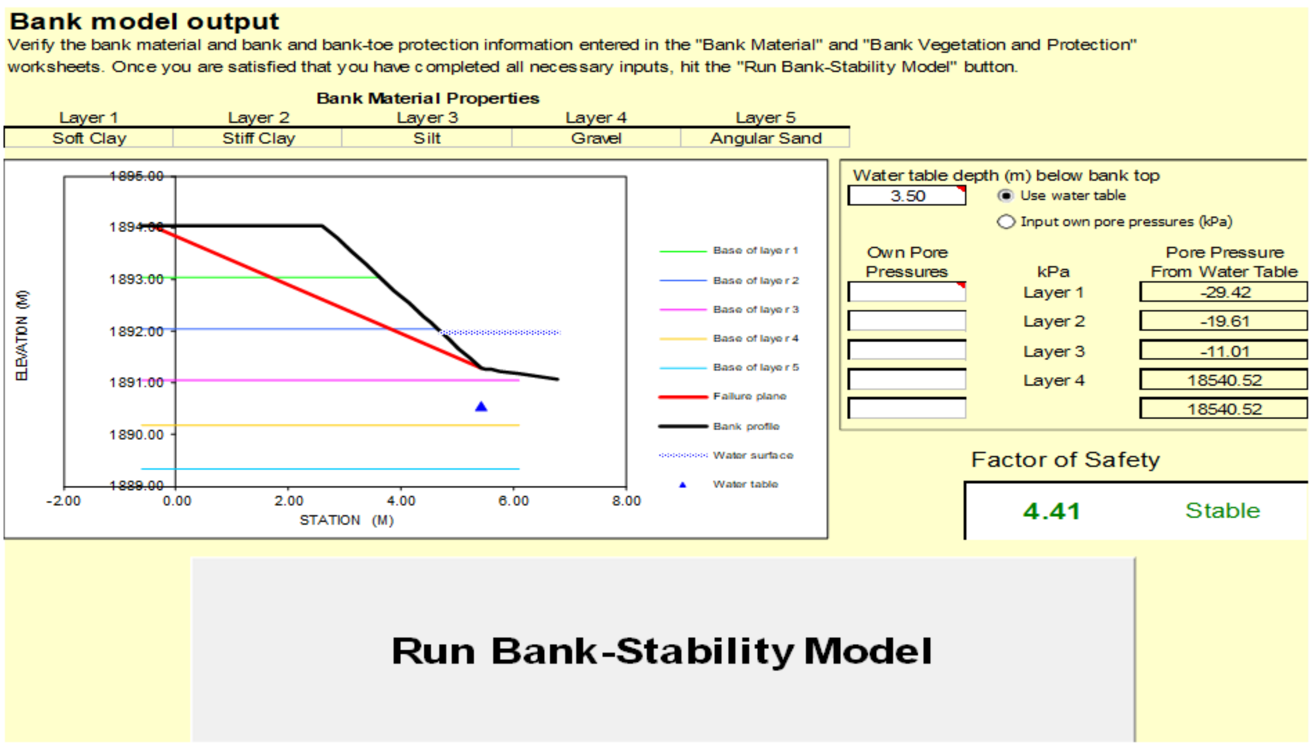


Figure 15. Stable stream bank of the upper reach.

Figure 16. Unconsolidated and non-cohesive bank materials at the lower reach.

Table 3. Summary of BSTEM model result.

Reach	Ma. Lateral retreat (m)	Bank Erode area (m^2)	Toe eroded Area (m^2)	Bed eroded area (m^2)	Factor of safety
Upper	0.28	0.203	0.137	0.043	4.41
Middl	0.319	1.626	0.95	0.067	0
Lowe	0.58	1.591	0.646	0.212	3.46

4. Conclusion

Bank erosion in alluvial rivers is mainly caused by weak hydraulic and geotechnical forces acting on bed and bank surfaces. These phenomena result in property damage along the river reach. The study investigates the detection and monitoring of river bank instability using HEC-RAS and BSTEM models in the lower reaches of the Shelie River. It primarily focuses on analyzing riverbank erosion, assessing bank stability, and predicting lateral bank migration rates. According to the model results, the upper, middle, and lower reaches had factors of safety of 4.41, 0.0, and 3.46, respectively. Naturally, the middle reach has shallow bank heights and channel slopes, a failed plane angle, and less vegetation coverage. This is the reason why the lower reach has a lower factor of safety than the upper reach. In addition, in the lower reaches, sand mining and trench excavation for irrigation are carried out for an extended period during the dry season. In addition, irrigation water and household liquid waste return to the Shelie River as seepage through cracks in the soil, thereby wetting the stream bank materials.

This could facilitate the stream banks instability and mass bank failures. As elderly people claim that flood risk and river bank collapse in the upper reaches are not as severe as those in the downstream reaches, this is due to the shallow channel depth, which allows water to escape and inundate its surroundings easily. Mostly, stream banks fail due to excessive toe erosion by streams, weak hydraulic and geotechnical forces, flow undercutting, bank sloughing, and the development of high water pressure. From soil lab studies, the dominant materials are fine sand and silt throughout the reach. These materials have less cohesive resistance and can be easily eroded by flowing water. External interventions such as sand mining, and discharge release from houses households, and vegetation clearance are the main factors that accelerated bank instability for the Shelie River.

For bank stability and toe erosion model calibration, analysis needs parameters such as stratigraphy, cohesion, angle of friction, and critical shear. Bed material type, flow depth, and longitudinal slopes are additional data collected from soil lab results and field work. For this study, default soil parameters were used as input for the BSTEM model. To avoid uncertainty, more representative soil samples with accurate geotechnical values should be used for long reach.

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Conflicts of Interest
The authors declare that there is no conflict of interest regarding the publication of this paper.

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