

Final Report

Hydrodynamic Modeling for Riverbank
Protection- A case Study for Bagribari Area
along Puthimari River

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SUMMARY OF THE PROJECT

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ABSTRACT

The present study developed a coupled hydrological–sediment transport–bank stability modeling framework to analyze the bank erosion processes along the Puthimari River near the Bagribari area in Assam. Bagribari is one of the most severely affected regions in the Puthimari basin in the Assam valley, experiencing recurrent flood and erosion hazards during almost every monsoon season. To simulate river discharge, the SWAT hydrological model was calibrated and validated, demonstrating satisfactory performance with Nash-Sutcliffe Efficiency (NSE) values of 0.74 and 0.77, and coefficient of determination (R^2) values of 0.75 and 0.79 for the calibration and validation periods, respectively. The SWAT-simulated discharge was then used as the upstream boundary condition in HEC-RAS, while the downstream boundary was defined using the normal depth approach. The river geometry for HEC-RAS was developed using a 12.5 m resolution ALOS Digital Elevation Model (DEM).

Field investigations were carried out to collect soil samples from various locations along both riverbanks. These samples were analyzed to determine their geotechnical properties, which were subsequently used to construct the sediment transport file in HEC-RAS. Flow and sediment load data derived from rating curves, along with sediment gradation for different flow conditions, were incorporated into the model. The Bank Stability and Toe Erosion Model (BSTEM), integrated within HEC-RAS, was employed to assess bank erosion alongside bed erosion, using the site-specific soil parameters and gradation data.

The model simulation was executed by integrating the geometry, flow, and sediment files into a comprehensive plan file. Results indicated low factor of safety (FoS) values for riverbanks, generally less than 1.5, during the initial years of simulation, highlighting high susceptibility to erosion. Although the FoS values showed marginal improvement over time, approaching the critical threshold of 1.5, the riverbanks remain at considerable risk and cannot be considered permanently stable against erosion. Geobag revetments, vegetation bank stabilization, construction of spurs, boulder toe pitching, construction of earthen embankments are some of the suggested measures for bank protection in the Bagribari area.

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CHAPTER 1 INTRODUCTION

1.1 General

Rivers warrant study for three main reasons: first, because of their existence in physical landscape and their significance for producing fluvial landforms; second, because of their importance in relation to many other geomorphologic processes in fluvial dominated landscapes; and third, because of their significance for human use. For these reasons, the drainage basin has been acknowledged as the fundamental geomorphic unit, in which the river is the main artery along which energy is available.

The effect of direct modification of river and their catchment areas by human beings can produce effects elsewhere along the course. It is therefore, necessary to measure the flow of the rivers. Understanding of how rivers have developed in the past and are developing and changing today is essential as a prerequisite to the appreciation of how rivers may change in the future- something that may be largely inspired by, and exceedingly relevant to the activities of human being. Rapid migration of channels or shifting of courses may cause the floodwaters to spill in unexpected areas and may alter the total area flooded by a particular discharge (Dunne, 1988). Similarly, when meanders grow, rivers are lengthened and the gradient is decreased (Schumm, 1985). These conditions in turn may cause the flood to rise (Jorgensen et al. 1994). Avulsion, which is common in rivers with erodible banks, can increase flood hazards by diverting floodwaters in areas, which were formerly above high flood level (Dunne, 1988). Several prominent earthquakes affected the tectonically active NE-Himalayan region of India in the recent past. The 1897 earthquake for instance, raised the riverbed by several meters and caused extensive flooding. A similar disturbance after the 1950 earthquake has led to an increase in flooding by raising the base level of the Brahmaputra and other tributaries and by creating temporary artificial dams across the flow path is clearly attributable. The rivers of the Indian subcontinent exhibit considerable variability in their forms, configuration and channel process in spite of the common monsoon climate. The Brahmaputra valley surrounded by numerous natural hazards such as earthquakes, landslides, heavy sediment load, and excessive rainfall with remarkable massive flood potential needs considerable researches into the morphologic and behavioral characteristics of the rivers. An understanding of the geomorphic, hydrologic and hydraulic processes controlling channel shape, size, gradient and plan-form of different rivers is a prerequisite to the better implementation of affective management

approaches. Undoubtedly, this requires an effort, involving meteorologists, hydrologists, fluvial geomorphologists, sedimentologists and engineers (Kale, 1998).

1.2 Streambank erosion

Bank erosion occurs when grains or assemblages of grains are removed from the bank face by the flow. Erosion consists of two distinct events: detachment; and entrainment. Sufficiently strong forces of lift and drag exerted on the bank by the flow may detach and entrain grains directly from the intact soil, but more commonly grains are loosened and even detached prior to entrainment by weakening and weathering under sub-aqueous or sub-aerial conditions. The nature of the processes responsible, and the form of grain or grain assemblage entrained, depends on the engineering properties of the bank material. Of particular importance is the presence or absence of cohesion. Stream bank erosion is a natural process that over time has resulted in the formation of the productive floodplains and alluvial terraces. Paradoxically, even stable river systems have some eroding banks. However, the rate at which erosion is occurring in stable systems is generally much slower and of a smaller scale than that which occurs in unstable systems. Events like flooding can trigger dramatic and sudden changes in rivers and streams. However, land use and stream management can also trigger erosion responses. Erosion can also be accelerated by factors such as, stream bed lowering, inundation of bank soils followed by rapid drops in flow after flooding, saturation of banks from off-stream sources, redirection and acceleration of flow around infrastructure, obstructions, debris or vegetation within the stream channel, removal or disturbance of protective vegetation from stream banks as a result of trees falling from banks or through poorly managed stock grazing, clearing or fire, bank soil characteristics such as poor drainage or seams of readily erodible material within the bank profile, wave action generated by wind or boat wash; excessive or inappropriate sand and gravel extraction and intense rainfall events.

The various mechanisms of stream bank erosion generally fall into two main groups, bank scour and mass failure. Bank Scour is the direct removal of bank materials by the physical action of flowing water and is often dominant in smaller streams and the upper reaches of larger streams and rivers. As flow speed increases, the erosive power of flowing water also increases and scour may occur. Increases in flow speed can be the result of natural and/or human induced processes. Undercutting of the bank toe is an obvious sign of scour processes. Effective strategies for combating scour are generally aimed at reducing flow speed through revegetation and in some cases through strategic bank or channel works. Mass failure describes the various mechanisms of bank erosion that result in sections of the bank sliding or toppling into the

stream. Mass failure is sometimes described as collapse or slumping. Bare and near-vertical banks or areas of slumped bank materials are obvious signs of these processes. The causes of these types of failures are often difficult to determine but can include natural and/or human factors.

1.3 The Puthimari River

Puthimari is one such north-bank tributary of the Brahmaputra that contributes a substantial amount of discharge and sediment to the mainstream. It is a transnational river flowing through Bhutan (32km) and Assam (80km) in northeast India. The river's source is at 3750m above mean sea level at Tethyan Himalaya in the Eastern Himalayan region in Bhutan, and the mouth is at the confluence with the Brahmaputra River in Assam, India. Before entering India, the Puthimari River is named Oontany river in Bhutan (IWAI 2015). With its two major tributaries, namely Nona and Baralia, this river system is characterised by different geomorphic features that include meanders, floodplains, river islands, etc. The river flows in a north-south direction, and in the downstream plain areas, the Brahmaputra flows in an east-west direction, forming wide floodplains in the Puthimari basin. With an average annual rainfall of 1600 mm and more intensified rainfall in the monsoon season, Puthimari experiences a large volume of discharge, resulting in heavy floods downstream (Taher 1975). The safety of those living along the Puthimari River is threatened by the river's frequent rise in water level, brought on by strong monsoon rains and the subsequent floods that inundate the floodplain. This situation can occasionally become considerably more severe due to embankment breaches. In this situation, the afflicted people have no choice but to temporarily take refuge on the streets and in the neighborhood to protect themselves from the wrath of the terrible Puthimari River (India Today NE 2023). The local community believes that the water level rise and subsequent flood in 2023 is worse than the previous year, and the likelihood of this worsening will increase if no effective preventive action is made to address the problem beforehand (India Today NE 2023). From one statistical analysis carried out by Devi (2022), the most severe flood in the basin occurred in 1988 in its recorded history followed by floods in the years 1993 and 2007. From a damage point of view, the 2004 flood was the most severe, where a number of villages were submerged and led to the loss of people and livestock. The heavy flood situation due to incessant rainfall, specifically in the monsoon season, still continues in this basin. It needs a proper scientific study so that appropriate protective measures can be implemented to prevent flood hazards.

1.3.1 The Bagribari area and its erosion problem

The Bagaribari area along the Puthimari River in the Tamulpur Division is particularly susceptible to frequent erosion. The adverse consequence of streambank erosion results not only in accelerated sediment yields, but also in changes in stream channel instability. Streambanks of alluvial channels are usually composed of loose materials, which are unsaturated in ambient conditions. Unsaturated soils are subjected to negative pore water pressures, which cause an apparent cohesion. According to the Water Resources Department, the river Puthimari has “an acute meandering nature in its journey through the alluvial plains and has a series of very sharp curves with reversed flow to the original channel” and “is very flashy, having heavy silt-loaded discharge during the monsoon period”. The flood problem of the Puthimari River basin has a chronic history. The flood of 1988 was found as the highest flood ever recorded in the Puthimari river basin, with a 5.02 m deviation from the danger level. The flood marked the highest water level and water discharge ever recorded in the flood history of the Puthimari River. This flood has been found 2nd largest from the hazard perspective also. In this flood, 388 numbers of villages were affected and the total population affected by the flood was 4.22 lakhs of the Puthimari river basin (Revenue Department, Govt of Assam). In the year 1988, the Puthimari River inundated a vast area in the Kamalpur Revenue circle due to a breach on the left bank. Heavy damage to the dykes and embankments occurred due to seepage, leakage, boiling, and overtopping in many areas (Master Plan, Brahmaputra Board, 1995). The second and third largest floods of the Puthimari River basin have been identified in the years of 1993 and 2007, with flows of 4.57 m and 4.13 m above the danger level. The flood of the year 2004 has been recorded as the highest from the damage perspectives of the Puthimari river basin.

1.4 The Bank Stability and Toe Erosion Model (BSTEM) in HEC-RAS

The USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) is also part of HEC-RAS. It simulates three fundamental erosion processes that change the shape of the channel and the stability of the banks. The first step is for the bank to tumble down. A geotechnical specialist needs to assess the structural stability of the riverbank. This component assesses how stable the slope is by looking at the balance between pushing forces (such the weight of the bank material and hydraulic pressures) and resisting forces (like the strength and cohesiveness of the soil). When the driving forces are greater than the resisting forces, the model depicts a predicted failure surface called the critical failure plane.

The second stage, toe scour, looks at the hydraulic erosion that occurs toward the bottom of the riverbed. This form of erosion happens because of shear stress distribution throughout the wetted perimeter, which is highest toward the toe of the bank. The material at the toe begins to break down when the shear stress is too high. This might make the slope weaker and make the top sections of the bank more prone to fall.

The next step, which is equally as crucial, is to change the channel bed. This process looks at how the riverbed changes in height due of problems with sediment movement. When there is more sediment than the capacity to transfer it, the bed becomes eroded or destroyed. On the other side, when the supply is higher than the transit capacity, deposition occurs, which increases the bed level. These variations in height affect how water flows, which has a chain reaction impact on the stability of the bank toe and the slope's collapse.

Over time, these three mechanisms operate together in different ways. For example, if the bed becomes worse, it can cause more toe scour, which might make the bank fall down. When banks collapse, they may also deposit a lot of silt into the channel, which can modify how sediment travels and settles downstream. When used with HEC-RAS, BSTEM shows you all you need to know about how riverbanks are eroding and changing form.

1.5 Relevance of the study undertaken

The river Puthimari has got the concern of many researchers due to its highly erosive nature on both the banks. The Bagribari region, which lies next to the Puthimari River, has major and persistent problems with bank erosion that put the infrastructure and the lives of the people who live there at great danger. Because the river winds through this region, the thalweg, or route of deepest flow, typically moves toward the outer bends, putting a lot of pressure on the fragile, unconsolidated alluvial banks. These banks don't have the root reinforcement they need to hold up to erosion because stabilizing riparian vegetation has been mostly cut down for farming and construction. As a result, they typically collapse during big slumps or mass wasting episodes, which move blocks of silt into the river channel. Frequently occurring unpredictable flash flood, heavy rainfall in the basin, flat gradient to drain out the high discharge of the river and heavy sediment load are few major causes of flood and erosion in the basin along with other tectonic activities. The adverse consequence of increased streambank erosion has led to changes in stream channel instability. These instabilities of consequential shifts produce higher sediment yields. As the source of the river lies in the Bhutan Himalaya, large amount of water and silt is carried by it particularly during the summer. The embankment

of Puthimari River was breached at Pub-Bogribari and Maregaon on 30th October, 2008 (The Assam Tribune, Guwahati, Monday). In the year 2019, heavy flood occurred in puthimari river basin. The village Bogribari village of Goreswar Revenue Circle of Baska District was totally submerged by the River. Heavy floods occurred in this area due to the rising water level of river puthimari and its tributary Sukla (Niyomiya Barta, 16th July, 2019). Again in 2020, the Puthimari river breached its embankment at Bogribari and several villages under Tamulpur sub-division were inundated within Baksa District.

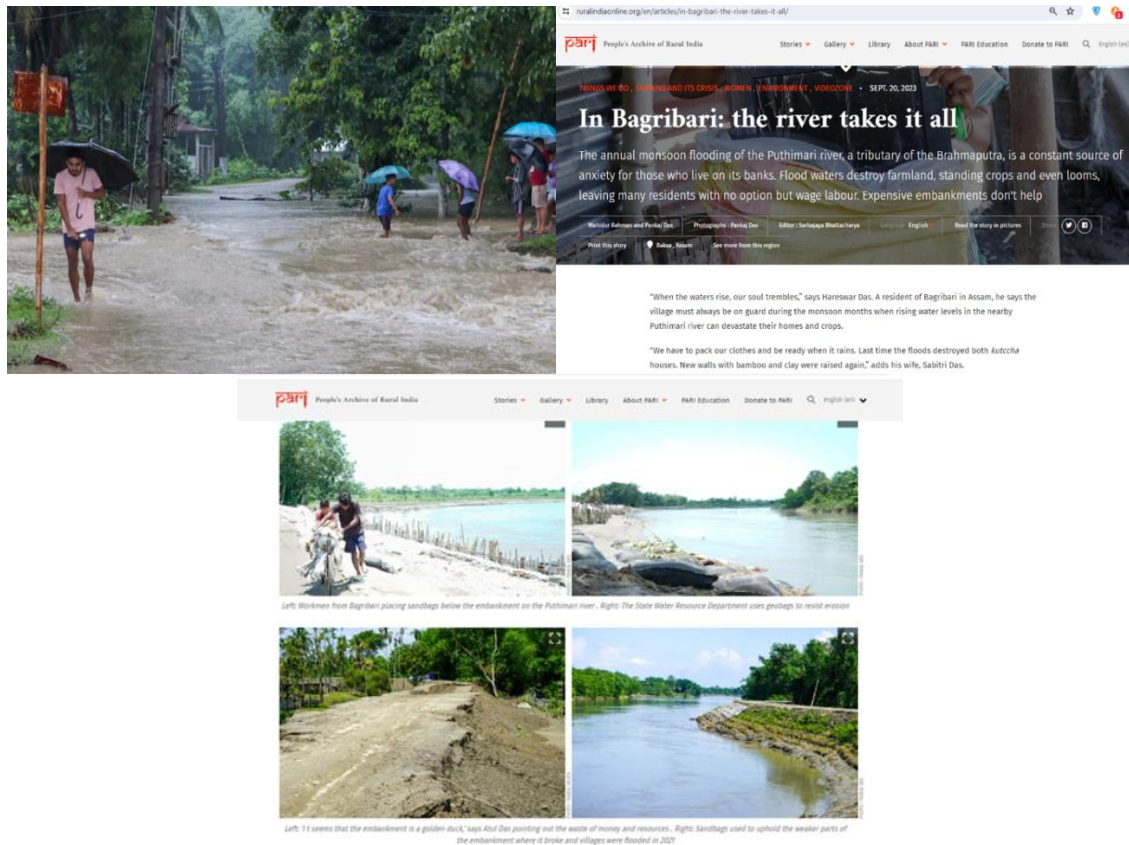


Fig.1.1 Few news clippings showing the erosion problem of the Bagribari area

1.5 Objectives

The study has been undertaken with the following objectives:

1. To study the bank erosion/deposition and bankline migration status of the Puthimari river near Bagaribari area and to estimate the rate of riverbank erosion during last three decades.
2. To develop a process-based coupled model integrating HEC-RAS sediment transport capabilities and Bank Stability and Toe Erosion Model (BSTEM) model for prediction of streambank retreat.
3. To suggest mitigation measures for sustainable bank stability

CHAPTER 2 REVIEW OF LITERATURE

2.1 General

Channel migration and associated riverbank erosion are among the most dynamic geomorphological processes and, therefore, of considerable scientific interest. The adverse consequence of increased streambank erosion results not only in accelerated sediment yields, but also to change in stream channel instability and associated stream type changes. [Rinaldi et.al \(1999\)](#) proved that streambanks of alluvial channels are usually composed of loose materials, which are unsaturated in ambient conditions. Unsaturated soils are subjected to negative pore water pressures, which cause an apparent cohesion. Braided river represents a high-energy fluvial environment often characterized by non-cohesive banks lacking vegetation and consequently, high rates of bank erosion and bed load transport ([Thomas et al. 2002](#)). To avoid the catastrophic outcome of bank erosion and to implement appropriate mitigation measures, a proper modeling approach is needed that enables the prediction of the change in river morphology and its associated consequences. In other words, it is necessary to identify areas that are vulnerable to bank erosion and then to predict the changes in the river channel. This can be achieved by coupling hydrodynamic and bank stability models ([Nardi et al. 2013](#)).

Riverbank erosion is usually approached by using a combination of bank stability methods and hydrodynamic models to predict the vulnerable areas and estimate the erosion rate ([Nardi et al. 2013](#)). Simulation of bank erosion requires a numerical model capable of coupling the in-channel vertical erosion process with the lateral bank erosion process ([Lai 2017](#)).

One of the most commonly used and most advanced streambank stability model, the BSTEM is a physically-based model developed by the National Sedimentation Laboratory in Oxford, Mississippi, USA ([Simon et al. 2000](#)) and has been used for simulation of hydraulic and geotechnical processes responsible for mass failure.

2.2 International Status

Till date, researchers around the globe have developed several numerical models to evaluate bank erosion. For instance, on the basis of bank erosion theory of [Hasegawa \(1981\)](#) and sediment transport theory of [Nagakawa and Tsujimoto \(1980\)](#), [Nagata et al. \(2000\)](#) developed a numerical model to study the morphological behavior of a meandering river. [Jang et al. \(2005\)](#), from their numerical model, gave the concept of submerged angle of repose of bank

materials in riverbank erosion. [Varauchakis et al. \(2016\)](#) developed one statistical model called the locally weighted logistic regression model (LWLR) that helps to identify the geomorphological and hydrological variables responsible for the prevention or stimulation of riverbank erosion in the Koiliaris river basin in Crete. [Simon et al. \(2000\)](#) from their study on Goodwin Creek, Mississippi where they used the Bank stability and toe erosion model concluded that field data and dynamic bank stability algorithm can be used together to predict the timing of bank failure. In a river bend of the same river, [Langendoen and Simon \(2008\)](#) used CONCEPTS 1D vertical model with a bank erosion model applicable to multilayer cohesive soil to analyse the bank retreat phenomenon. [Simon Gibson et al. \(2015\)](#) used a coupled modeling approach of BSTEM along with HEC-RAS for long-term simulation to predict observed cross sections. [Simon et al. \(2003\)](#) demonstrated a comprehensive coupled model that combines fluvial erosion, changes in pore water pressure and mass bank stability to study the hydraulic influence of the flow on bank erosion. However, in the seepage model (SEEP/W), they did not consider the bank geometry variations caused by fluvial erosion. [Dapporto and Rinaldi \(2003\)](#), integrated fluvial erosion, seepage and mass failure to simulate a numerical model for bank erosion analysis for the Sieve river in Italy. [Canestrelli et al. \(2016\)](#) and [Langendeon et al. \(2016\)](#) attempted to blend fixed and moving bed approaches for bank erosion analysis in hydrodynamic modelling and meander evolution, respectively. Combining basal erosion and mass failure, [Chen and Duan \(2008\)](#) developed a bank stability model in West Jordan river, Utah. [Khalaf \(1999\)](#) used a 2D morphodynamic model in the Tigris river to predict the changes in bed topography and flow. [Dorfmann and Knoblauch \(2009\)](#) compared 2D and 3D morphodynamic models MIKE21C and SSIIM and found high sensitivity of SSIIM to bed roughness. Delft2D and Delft3D morphodynamic models were applied in the Colorado river reach by [Logan et al. \(2010\)](#) to analyse the roles of various mechanisms in river morphological change. [Sirdari et al. \(2013\)](#) applied 3D SSIIM morphodynamic model to understand the morphology of river bed and bedload transport in a river confluence in Malaysia. [Moghaddam and Rennie \(2015\)](#) tried to improve the calibration and validation of Delft3D model utilizing ADCP and found the importance of eddy viscosity for calibration.

[Varauchakis et al. \(2016\)](#) proposed a statistical tool by combining logistic regression and locally weighted regression to develop a statistical model called locally weighted logistic regression model (LWLR) for the determination of riverbank erosion probability in the Koiliaris river basin in Crete. [Langendoen and Simon \(2008\)](#) incorporated a comprehensive bank erosion module into a 1D vertical model, CONCEPTS, which was applicable to multi-

layer cohesive stream banks to simulate the bank retreat of a bendway of the Goodwin Creek, Mississippi. As an alternative solution to CONCEPTS, [Gibson et al.\(2015\)](#) recently integrated BSTEM 5.4 with HEC-RAS 5.0, and showed that the two models were able to appropriately predict observed cross-sections over a long-term simulation. [Simon et al. \(2000\)](#) used BSTEM in Goodwin Creek, MS to show that a dynamic bank stability algorithm can be used in combination with specific field data to accurately represent the timing of bank failures. [Khanal et al. \(2016b\)](#) used BSTEM 5.4 in Barren Fork Creek, OK and compared model performance for predicting fluvial erosion when a non-linear detachment model is used versus linear excess shear stress equation. They found that the linear model both over and under predicted retreat, depending on the solution technique used to evaluate the JET data.

[Rahul et al. \(2023\)](#) conducted a review of sediment transport modeling using HEC-RAS software. The author emphasizes the importance of sediment movement in flood monitoring since flood management techniques are mostly based on peak flood levels. Bed levels may alter each year as a result of sediment deposition and bed removal caused by channel scouring. As a result, flood levels may vary within the same discharge, and the flow pattern of natural channels may shift as a result of siltation, altering the region's flood pattern. The ability of HEC-RAS to simulate sediment dynamics, such as variations in riverbed elevation, scouring and siltation patterns, was methodically investigated in their research. [Shukri et al. \(2024\)](#) conducted a study to simulate analysis of the sediment transport rates at Sg. Muda, Kedah River area by using HEC-RAS (1D) quasi unsteady flow. Their study's primary objective was to understand the cause of erosion and deposition by sediment movement resulting from the region's rapid growth and environmental degradation. Overall, the research showed that sediment dynamics are greatly impacted by dam management, with lower flows exposing mid-channel lands and lowering water surface heights. The author came to the conclusion that a variety of hydraulic and environmental conditions cause long-term sedimentation patterns to differ from year to year. [Joshi et al. \(2019\)](#) developed a sediment transport model for the Maumee River using the HEC-RAS to assess the effects of sediment on river morphology. Their research came to the conclusion that the prediction power of the model may be enhanced by adding more thorough bed load and sediment gradation data from more cross-sections. [Hummel et al. \(2012\)](#) carried out a comparison analysis to assess how well the quasi-unsteady HEC-RAS 4.1 model and 1D Finite Volume Method (FVM) based model perform in simulating flood flow and sediment transport in the Pantano Wash, a dryland river in the state of Arizona. The author found that Yang's and Engelund-Hansen's techniques, which had the lowest mean

error and the greatest correlation among the seven sediment transport formulae accessible in HEC-RAS, demonstrated the best agreement with actual field data in terms of effective bed elevation change. [Rasouli et al. \(2020\)](#) did research to suggest the implementation of the BSTEM model for monitoring and measuring the stream bank and toe erosion for the stabilization process in Amu River. According to their study, the primary causes of bank instability along the Amu River are mass failure and toe erosion. Crucially, the researchers employed BSTEM's root reinforcement capabilities to analyze how vegetation enhances bank stability. [Haghiabi et al. \(2012\)](#) conducted a comparative study using the HEC-RAS4 and MIKE11 model to evaluate sediment transport and identify critical erodible points and areas with potential sedimentation aggregation along Karun River, Iran. They found significant sedimentation in the Ahwaz section over the five-year simulation period, which results in formation of large sand bars due to sedimentation and lack of regular dredging of the river. [Rahman et al. \(2022\)](#) conducted a detailed investigation on the sediment transport dynamics of the Langat River Basin (LRB) in Selangor, Malaysia, with a focus on understanding erosion and deposition patterns using HEC-RAS modeling tools. The primary objective of their study was to assess sediment transport capacity and predict long-term impacts on river morphology.

2.3 National Status

[Ghosh et al. \(2016\)](#) used Bank Assessment for Non-point source Consequences of Sediment (BANCS) model for evaluating Stream Bank Erosion Hazard Potential (SBEHP) for a stretch of river Bakreshwar of Eastern India. They concluded that Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) is not a sound bank erosion hazard predictive model for their study. [Karmaker and Dutta \(2010\)](#) applied an analytical model in a river bend with active bank erosion rate in the middle reach of Brahmaputra river. Their results showed that the analytical model works well for predicting the seasonal extent of bank erosion. [Biswas et al. \(2016\)](#) proposed a bank erosion model including the influence of the lateral bed slope on the erosion rate of suspended sediment in lower reach of river Brahmaputra to predict bank shifting and sand bar behaviors and integrated to a 2D numerical model. The model predicted bank shifting suspended loads and bed load with good accuracy. [Sundaravadivelu et.al. \(2005\)](#) studied the erosion and deposition near the breakwaters for a stretch in Pondicherry coast, India by comparing the Satellite Imageries with Hydrographic Chart and Survey of India (SOI) Toposheet. It provided a clue of equilibrium achievement between erosion and deposition.

[Sravanthi et al. \(2015\)](#) interrelated sediment transport model MIKE 21 Mud Transport (MT) with MIKE 21 Hydrodynamics (HD) module to understand sediment transport along central Kerala coast. During the period 1987-1998, flood data of 21 gauge/discharge sites on the main Brahmaputra River and its 12 major tributaries were studied by [Dhar and Nandargi \(2000\)](#) with a view to discover which sites and tributaries experience frequent floods in different monsoon months and how high flood magnitudes are. [Goswami \(1991\)](#) studied on the River Brahmaputra and said that the Brahmaputra is a large alluvial river with a high degree of braidedness. The Brahmaputra flows through a seismically active region, which has the effect of causing it to carry one of the highest sediment loads in the world. [Singh \(2006\)](#) studied the causes and impact on spatial variability of erosion in the Brahmaputra Basin. The erosion rates among the sub-basins of the Brahmaputra vary over 1-2 orders of magnitude. [Das et al. \(2017\)](#) conducted a sediment transport analysis for a reach of the Barak River, spanning from Annapurna Ghat to Badarpur Ghat, using the latest version of HEC-RAS. They first calibrated the model for hydraulic conditions of the river, and using Manning's roughness coefficient of 0.07 gives them the best value of Nash-Sutcliffe Efficiency of 0.92. [Mondal et al. \(2016\)](#) presented a study on the hydrodynamic modeling of the Ichamati River using the one-dimensional HEC-RAS model to understand flow behavior, sedimentation processes, and ecological implications in the flood-prone regions of the river. Their research found that the de-siltation of the stretch of Ichamati river under survey i.e. middle part showed impacts which were positive in ways more than one.

CHAPTER 3 MATERIALS AND METHODS

3.1 Study area

Puthimari is a north bank tributary that forms a transboundary watershed covering Bhutan (~43%) and the state of Assam in northeast India (~57%). The river's source is at 3750m above mean sea level at Tethyan Himalaya in the Eastern Himalayan region in Bhutan, and the mouth is at the confluence with the Brahmaputra River in Assam, India. Before entering India, the Puthimari River is named the Oontany River in Bhutan (IWAI 2015). With its two major tributaries, namely Nona and Baralia, this river system is characterized by different geomorphic features that include meanders, floodplains, river islands, etc. The river flows in a north-south direction, and in the downstream plain areas, the Brahmaputra flows in an east-west direction forming wide floodplains in the Puthimari basin. With an average annual rainfall of 1600 mm and more intensified rainfall in the monsoon season, Puthimari experiences a large volume of discharge resulting in heavy floods downstream (Taher 1975). The approximate basin area is 3225.47 sq.km. Every year during monsoon, the water level rises and causes severe floods threatening the livelihood of the riparian population, and affecting the socio-economy of the watershed as well. Along with heavy discharge, the river carries a huge sediment load along its course contributing to the Brahmaputra at its outlet. Bagribari is an area that falls along the banks of the river Puthimari towards its downstream side. Every year, due to excessively heavy rainfall, especially during the monsoon season, the river causes severe floods and erosion in this region. This Bagribari area has been considered in this study to understand the interactive bank erosion processes responsible for streambank erosion.

The Puthimari basin location map is represented in Fig. 3.1.

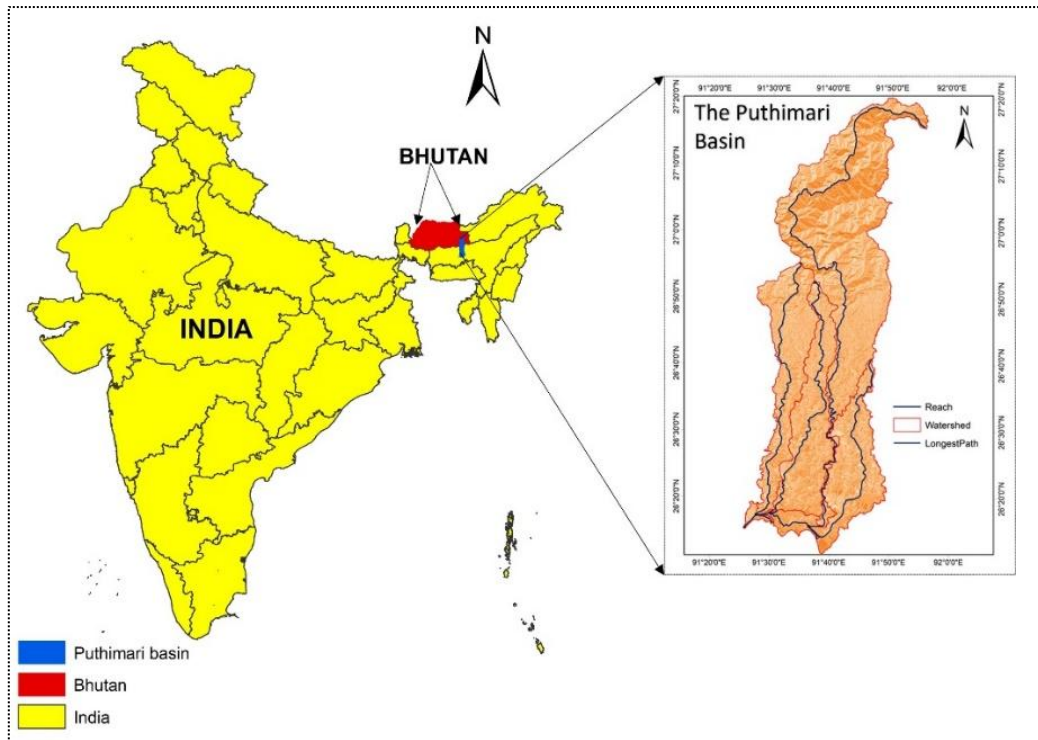


Fig. 3.1 Location of the Puthimari basin

3.2 Data used

To carry out different analyses, the present study utilized the open-source topographic and meteorological data available from various websites. For watershed delineation, the Shuttle Radar Topographic Mission Digital Elevation Model (DEM) of 30m spatial resolution was used. Using a weather generator table for the Indian region, the solar radiation, relative humidity, and wind speed were simulated in ArcSWAT. For calibration and validation of the SWAT model, daily rainfall ($0.25^{\circ} \times 0.25^{\circ}$) and temperature ($1^{\circ} \times 1^{\circ}$) data from 1999 to 2010, available in the India Meteorological Department (IMD) portal, were utilized. The LULC map of 1999 was prepared using the Landsat-5 Thematic Mapper, and that for 2019 was prepared using the Landsat-8 Operational Land Imager (OLI), both of 30m resolution. Observed discharge data for the Puthimari River at the outlet of the Puthimari River from 1999 to 2010 were acquired from the Department of Water Resources, Government of Assam, India. The FAO (Food and Agriculture Organisation) and NBSS-LUP (National Bureau of Soil Science and Land Use Planning) soil maps were used for preparing the soil map of the basin.

ALOS DEM of 12.5m resolution was used to create the geometry file in HEC-RAS. To analyse the bank erosion process, the BSTEM requires different soil properties of both the bed and banks of the river. The properties used are saturated bulk density, friction angle, cohesion, Phi

b, critical shear stress, and erodibility. Apart from that, a bed gradation profile was also required as an input to the HECRAS sediment analysis model.

3.3 Methodology

The overall methodology adopted in this study is shown in Fig.3.2.

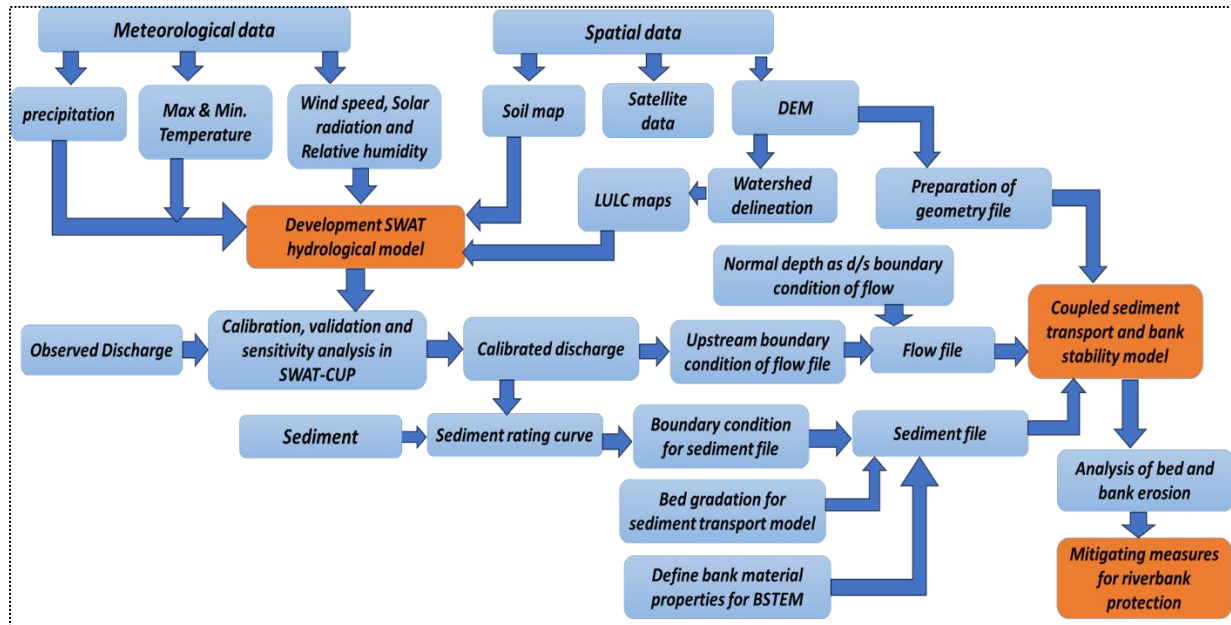


Fig. 3.2 Methodology adopted in the current study

3.3.1 Simulation of SWAT hydrological model

Initially the SWAT model was used to simulate the discharge of the river near the Bagribari area. The observed discharge data falls far below the exact location, and thus it was needed to get calibrated discharge at an upstream location that falls near Bagribari.

SWAT is a freely available semi-distributed hydrological model. As described earlier, SWAT can perform efficiently under different climate and LULC scenarios and gives continuous time-scale simulation over longer periods. The feature of dividing a basin into several sub-watersheds, and then further dividing those sub-watersheds into several hydrologic response units (HRU) having uniform soil, land use, and slope features, is what gives the SWAT model its accuracy. Simulation at the HRU level makes the model more reliable and efficient for hydrologic analysis.

The water balance equation used in the SWAT model is expressed as:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - W_{seep} - E_a - Q_{gw}) \quad (1)$$

Where, SW_t , SW_0 , R_{day} , Q_{surf} , E_a , Q_{gw} are the soil humidity, soil base humidity, volume of rainfall, surface runoff, evapotranspiration and underground runoff in the units of mm. t stands for time in days and W_{seep} stands for water seepage into the deeper layer from the soil.

The model was set up in ArcSWAT. The 30m resolution SRTM DEM was used for watershed delineation followed by HRU analysis. Five categories of slope were defined (0–10%, 10–20%, 20–30%, 30–50% and >50%) to characterize the variety of the surface. 9 nos. of subbasins and 94 nos. of HRUs were created in the watershed. Rainfall and temperature data acquired from IMD were fed into the model as weather data. The model was then run considering two years of warm-up period. The basic processes adopted in the SWAT model for loss, evapotranspiration, and routing methods were Soil Conservation Service- Curve Number, Penmann-Monteith, and variable storage methods, respectively.

3.3.1.1 Model calibration, validation, and sensitivity analysis

The SUFI-2 algorithm was selected for calibrating, validating, and analyzing the sensitivity of the SWAT model parameters in SWAT-CUP. Taking three years of the warm-up period from 1996 to 1998, model calibration was performed for the period 1999–2005, and subsequently, validation was done for 2005–10.

The model's efficiency was assessed based on the Nash-Sutcliffe Efficiency (NSE) coefficient, Coefficient of Determination (R^2), and Percent Bias (PBIAS). A positive PBIAS value indicates underestimation by the SWAT model and vice versa.

The formulae for these statistics are as follows:

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (2)$$

$$R^2 = \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \quad (3)$$

$$PBIAS = \frac{\sum_{i=1}^n (O_i - P_i) * (100)}{\sum_{i=1}^n O_i} \quad (4)$$

where O_i is i^{th} observed streamflow; \bar{O} is mean observed streamflow; P_i is i^{th} predicted streamflow, \bar{P} is mean predicted streamflow and n denotes the total number of observations.

A comparison was made between the uncalibrated model-simulated discharge and discharge measured at the river's outlet. Based on the patterns of the simulated and measured

hydrographs, 17 watershed parameters (Table 2) were selected for calibration. To understand which of these parameters are sensitive to variability in discharge, sensitivity analysis was performed in the first iteration of SWAT simulation involving 500 number of simulations. The influential level of different parameters on streamflow simulation were ranked based on a global sensitivity analysis, where the significance and measure of sensitivity were determined based on the t-statistics and the p-value. The parameters were ranked based on the concept that a parameter is more sensitive when its absolute t-stat value is greater or the p-value is smaller. This ranking of the parameters aided in the subsequent calibration process, which allowed for greater emphasis to be placed on the sensitive parameters. The SWAT model was then validated over a period of 6 years (2005-2010) after appropriate calibration, using the same set of parameters and number of simulations.

Finally, from the calibrated model, the discharge at an upstream subbasin covering the Bagribari area were extracted for further analysis in HEC-RAS.

3.3.2 Bank erosion analysis for the Bagribari area along the River Puthimari

The present proposal aims to develop a coupled sediment transport and bank stability model to predict the bank retreat in Puthimari river, near Bagribari, Assam. The physically-based Bank Stability and Toe Erosion Model (BSTEM) developed by National Sediment Laboratory, United States Department of Agriculture (USDA) is proposed to be integrated with HEC-RAS sediment transport modeling. BSTEM handles the mechanistic basal erosion and mass failure of a bank, while the mobile bed capabilities of HEC-RAS software compute vertical bed changes in response to dynamic sediment mass balance and bed processes. Thus, the coupling of HEC-RAS and BSTEM will enable simulation of both bed and bank processes as these two models are interrelated. The overall methodology of BSTEM is shown in Fig. 3.3.

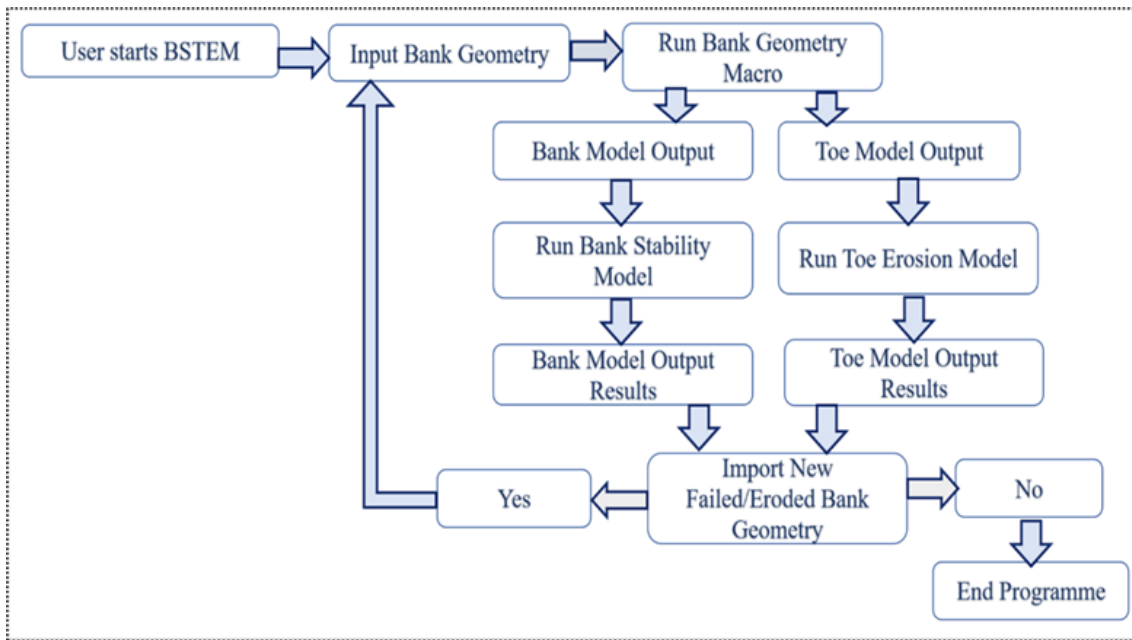


Fig.3.3 Process followed by the BSTEM to calculate bank stability condition and toe erosion scenario (Source: Thapa 2016)

Fig.3.4 represents the schematic of the "vertical slice" method from Langendoen and Simon (2008) used in the current version of BSTEM in HEC-RAS

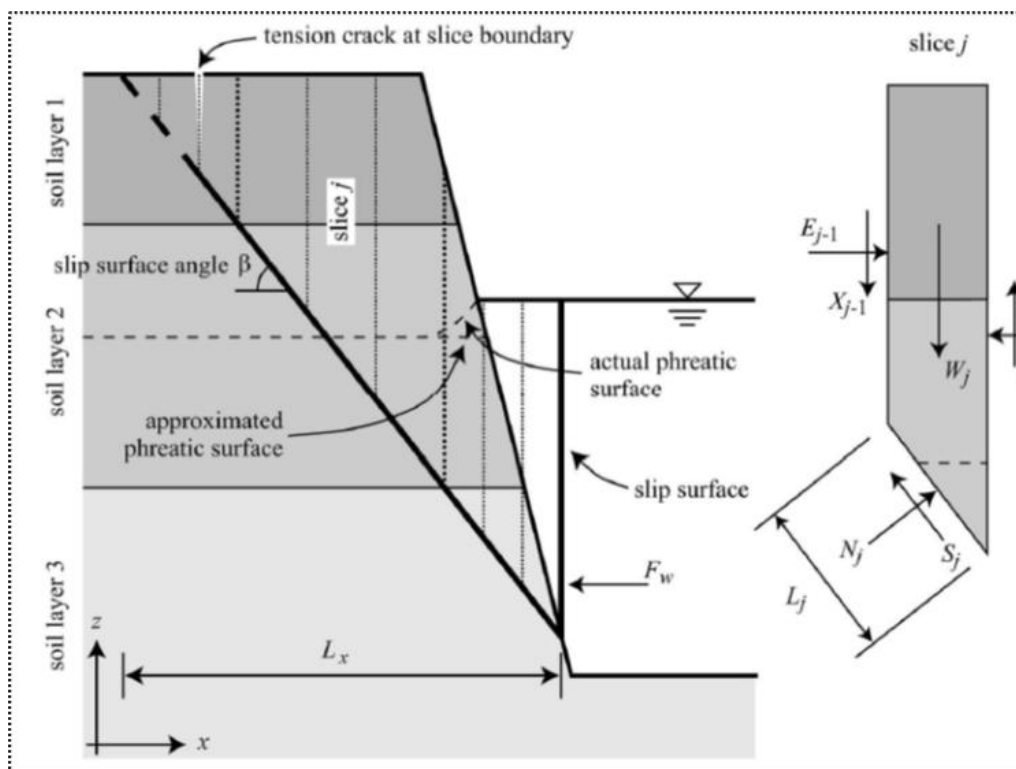


Fig. 3.4 Schematic of the "vertical slice" method from Langendoen and Simon (2008) used in the current version of BSTEM in HEC-RAS (Source: HEC-RAS-BSTEM user manual, 2015)

3.3.2.1 Theory behind BSTEM model

To model bank stability, BSTEM calculates a factor of safety (FoS) using three different limit equilibrium-method models: horizontal layers, vertical slices, and cantilever shear failure. In general, FoS is calculated as the ratio between the resisting forces and the driving forces along a potential failure plane. The resisting forces can be defined by the Mohr-Coulomb equation:

$$s_r = c' + (\sigma - \mu_w) \tan(\varphi')$$

Where s_r is the shear strength of the soil (kPa), c' is the effective cohesion (kPa), σ is the normal stress (kPa), μ_w is the porewater pressure (kPa), and φ' is the effective internal angle of friction in degrees.

Soil weight is the dominating driving force defined by, $sd = W \sin(\beta)$

where sd is the driving stress (kPa), W is the weight of the wet soil block per unit area of failure plane (kN m^{-2}), and β is the angle of the failure plane in degrees.

The toe erosion component of BSTEM estimates bank undercutting as a result of fluvial erosion (Simon et al., 2000). The model predicts erosion based on an excess shear stress equation. Erosion rate, ε (m/s), is calculated as,

$$\varepsilon = \kappa (\tau_o - \tau_c) a$$

where κ is the erodibility coefficient ($\text{m}^3/\text{N}/\text{S}$), τ_o is the average shear stress (kPa), τ_c is the soil's critical shear stress (kPa), and a is an exponent usually assumed to be unity.

In BSTEM, the boundary shear stress is corrected for the effects of curvature using the “no-lag kinematic model”

$$\tau_o = \frac{\gamma_w n^2 (u + U)^2}{R^{1/3}}$$

where n is Manning's roughness coefficient, u is the reach-averaged water velocity (m/s), and U is the increase in the nearbank velocity (m/s).

Table 3.1 Required user-input parameters for BSTEM (after Simon et al. 2011)

		Driving Force		Resisting Force	
Parameters	Purpose	Source	Parameters	Purpose	Source
<i>Hydraulic Processes: Bank Surface</i>					
Channel slope (S)	boundary shear stress (τ_c)	field survey or design plan	particle diameter (D) (cohesionless)	critical shear stress (τ_c)	bulk sample particle size (cohesionless); default values in model
Flow depth (h)	boundary shear stress (τ_c)	field survey, gauge information, design plan	critical shear stress (τ_c) (cohesive)	critical shear stress (τ_c)	jet test (cohesive); default values in model
Unit weight of water (γ_w)	boundary shear stress (τ_c)	considered constant, 9810 N m ⁻³	particle diameter (D) (cohesionless)	erodibility coefficient (k)	bulk sample particle size (cohesionless); default values in model
			critical shear stress (τ_c) (cohesive)	erodibility coefficient (k)	jet test (cohesive); default values in model
<i>Geotechnical Processes: bank Mass</i>					
Unit weight of sediment (γ_s)	Weight (W), Normal force (σ)	core sample in bank unit; default values in model	Unit weight of sediment (γ_s)	Weight (W), Normal force (σ)	core sample in bank unit; default values in model
Bank height (H)	Shear stress	field survey or design plan	effective cohesion (c')	shear strength (τ_f)	borehole shear, direct shear, triaxial shear; default values in model
Bank angle (α)	Shear stress	field survey or design plan	effective friction angle (ϕ')	shear strength (τ_f)	
			pore water pressure (u_w)	Shear strength (τ_f)	interpolated from water table

3.3.2.2 Creation of the geometry file

The project started with the setting up of the unit system. In the RAS-mapper option, the coordinate system was then set to UTM. The geometry file was created in RAS-mapper. ALOS DEM of 12.5m resolution data was loaded into RAS Mapper and served as the base for extracting river geometry. Subsequently, the river centre line that represents the main flow path of the river, left and right banklines of the river, flowpath lines that represent the paths water is expected to flow both within and outside the main channel, and cross sections at regular intervals were digitized. All of these digitized features were compiled into a geometry file, which is a critical component in running simulations in HEC-RAS. The Manning's roughness values for the river, as well as for both right and left banks, were provided.

3.3.2.3 Creation of the flow file

A sediment transport model can be run either as a quasi-unsteady flow, which models the hydrograph in a series of steady flows, or in the full unsteady flow mode. But the quasi-unsteady mode tends to be more stable. The quasi-unsteady hydrodynamic model simulates the flow series with a sequence of steady flow computations. Hydrodynamic parameters for the sediment model are computed with the HEC-RAS steady flow engine, and then applied over specified time windows to compute sediment transport temporally.

In this study, a quasi-unsteady flow file was created for the sediment transport analysis. The flow series data obtained from the SWAT simulation was given as the upstream boundary condition. Fixed start date and time were also provided. Normal depth of 0.0003 was given as the downstream boundary condition. Normal depth computes the stage at the downstream boundary condition using Manning's equation, and in order to do this, Manning's equation needs a friction slope, which has been provided here as the downstream boundary condition. In addition to the boundary conditions, sediment transport modeling also requires temperature data. Temperature is important in sediment transport because temperature affects the viscosity of water, which affects both fall velocity and transport. Thus, temperature data was also incorporated in the flow file.

3.3.2.4 Creation of the sediment transport file

The sediment transport model in HEC-RAS requires two primary types of input data: bed data and boundary data. Bed data refers to the initial conditions of the riverbed, including where sediment is stored within the channel bed (control volume). This involves defining the bed sediment gradation, the distribution of sediment sizes, for each cross-section. A sediment thickness (reservoir) of up to 2.5 meters below the thalweg was specified, representing the depth of sediment available for transport. Using the delineated bank extents, the movable bed limits were defined to indicate the portion of the bed that can participate in sediment transport.

Where direct gradation data were not available, interpolation was used to estimate sediment size distributions across all cross-sections. This bed gradation data, typically expressed as a percent finer curve (size vs. cumulative percentage finer), characterizes the sediment composition of the riverbed.

The following methods were adopted in the model:

Transport function: Laursen (Copeland)

Sorting method: Copeland

Fall velocity method: Saulsby

For the boundary data, a sediment rating curve was developed and applied as the upstream boundary condition. This curve defines the sediment load associated with different flow conditions. The flow was categorized into three distinct ranges, and for each range, the total sediment load was calculated based on a pre-established flow-load relationship. These total

loads were then partitioned by grain size class, assigning a percentage of the total load to each sediment size category. This comprehensive setup ensured accurate representation of sediment transport dynamics within the model.

The next step is to provide bank data. The BSTEM toe erosion and bank failure analysis will be performed as part of a sediment transport analysis on the cross-section bank that has all the necessary parameters. Computing bank failure at every bank increases run times. Therefore, it BSTEM parameters were specified for banks that have a probability of failure. Setting up HEC-RAS cross sections (for the left or right bank) is composed of four segments: The Top of Bank which is the relatively flat portion of the cross section above the bank; The Bank which is the steepest part of the cross section; The Toe which is a mild slope between the bank and the channel, presumably composed of blocks of material that have fallen and accumulated at the base of the bank and are protecting the toe or some sort of rip rap or toe protection; and The Channel which is the region between the toe and the thalweg. For the selected cross-sections, the edge station, the toe station and the bank materials were provided for both left and right banks. The bank edge stations should be the inflection point between the bank and the top of the bank. All failure planes considered will intersect the top of the bank between the edge of the bank and the first cross-section station-elevation point.

BSTEM divides the bank into two sections, the Bank and the Toe. Conceptually, the toe is material composed of blocks of failed material or engineered toe protection. Therefore, failure planes are only computed through the bank surface above the Top of Toe. The Top of Toe often corresponds to a break in slope or material type but it does not have to. This parameter can be automatically set to the HEC-RAS left and right bank station for every cross section that has bank material defined. The bank material properties given for the selected cross sections were, saturated bulk density, friction angle, cohesion, ϕ , critical shear stress and erodibility. HEC-RAS uses these user defined parameters with hydrodynamic and geometric data to compute a factor of safety for a range of possible failure planes by computing the ratio of the resisting forces to the driving forces. HEC-RAS requires another bank material parameter that is required but not used until after the failure calculation. In order to partition any failed material into grain classes for transport by the sediment transport model, the bank material has to have a bed gradation associated with it. Thus, the bed gradation for the selected cross-sections were provided in the BSTEM model. The number of failure plane computation nodes selected were 50, and the number of time steps between bank failure computations were selected to be 1. Again, Engelund-Hansen transport function and Max-Prevalence scour mixing method were

selected for the BSTEM model. If a soil layer has less than 20 percent cohesive material, BSTEM will apply the transport function to compute toe scour.

Table 2 gives the BSTEM output variable names with descriptions.

Table 3.2 BSTEM output variables

Variables	Description
BSTEM Mass (Vol)	Total sediment mass (or volume) mobilized - from both crosssect- on banks - by toe scour and bank failure for each cross section
BSTEM CumMass (Vol)	Cumulative mass (or volume) mobilized from the cross section for both banks and both BSTEM processes since the beginning of the simulation.
BSTEM Long CumMass (Vol)	The cumulative mass mobilized from the toe and banks since the beginning of the simulation, summed from upstream to downstream.
L/R BSTEM Mass Failure L/R BSTEM Mass Failure	Mass removed from the left or right bank by bank failure processes for each computation increment.
L/R BSTEM Toe Mass L/R BSTEM Toe Mass	Mass removed from the left bank by toe scour for each computation increment.
L/R Factor of Safety	Minimum factor of safety computed in the left or right bank for each computation increment.
BSTEM L/R Toe Station	The lateral station (i.e. the station-elevation point) of the toe.
BSTEM L/R Toe Elevation	The elevation of the station-elevation point identified as the toe
BSTEM L/R Top Station	The lateral station of the point identified as the "top of bank".
BSTEM L/R Top Elevation	The elevation of the station-elevation point identified as the "top of bank".
Movable Elv L/R:	The elevation of the movable bed limit.
Movable Sta L/R:	Tracks the lateral position of the movable bed limit.
Groundwater Elev	Ground water elevation computed in BSTEM

Finally, a plan file was created that brings the geometry file, flow file and the sediment file together. The sediment transport model was then run from 1999 to 2010 with 5 minutes computational interval.

3.4 Field visit and laboratory analysis of soil samples

A field visit was conducted to the Bagribari area for reconnaissance survey and to check the erosion pattern of the Puthimari river in the area. The study team interacted with the local people to understand the havoc created by the river during monsoon, both with floods and associated bank erosion. The vulnerable locations for bank erosion along both banks of the river were identified a priori through the migration studies using multi-temporal satellite data. These locations were then verified in the field. Soil samples from four locations on each bank as well as bed sediments, were collected from the field. These samples were then analysed in the laboratory to get different engineering properties, which were then incorporated in the

sediment transport model in HEC-RAS. Figure 3.5 presents (a) selected field photographs and (b) laboratory activities related to the sample analysis.



Fig. 3.5 (a) Photographs taken during field visit



Fig. 3.5 (b) Activities during laboratory analysis of soil samples

CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 Runoff simulation using SWAT

The LULC of 1999 was used for calibration of the SWAT model in SWAT-CUP and then obtained an optimum discharge at the outlet of the Puthimari basin. During the first iteration of 500 simulations involving 17 watershed parameters, sensitivity analysis was performed using global sensitivity analysis. Based on absolute values of t-stat, the parameters were ranked in terms of their sensitivities, as shown in Table 2. Similar to many other watersheds, the sensitivity of the parameter related to curve number, i.e., CN2 was the highest. In order of sensitivity, the other sensitive parameters are ALPHA_BF, OV_N, CH_K2, CH_N2, SOL_BD, GW_DELAY, and SOL_AWC. Subsequent iterations were performed twice to reach an optimum discharge evaluated using NSE, R2, PBIAS, p-factor, and r-factor. The fitted parameter values after successful calibration are shown in Table 4.1. In the table, the fitted values of CN2, SOL_AWC, SOL_Z, SOL_BD, SOL_K, and SLSUBBSN are the 1+ multiplier constants while the rest are the actual values of their corresponding parameters.

Table 4.1 Parameters used in model calibration, their sensitivity ranking, and their fitted values

Parameters with description	t-stat	p-value	Sensitivity Rank	Parameter Ranges		Fitted values
				Min	Max	
CN2: Curve number for AMC-II	-16.86	0.00	1	-0.2	0.2	0.019
ALPHA_BF: Baseflow recession constant	-15.98	0.00	2	0	1	0.073
OV_N: Manning's 'n' for overland flow	12.39	0.00	3	0.01	0.25	0.100
CH_K2: Main channel's effective hydraulic conductivity	6.09	0.00	4	0	150	142.05
CH_N2: the main channel's Manning's 'n' value	5.25	0.00	5	0	0.3	0.229
SOL_BD: Moist bulk density	2.88	0.004	6	-0.3	0.3	0.118
GW_DELAY: Delay time of groundwater	-2.44	0.01	7	30	450	355.50
SOL_AWC: The soil layer's available water capacity	2.24	0.03	8	-0.3	0.3	0.071
SOL_K: Saturated hydraulic conductivity	1.55	0.12	9	-0.3	0.3	-0.281
EPCO: Plant uptake compensation factor	0.94	0.35	10	0.01	1	0.813
GW_REVAP: 'revap' coefficient of groundwater	0.82	0.41	11	0.02	0.2	0.189
SURLAG: Surface runoff lag time	-0.59	0.55	12	1	24	19.79
RCHRG_DP: Deep aquifer percolation fraction	0.58	0.56	13	0	1	0.741

GWQMN: Shallow aquifer's threshold water depth required for occurrence of return flow	0.38	0.71	14	0	1000	637.00
ESCO: Soil evaporation compensation factor	0.31	0.75	15	0.01	1	0.488
SLSUBBSN: Average slope length	0.19	0.85	16	0	150	73.98
SOL_Z: Depth to bottom layer from the soil surface	0.08	0.94	17	-0.3	0.3	-0.256

After calibration, validation was performed with the calibrated parameters. Model performance metrics and daily flow hydrographs for both calibration and validation are illustrated in Table 4.2 and Fig. 4.1, respectively. The performance of a hydrological model simulating discharge with NSE and R² values between 0.65–0.75 is considered ‘good while a value greater than 0.75 is considered ‘very good’. Also, a discharge simulating model with a PBIAS between -10% and +10% is considered as ‘very good’. Furthermore, PBIAS is sensitive to differences in mass, while NSE is very sensitive to differences in peaks. Uncertainty in the prediction of discharge or any other hydrological variables is explained collectively by p-, and r- factors in a SWAT simulation. For discharge, to achieve an optimum uncertainty level in the modeling process, p-factor values of larger than 0.75, and r-factor values of smaller than 1.2 are widely accepted. A balance is necessary for these factors as one can be optimized at the expense of the other. On meeting these criteria, the uncertainty in the process is minimized. Therefore, the SWAT model developed for the Puthimari basin, based on the statistical values illustrated in Table 4.2, can be considered a very satisfactory model that could be used for further extrapolation of the time periods. Moreover, the patterns of the peaks and their timing and shape of the hydrographs of the observed and simulated discharge demonstrate the efficiency of SWAT.

Table 4.2 Performance statistics for SWAT calibration and validation

PERFORMANCE INDICES	CALIBRATION (1999-2005)	VALIDATION (2006-2010)
NSE	0.74	0.77
R ²	0.75	0.79
PBIAS	-3.0	-2.7
r-factor	0.99	1.10
p-factor	0.79	0.93

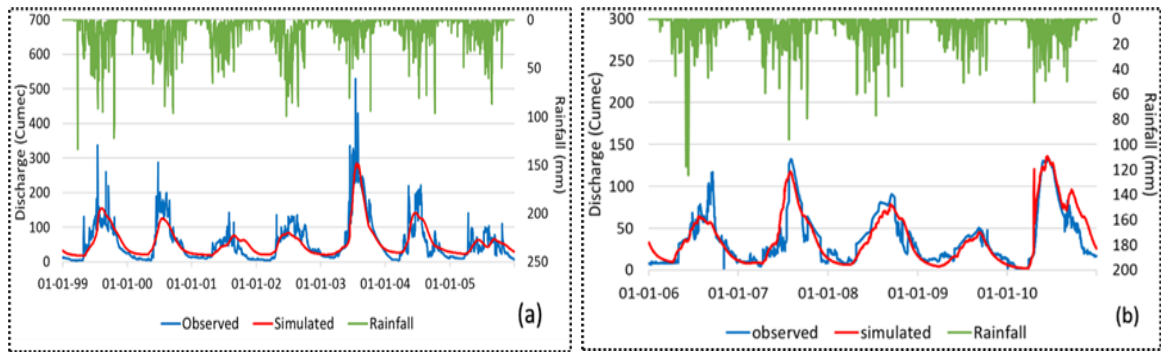


Fig. 4.1 Daily flow hydrograph during (a) calibration and (b) validation

4.2 Riverbank Migration analysis of Puthimari near Bagribari

Fig. 4.2 (a) shows the seven numbers of sub-basins delineated in SWAT. The Bagribari area falls in the sub-basin no. 5 as shown enlarged in Fig. 4.2 (b). Bagribari falls towards downstream and the migration of Puthimari in different years is shown in Fig. 4.2 (c).

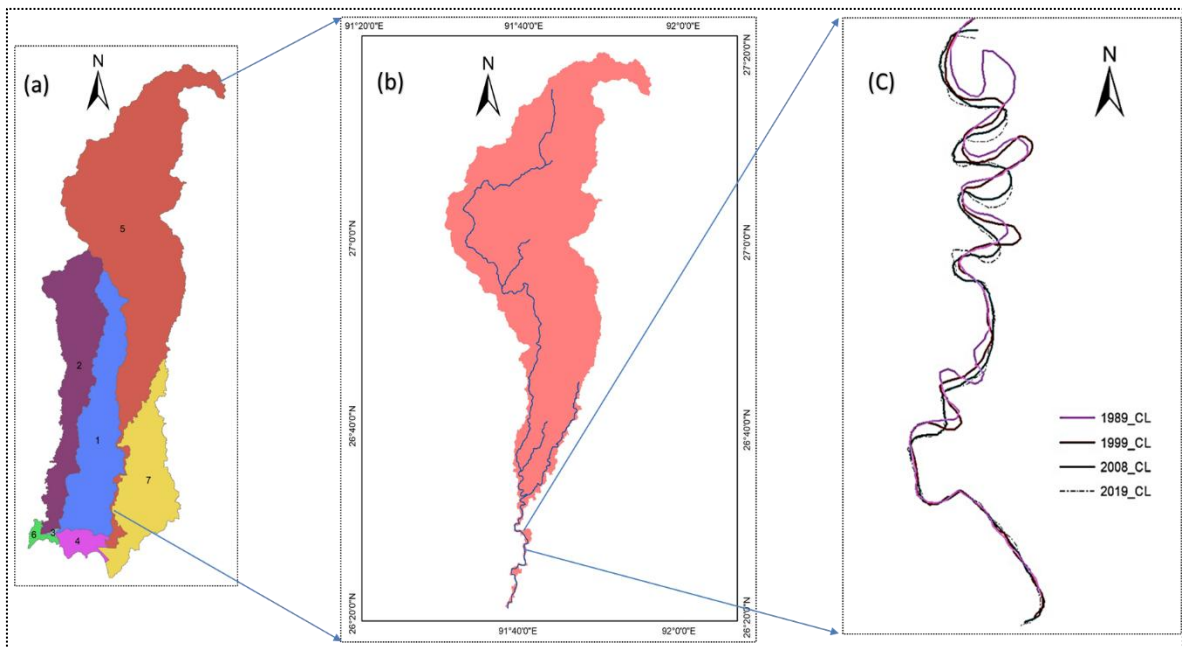


Fig. 4.2 (a) The delineated sub-basins of Puthimari in SWAT, (b) The sub-watershed covering the Bagribari area and (c) Migration of puthimari near Bagribari

The bankline of river Puthimari near Bagribari area has been digitized using Landsat data from 1989 to 2019 and was superimposed to analyse the migration of the river. The migration of the river near Bagribari from 1989 to 2019 is shown in Fig. 4.3.

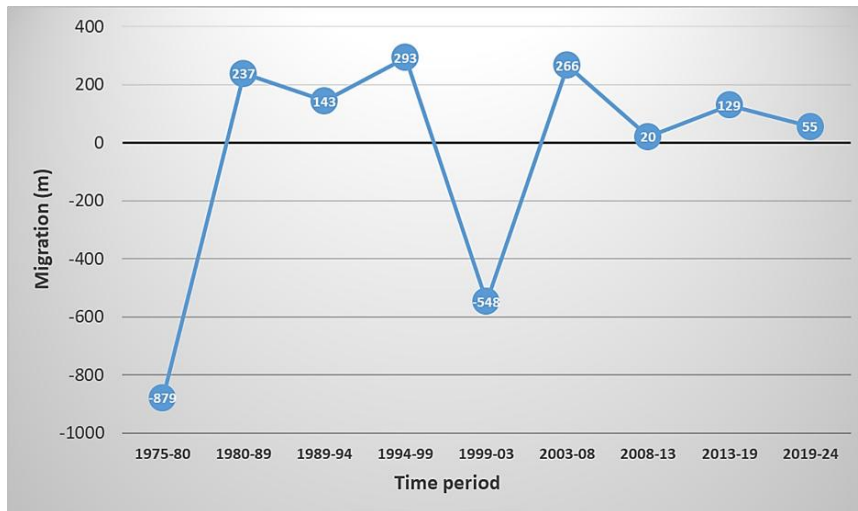


Fig.4.3 Bankline migration of river Puthimari near Bagribari area

Maximum erosion of 879 m was observed during 1975-80 followed by followed by 548m during 1999-2003.

4.3 Sediment transport modeling in HEC-RAS

Fig. 4.4 shows the ALOS DEM (middle) used in RAS-Mapper to digitize the river centre line, banklines and the flow paths. Subsequently, the geometry file was created.

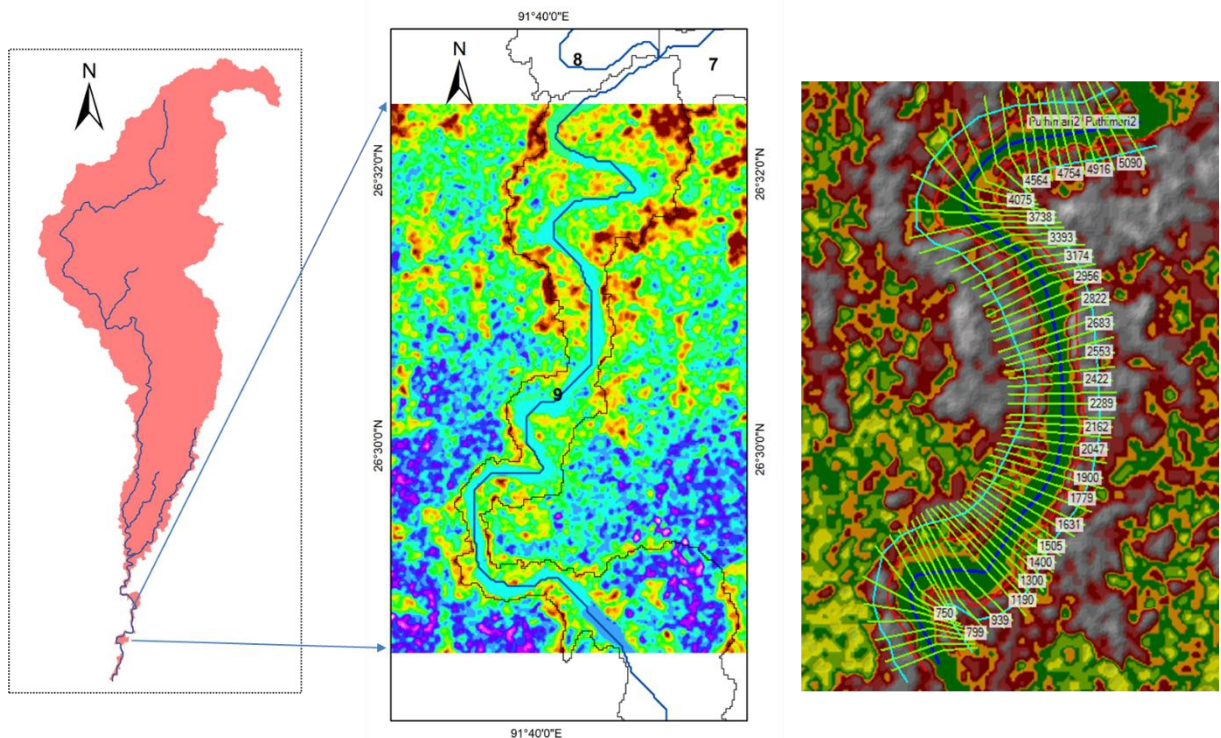


Fig. 4.4 The geometry file created in HEC-RAS

Following the creation of the geometry file, the quasi-unsteady flow file was created. Fig. 4.5 shows the wizard for entering boundary conditions (LHS) and temperature data (RHS) for the creation of the flow file.

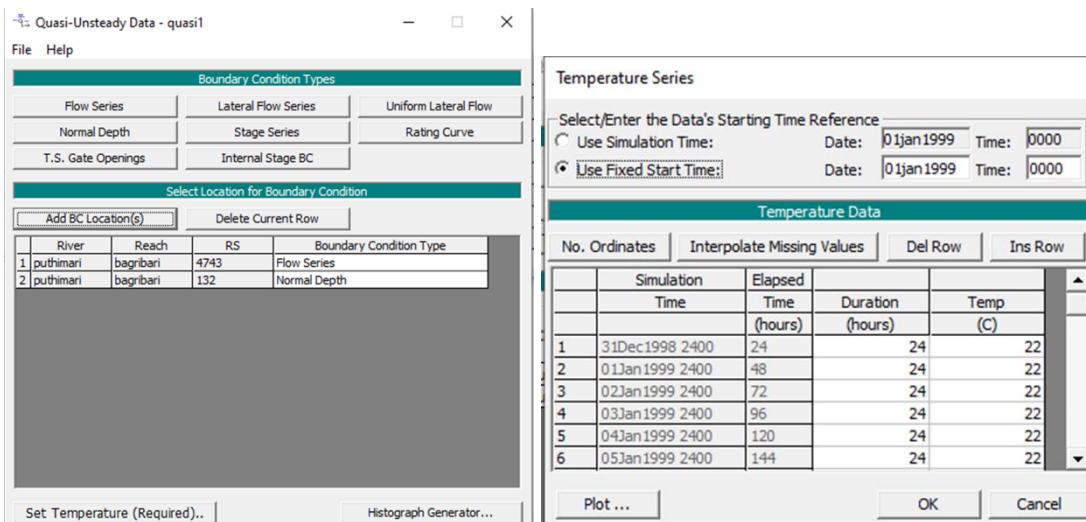


Fig. 4.5 Windows for boundary conditions (LHS) and temperature data (RHS)

In the next step, the sediment transport file was created. Fig. 4.6 shows the window for the initial conditions and transport parameters, showing the sediment reservoir generated after entering the maximum depth values at each cross-section (RHS).

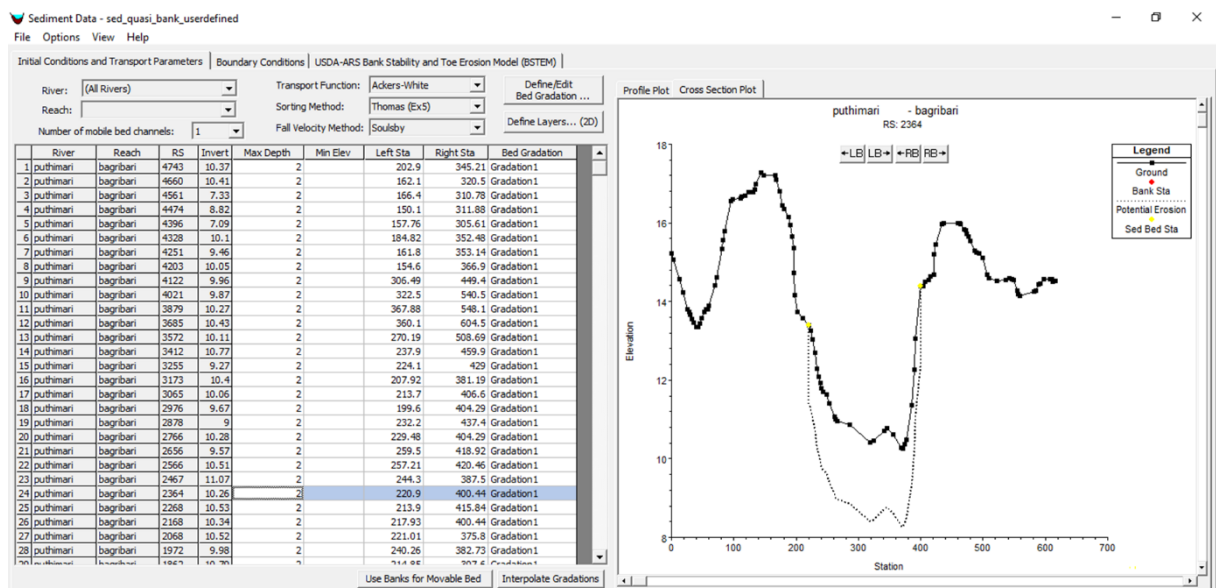


Fig. 4.6 Window for initial conditions and transport parameters

The bed gradation graph generated from the percent finer vs. grain size, that has been incorporated in the sediment file, is shown in Fig. 4.7.

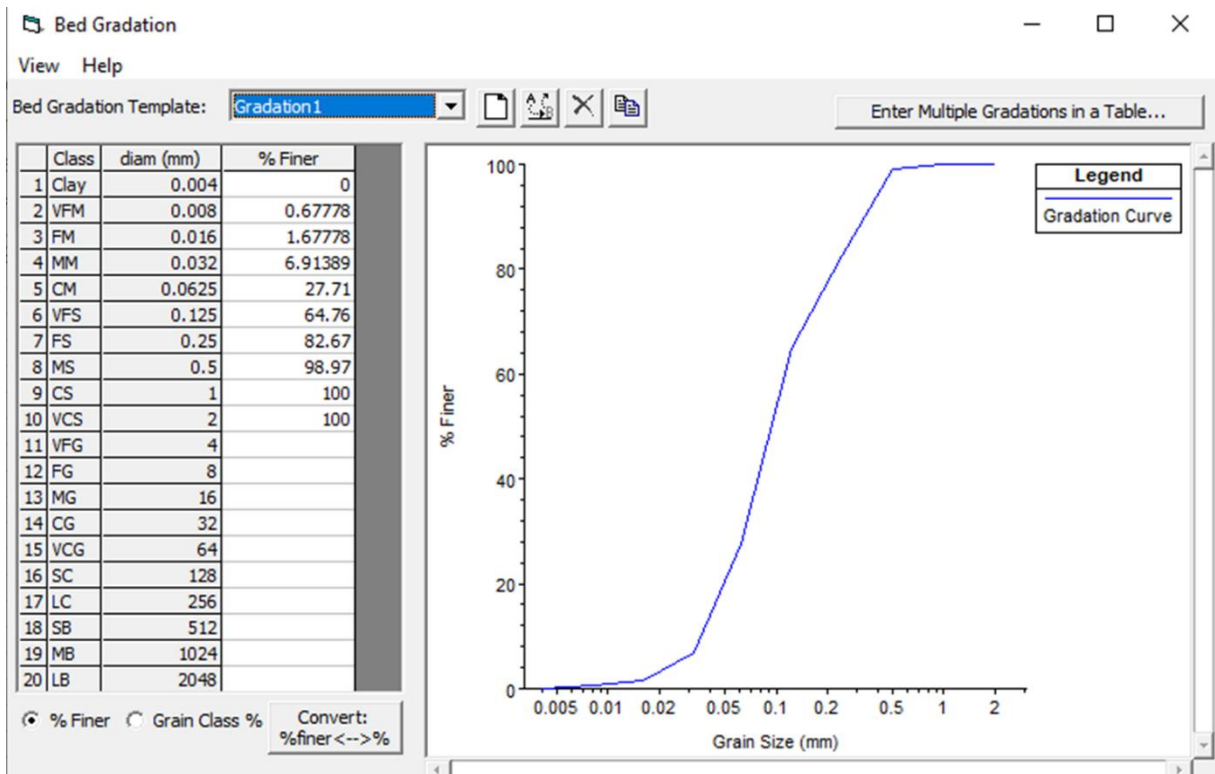


Fig. 4.7 Bed gradation graph

The soil was found to be mostly medium to fine silt.

For providing the upstream boundary condition, a rating curve was generated using the flow and sediment time series data in HEC-RAS. The generated rating curve is shown in Fig. 4.8.

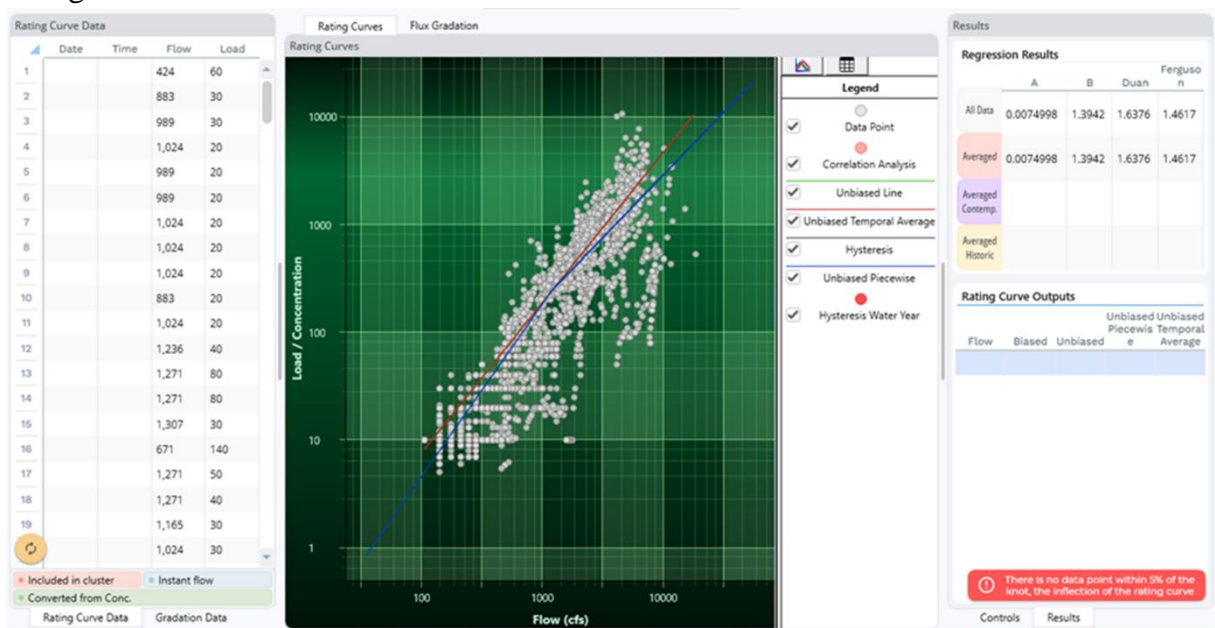


Fig. 4.8 Sediment rating curve generated from flow and sediment data

Based on the sediment rating curve and the relation between flow and load, the load for the three sets of flow values was incorporated in the file. Also, the grain size distribution of sediments for each set in percentage was provided. Fig. 4.9 shows the window for the upstream boundary condition of the sediment transport file in HEC-RAS.

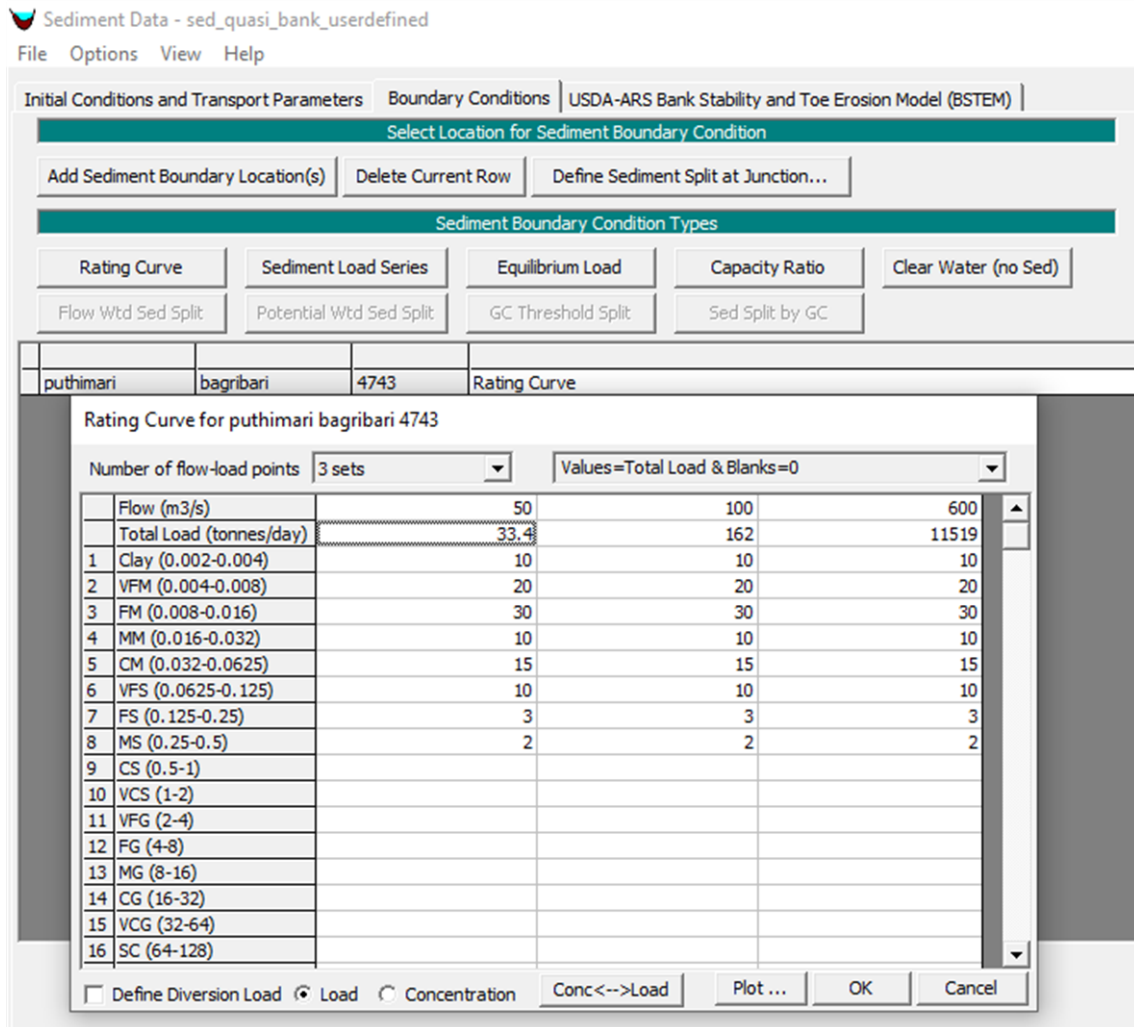


Fig. 4.9 Upstream boundary condition for sediment file based on rating curve

In the next and final stage, the bank geometry and soil properties were provided in the BSTEM module of the sediment transport file. Geometry data were extracted from the geometry file, while the bank soil properties were as per the results obtained from the laboratory analysis. The data entry in this BSTEM window is shown in Fig. 4.10.

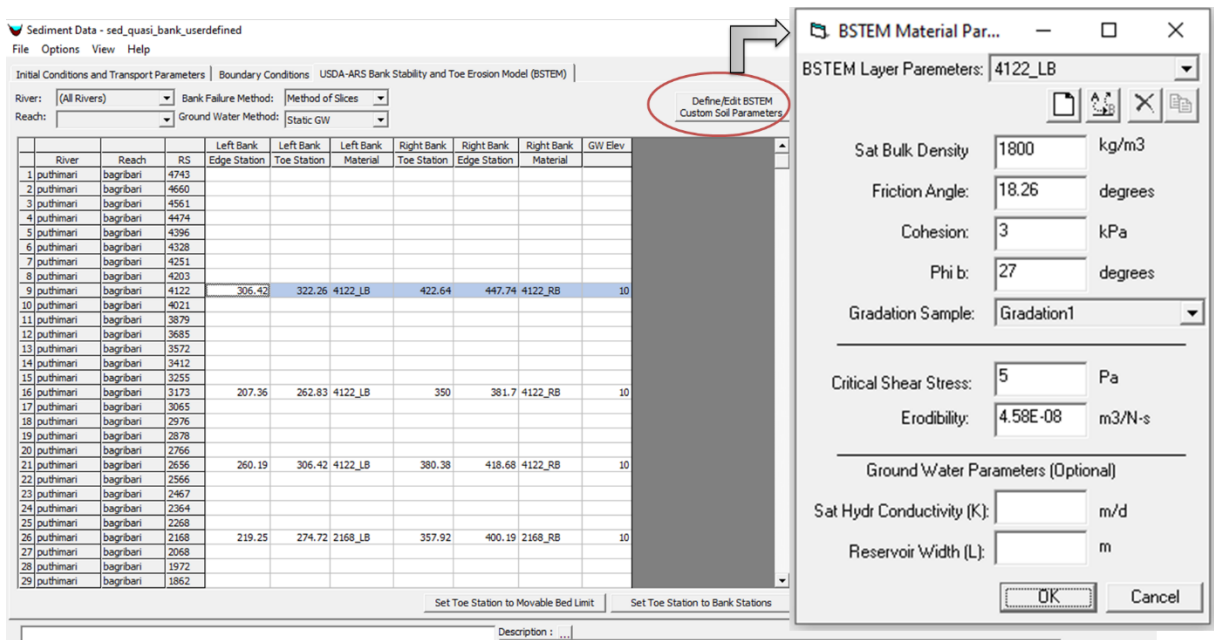


Fig. 4.10 Window for data entry in the BSTEM model

Finally, the plan file was created as shown in Fig. 4.11 and the sediment transport model was simulated.

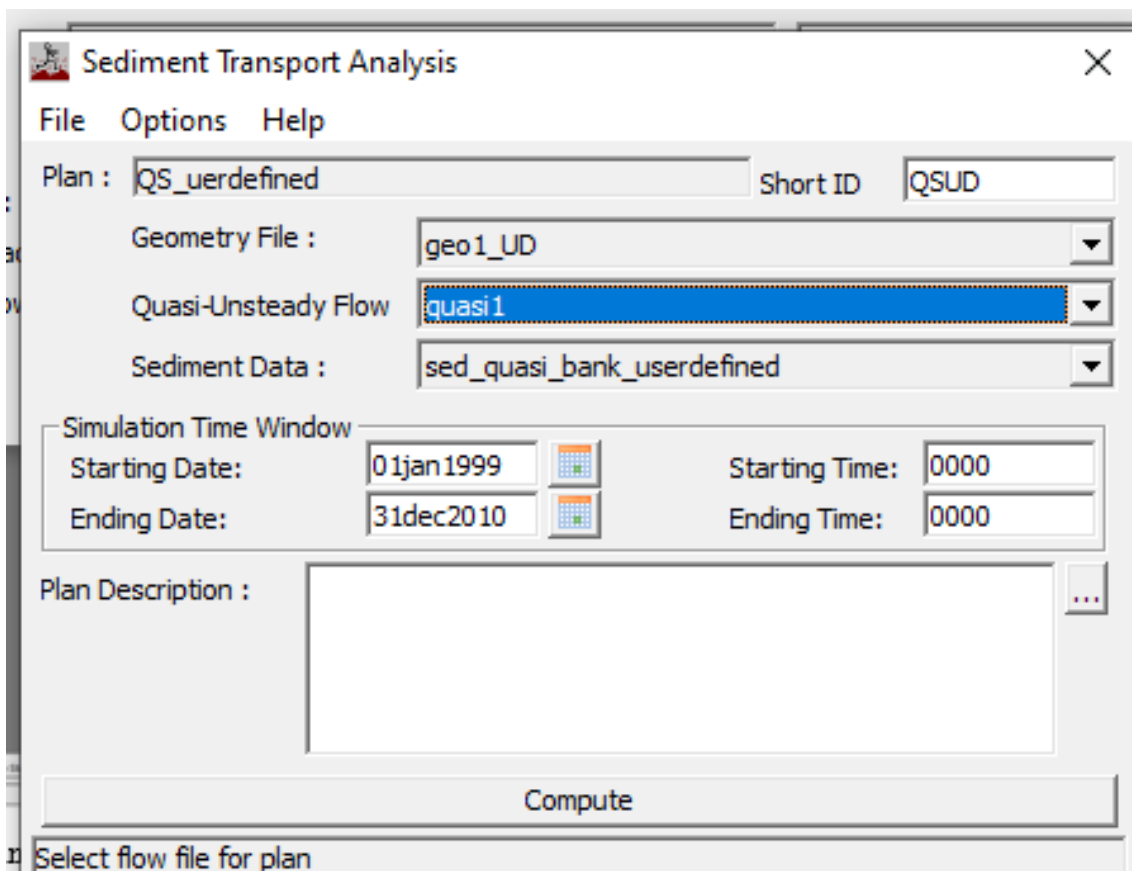


Fig. 4.11 Plan file for sediment transport analysis

4.3.1 Findings from the sediment transport analysis

Several cross-sections were initially generated during the creation of the geometry file in HEC-RAS. Fig. 4.12 shows a few sample cross-sections typically displaying information about the river station, channel banks, water surface profiles, and energy grade lines.

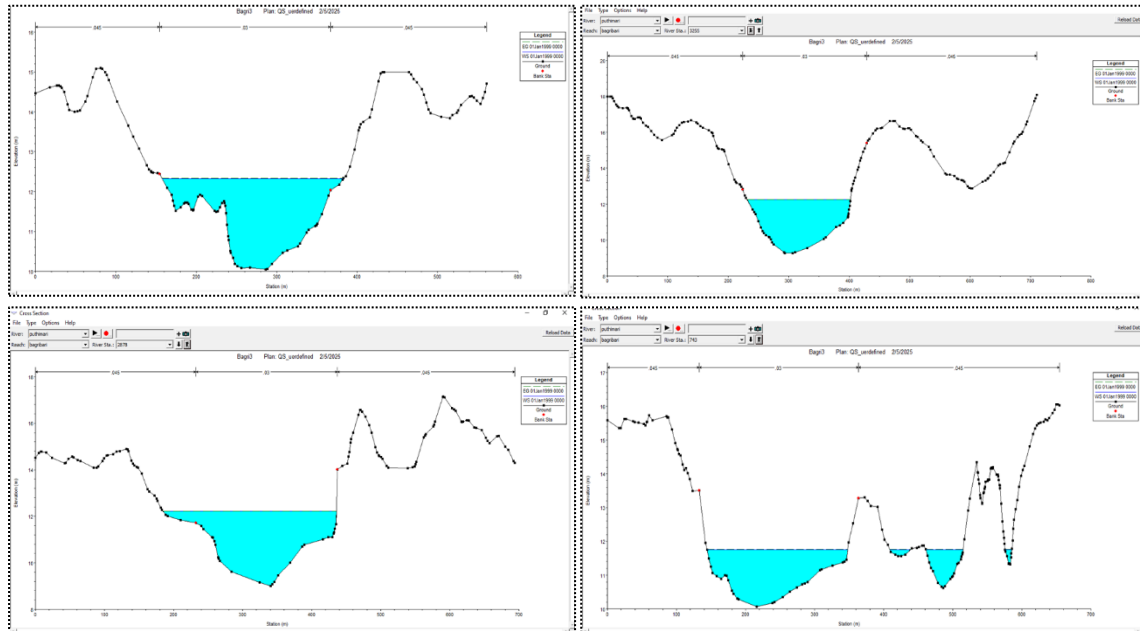


Fig. 4.12 Cross-sections generated from geometry in HEC-RAS

Simulation of the flow file gives the output for depth (max), velocity (max), and water surface elevation (max) which can be visualized in the RAS-Mapper. The maximum depth of the water during the simulation, indicating areas of inundation. The maximum water velocity during the simulation, highlighting areas of strong flow. The maximum water surface elevation reached during the simulation. Fig. 4.13 represents the 1D flow simulation outputs for depth (LHS), velocity (middle) and water surface elevation (RHS) respectively.

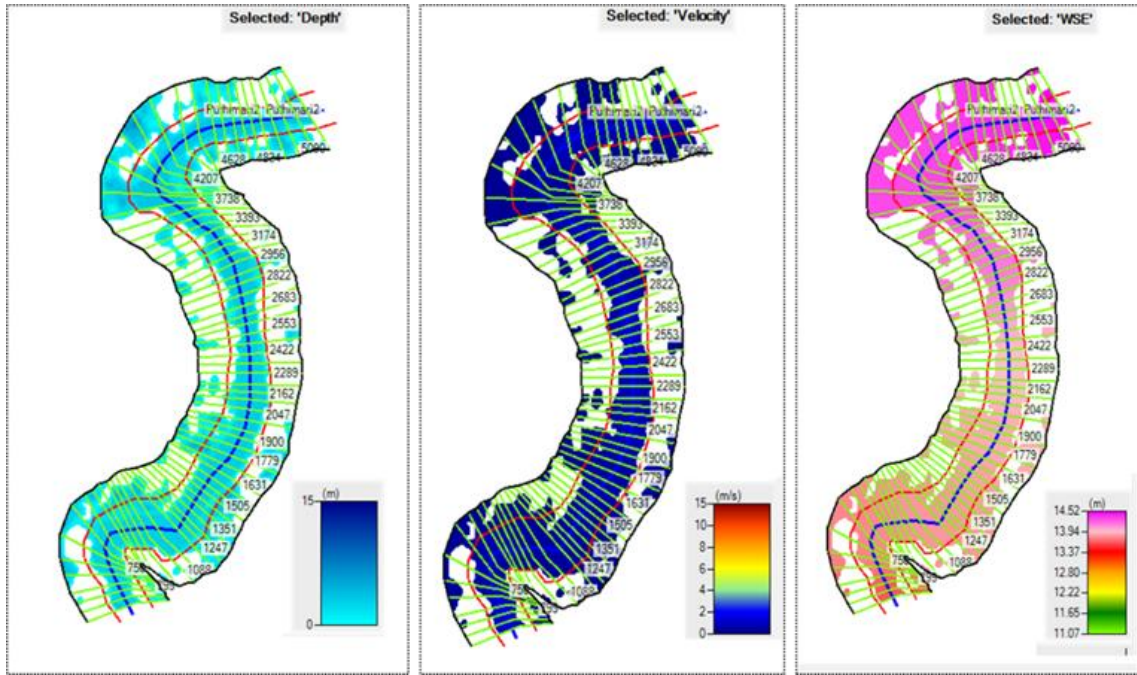


Fig. 4.13 HEC-RAS output showing depth, velocity and Water Surface Elevation

The BSTEM simulation gives the Factor of Safety values for the entire time series for the selected cross-sections for both the left and right banks. Fig. 4.14 shows the left bank factor of safeties while Fig. 4.15 show the right bank factor of saftelies.

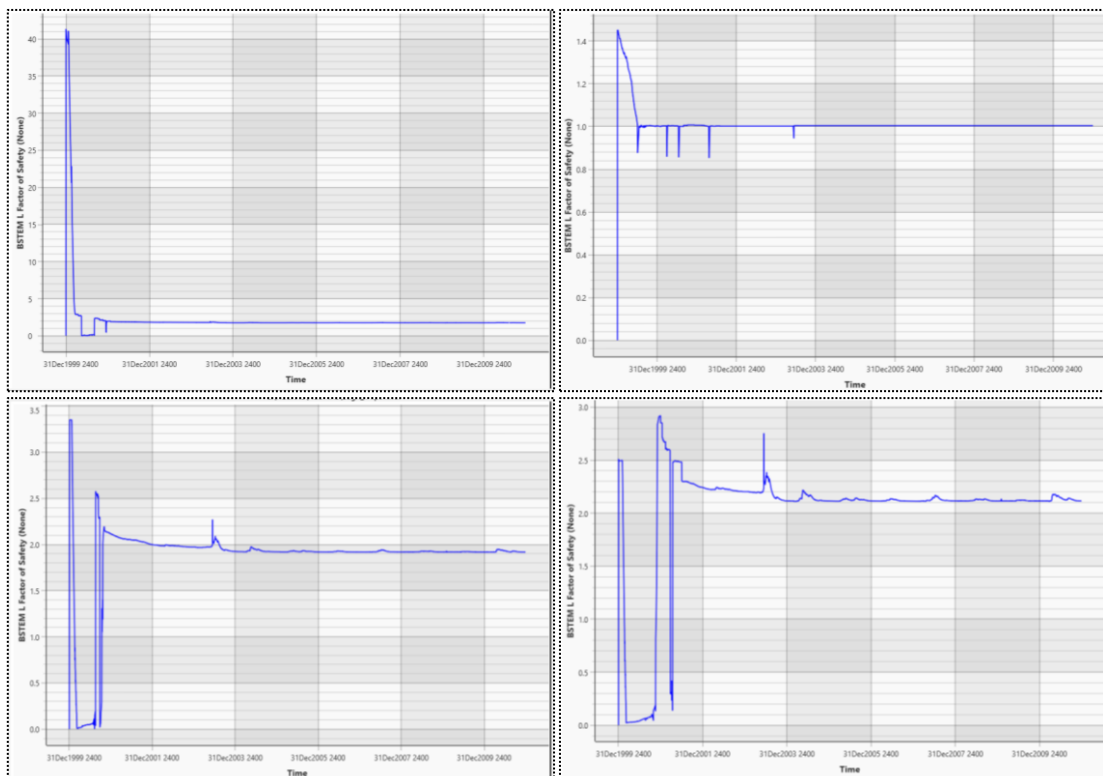


Fig. 4.14 Factor of safety for the left bank cross-sections

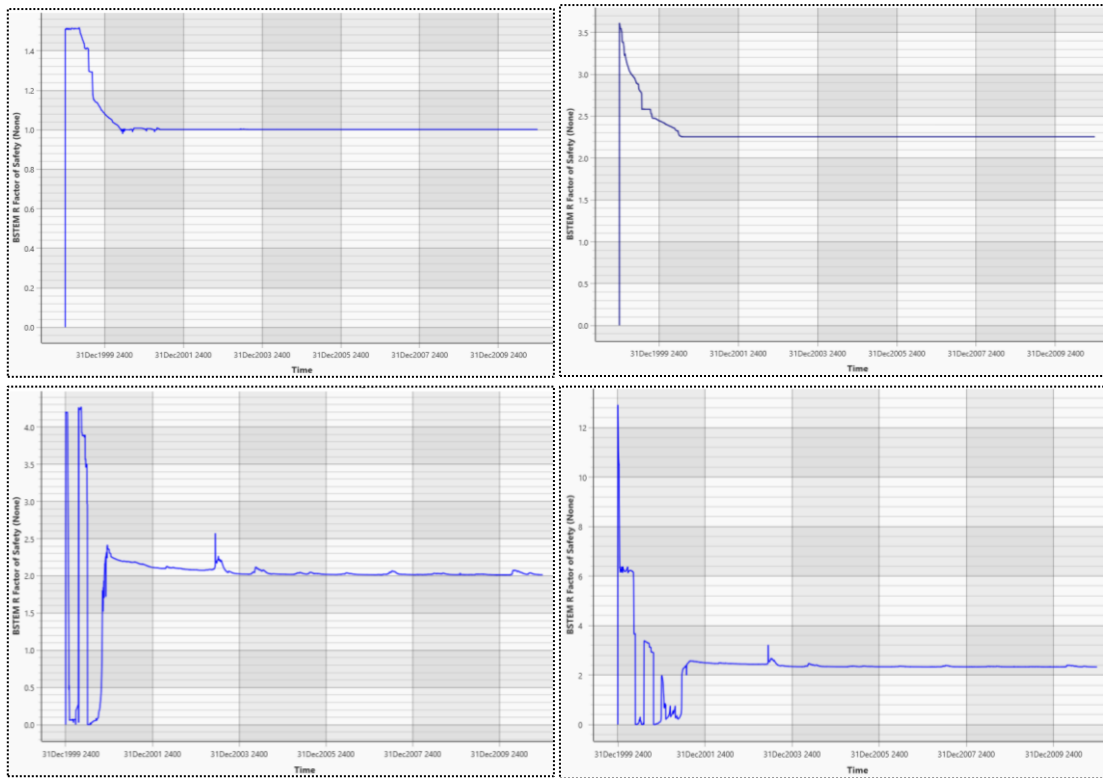


Fig. 4.15 Factor of safety for the right bank cross-sections

Factor of Safety (FoS) is a numerical value that represents how stable a structure or slope is under given loading conditions. It is calculated as:

$$FOS = \frac{\text{Resisting Force}}{\text{Driving Force}}$$

A Factor of Safety value of greater than equal to 1.5 is considered as safe, while below this, the bank is considered unstable. A value of 1.5 or more means that the resisting forces are at least 1.5 times greater than the driving forces. This provides a safety margin to account for uncertainties (e.g., variation in soil properties, loading, or groundwater conditions). Therefore, the slope or bank is considered safe. If the value drops below 1.5, it means the margin of safety is too low. The bank is more vulnerable to failure, particularly under external triggers like rainfall, river flow increase, or toe erosion. Hence, it is considered unstable or at risk of failure.

In the Bagribari area, the Factor of Safety (FoS) values across the selected cross-sections vary over time. The bank sections were predominantly vulnerable during the early years (1999–2003), exhibiting lower FoS values. This period possibly witnessed higher erosion or unfavorable hydrological conditions. In the later years, the FoS values improved,

indicating relatively enhanced stability. This could be due to natural bank stabilization, reduced erosive flow, or human interventions (e.g., embankments, vegetation growth). However, the banks are still not completely safe from erosion. Despite improvements, FoS values may still be below 1.5 in some sections or fluctuate due to seasonal or flow-related factors. The area remains partially vulnerable, especially during high-flow events.

The soils along the banks for the Bagribari area were found to be predominantly silt. Silty soils have low cohesion, which makes them weak in holding together under stress. Additionally, silty soils possess a relatively low angle of internal friction, indicating limited resistance to shear forces, especially when saturated. During high river flows or prolonged rainfall, silts easily absorb water, which further reduces their strength and increases susceptibility to mass failure. This combination of low cohesion and low friction angle results in reduced shear strength, making silty riverbanks vulnerable to slumping, toe erosion, and progressive failure. Consequently, sections of riverbanks composed primarily of silty soils often exhibit lower Factor of Safety values and require special attention in erosion control and stabilization planning.

4.4 Suggested measures for bank protection

For the Puthimari River in Assam, which likely experiences seasonal flooding and bank erosion due to high monsoonal flows, silt-dominated banks, and dynamic meandering, the following bank protection measures may be suggested:

Geobag revetments, consisting of sand-filled geotextile bags, are an effective and practical solution for protecting eroding riverbanks, particularly at critical toe locations. These bags are typically placed in a layered, pyramid-style arrangement (3-4 layers) along vulnerable bank sections (gentle slope 1V:2H) to enhance stability. This method has been successfully implemented in Assam, especially along the tributaries of the Brahmaputra River. Geobags help absorb the energy of flowing water, reducing its erosive force and preventing toe scouring, which is often the initial trigger for bank failure. Their ease of deployment and proven local effectiveness make them a suitable and affordable option for riverbank protection in erosion-prone regions.

Vegetative bank stabilization involves planting fast-growing, soil-binding vegetation such as vetiver grass, Napier grass, and native bamboo or shrubs to reinforce vulnerable riverbanks. These species are known for their deep and fibrous root systems, which enhance soil cohesion, particularly in silty banks, thereby improving long-term slope stability. This

nature-based solution not only reduces erosion but also offers a cost-effective and environmentally sustainable approach to bank protection, with added ecological benefits such as habitat restoration and landscape greening.

As a medium-term, moderately engineered solution, the **construction of permeable spurs or deflectors** can effectively reduce riverbank erosion. These structures, typically made of wood or boulders and angled upstream, are designed to divert the river's flow away from vulnerable banks, thereby minimizing direct hydraulic attack. Submerged or low-head spurs are particularly beneficial as they prevent excessive flow concentration while allowing sediment-laden water to pass through. Over time, these permeable structures encourage sediment deposition in their wake, gradually reinforcing the bank and contributing to its natural stabilization.

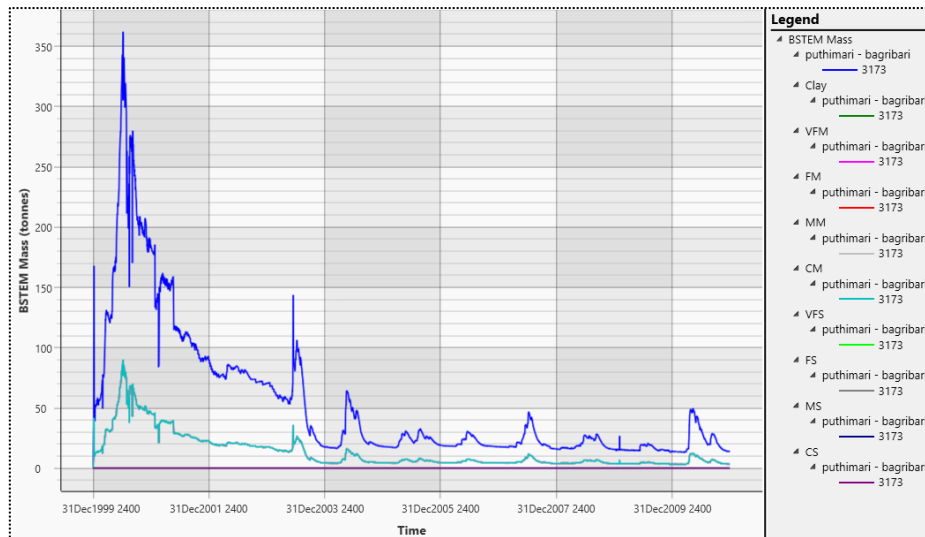
Stone or boulder toe pitching involves placing large stones or boulders along the toe of riverbanks, particularly in accessible areas, to serve as a protective armor against erosion. This method is highly effective in preventing toe cutting, which is often the primary cause of bank instability. By shielding the base of the slope from the erosive action of flowing water, toe pitching significantly reduces basal erosion. It is a durable solution with a long operational lifespan and generally requires minimal maintenance, making it a reliable option for strengthening riverbanks in high-risk zones.

As a long-term and integrated measure requiring higher investment, the **construction or reinforcement of earthen embankments** offers sustained protection for flood-prone areas. These structures should be built with proper slope protection, such as turfing or stone pitching, to ensure stability and durability under hydraulic stress. Incorporating internal drainage systems is essential to prevent internal erosion or piping during periods of high flow. When properly designed, embankments not only safeguard nearby villages from flooding but can also accommodate community access routes, enhancing both resilience and local connectivity.

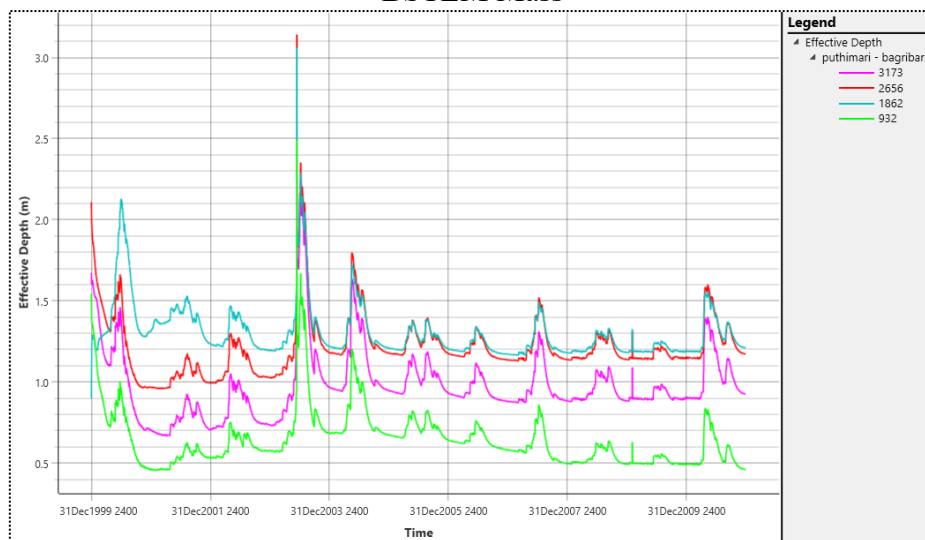
These interventions aim to stabilize the river course, reduce excessive meandering, and protect vulnerable bank sections.

4.5 Other important outputs from BSTEM simulation

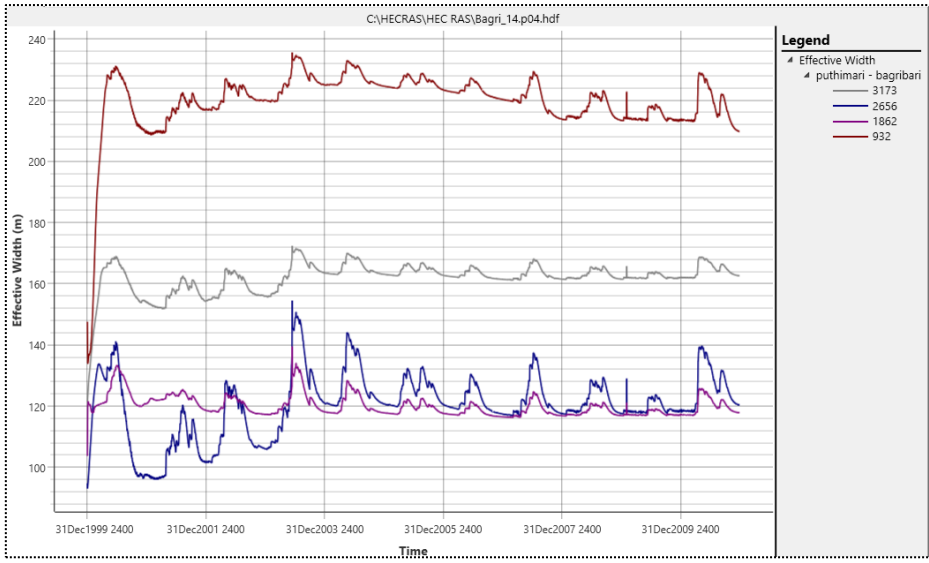
The other important outputs obtained from BSTEM simulation include, Mass failure along both the banks, effective depth, effective weight, fall velocity, Froude number, invert change, mass in, mass out, mass interactive, sediment concentration, shear stress, shear velocity etc. Below are the figures for some of the outputs obtained from the sediment transport analysis.



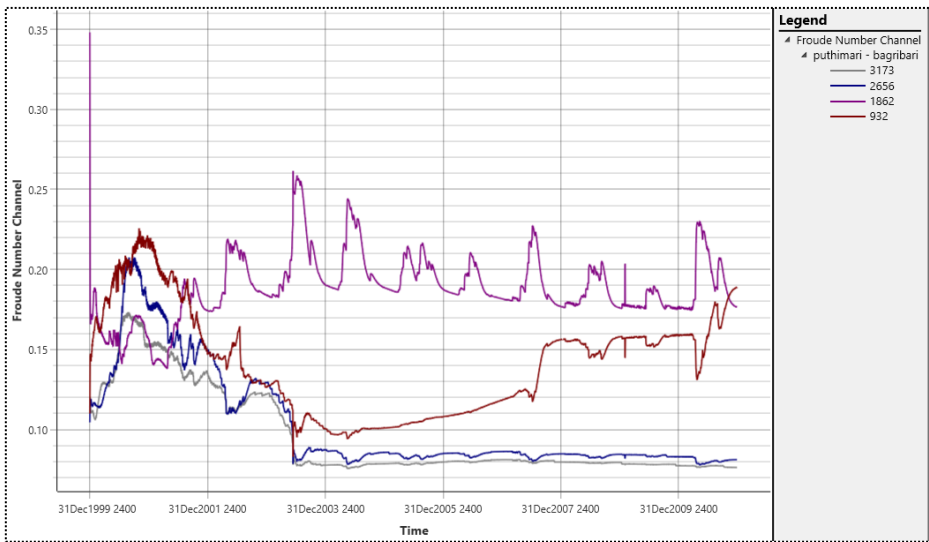
BSTEM Mass



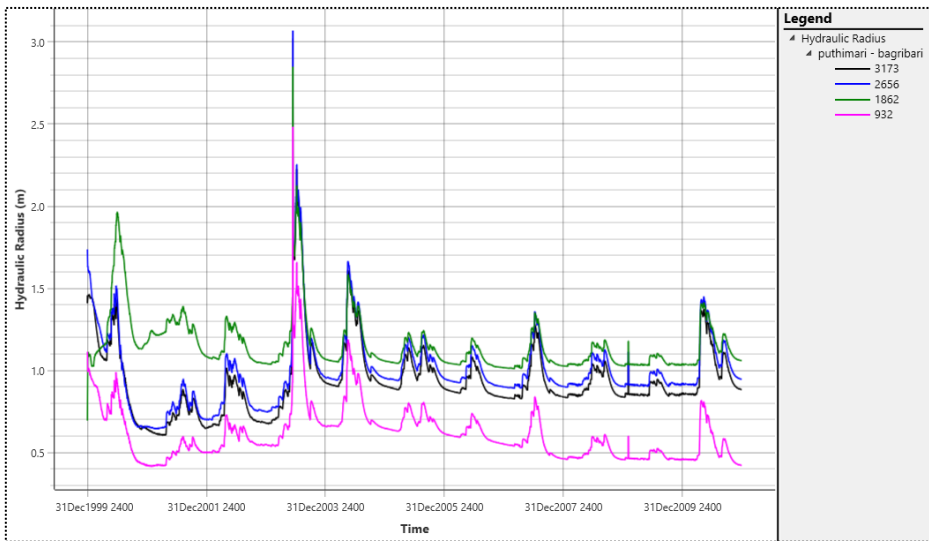
Effective depth



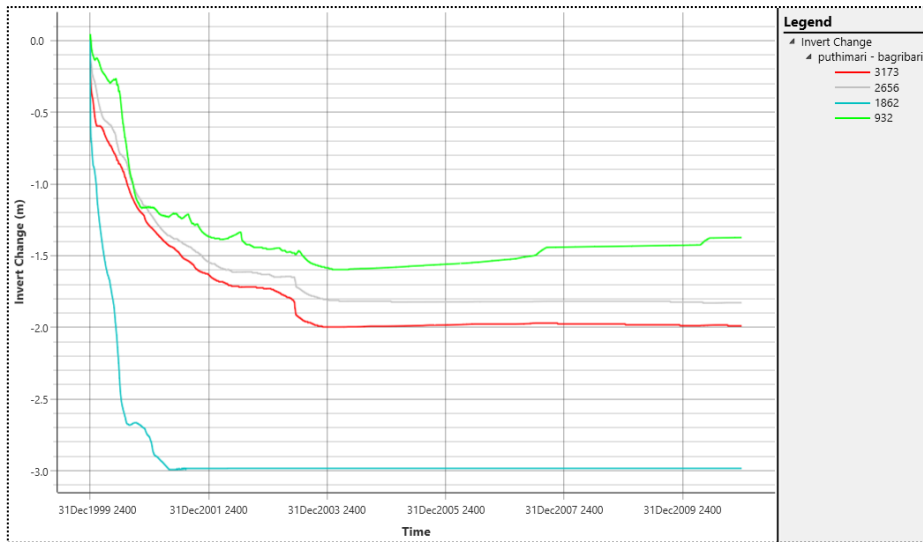
Effective width



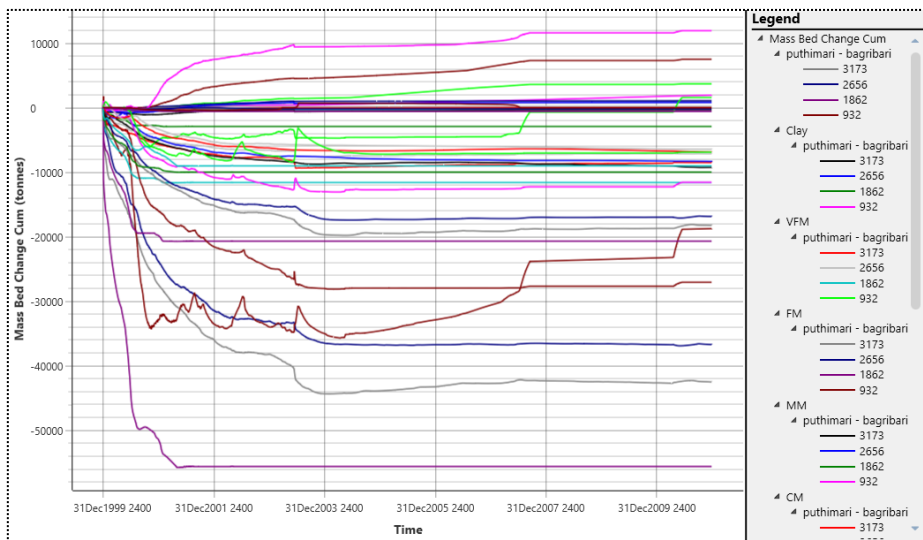
Froude number



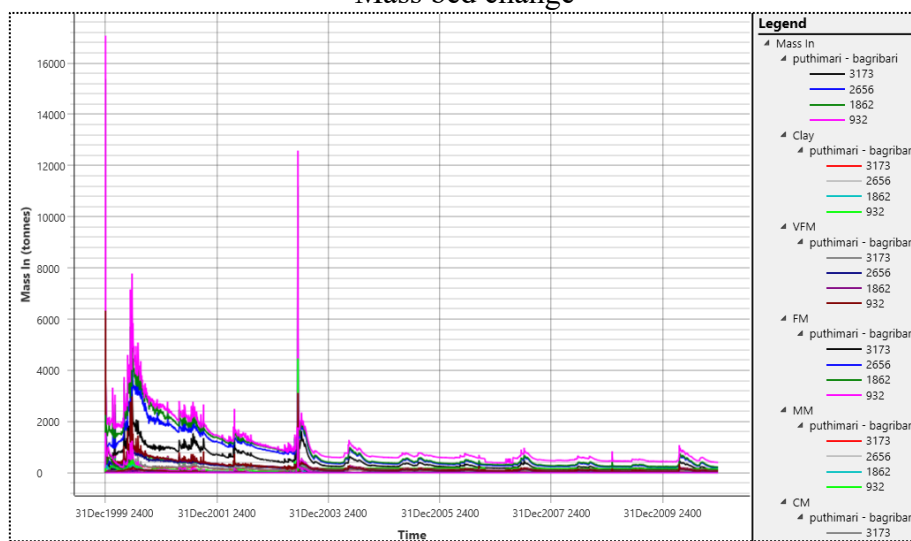
Hydraulic radius



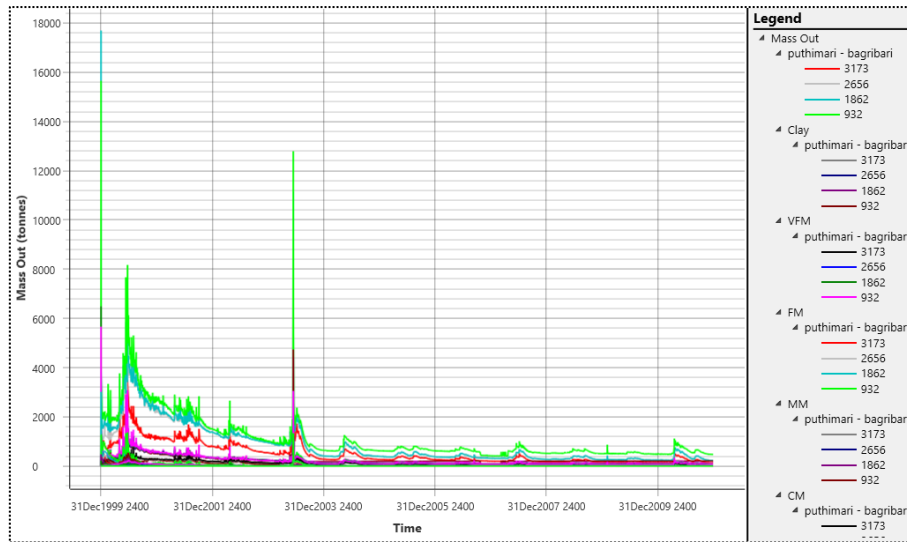
Invert change



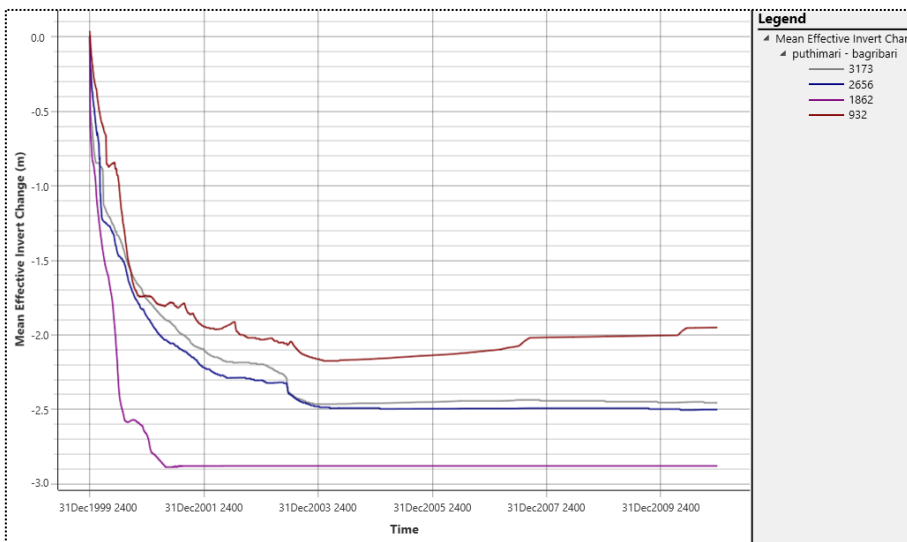
Mass bed change



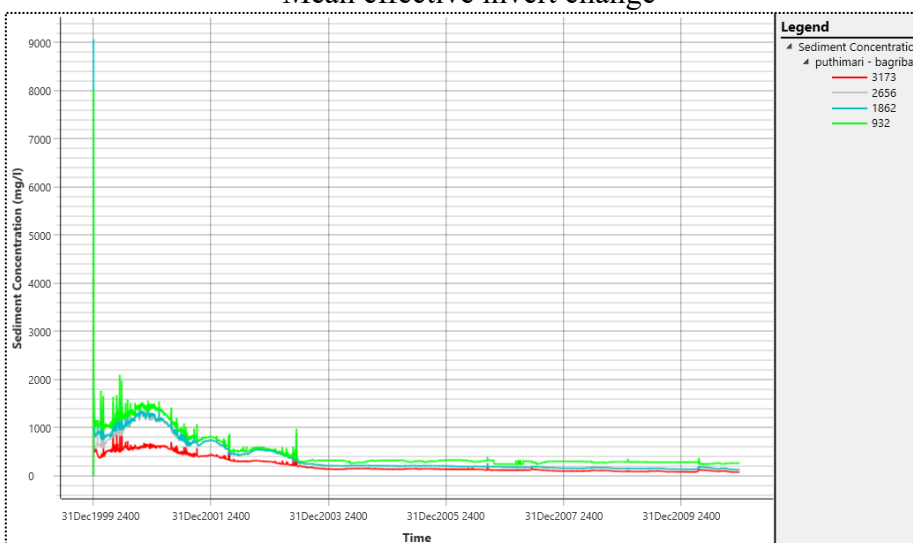
Mass in



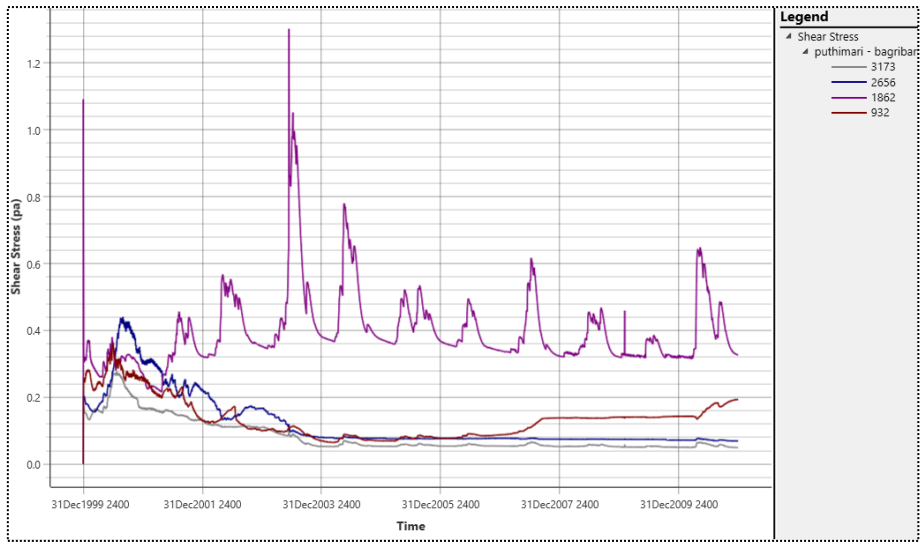
Mass out



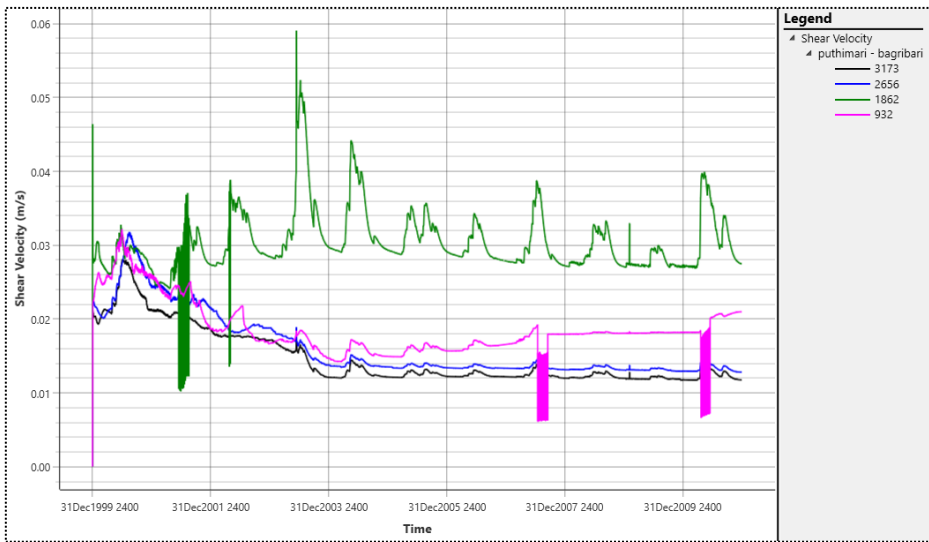
Mean effective invert change



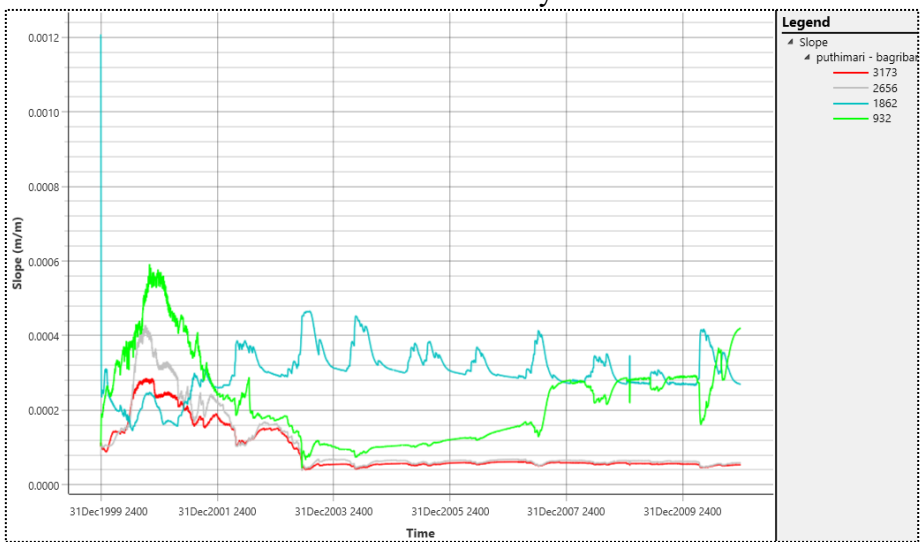
Sediment concentration



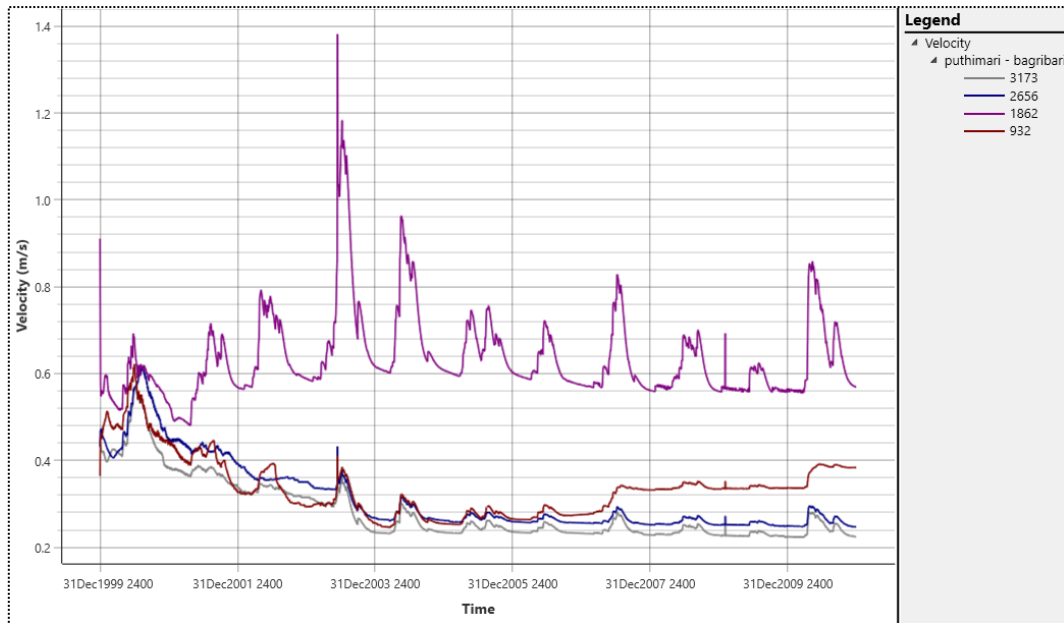
Shear stress



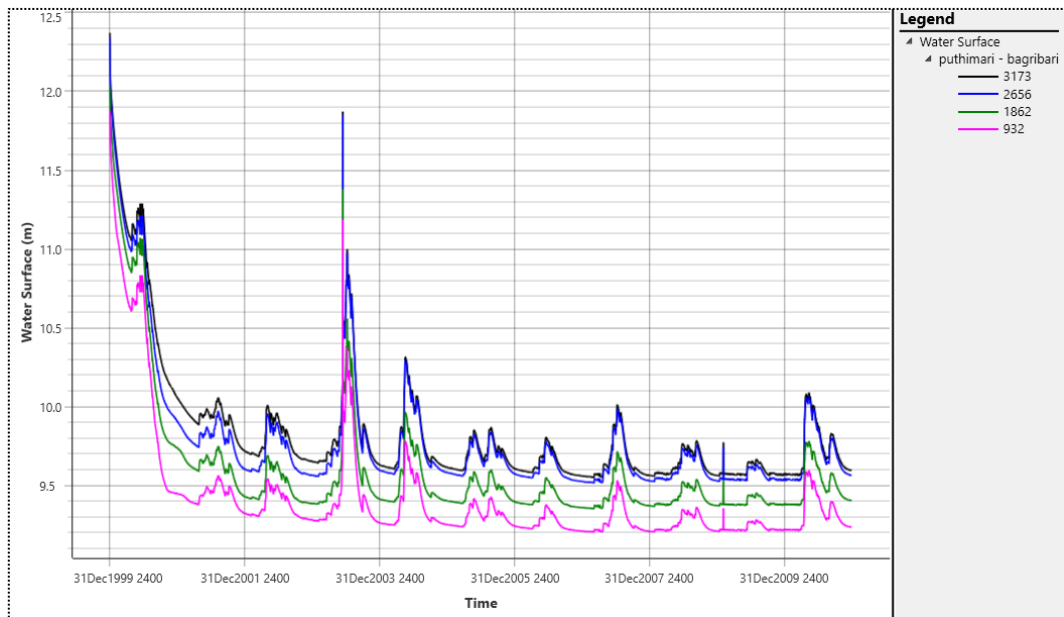
Shear velocity



Slope



Velocity



Water surface

Fig. 4.16 Some important outputs of HEC-RAS sediment transport model simulation

CHAPTER 5 SUMMARY AND CONCLUSIONS

The current study aimed to develop a coupled hydrological-sediment transport-bank stability model to understand the bank erosion processes along the river Puthimari in Bagribari area in Assam. The SWAT hydrological model was initially simulated to get the calibrated discharge at the study area location. SWAT performed well for both calibration and validation. The respective Nash-Sutcliffe Efficiency (NSE) values for calibration and validation were found to be 0.74 and 0.77. Also, 0.75 and 0.79 coefficient of determination (R^2) values were obtained for calibration and validation, respectively.

A 1D sediment transport model was developed in HEC-RAS, incorporating the Bank Stability and Toe Erosion Model (BSTEM) module to analyze both riverbank and bed erosion processes. BSTEM, integrated within the HEC-RAS 1D sediment transport framework, enables the simulation of riverbank failure mechanisms arising from fluvial erosion at the toe and geotechnical instability of the bank mass.

To set up the model, three key input files were prepared: the geometry file, flow file, and sediment file. The geometry was generated using ALOS DEM data with a 12.5-meter resolution. For the quasi-unsteady flow input, SWAT-simulated discharge was used as the upstream boundary condition, while the normal depth condition was applied at the downstream end.

A field reconnaissance survey was conducted in the study area to observe on-ground erosion patterns and collect soil samples from both the riverbanks and the channel bed. These samples were analyzed in the laboratory to determine key engineering properties. The analysis revealed that the majority of the soils were silty with medium compressibility. Using these properties, the sediment file was developed. A sediment rating curve was used to define the upstream boundary condition for sediment input, and sediment load values corresponding to three different flow magnitudes were derived and incorporated into the model. Additionally, sediment gradation data for each flow-load combination was provided.

Subsequently, a plan file was created by integrating the geometry, flow, and sediment files, and the model was executed. The simulation generated a range of outputs for both bed elevation changes and bank stability parameters. The results showed that the Factor of Safety (FoS) for selected cross-sections was below the critical threshold (typically 1.5) during the early years of analysis, indicating unstable banks. Geobag revetments, vegetation bank stabilization, construction of spurs, boulder toe pitching, construction of earthen embankments are some of the suggested measures for bank protection in the Bagribari area.

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