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Riverbank Erosion and Vulnerability Assessment for the Alluvial Section of Barak River in North-East India by In-situ Approach

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ABSTRACT

Riverbank erosion is a significant and distinct problem in the floodplains of alluvial rivers in North East India. The Barak River has experienced an alarming increase in bank erosion rate over the last few decades, resulting in embankment breaches and biodiversity loss, but there is a dearth of field studies to evaluate riverbank fluvial erosion. This study aims to assess the river bank erosion and Vulnerability Assessment of the Barak River in India using an in-situ submerged Jet Erosion Test (JET). The riverbank erosion was estimated for a span of the riverbank on one side of the stream using the excess shear stress equation and impinging jet theory. Data was collected using a JET along the riverbank to determine the erodibility parameter of the bank soil. The results show that the spatial variation in erosion parameters of river banks varies significantly, which is dependent on the specific location. Annual bank erosion was computed using measured erodibility parameters and stage record data, which shows the bank erosion of the Barak River will occur in many places, particularly at the critical area. The measured bank erosion was compared with the observed satellite imagery map for the 2000 – 2020. This study shows that JET results should be used with caution; further, the findings can be helpful in planning river training and management strategies for vulnerable areas and may serve as a model for similar alluvial river studies.

1. Introduction

Erosion of riverbanks is a severe concern for river engineering practices in many nations. River bank erosion is the natural process of wearing away and weakening a river's banks, typically caused by the flow of water. Many factors, including changes in river flow, such as increased water volume or velocity, changes in river course, and riverbed erosion, can cause river bank erosion. Human activities such as dam and levee construction, deforestation, and land-use changes can also exacerbate river bank erosion. Millions of people worldwide are affected by riverbank erosion every year. One of the worst instances of riverbank erosion occurred in September 2018 in the Naria region of Bangladesh, rendering approximately 5000 families homeless (Tha et al., 2022).

Assessment of riverbank erosion due to moving water in composite river banks is complex (Hanson and Simon, 2001). Every year, a significant amount of floodplains are lost due to river bank retreats. This involves severe socioeconomic impacts, including loss of biological diversity, increased costs of bank strengthening, and loss of riparian area and infrastructure (e.g., Bernhardt et al., 2005; Barman et al., 2019). The river authority is investing substantial money in protecting the river bank. However, a considerable amount can be conserved by evaluating the spatiotemporal variation in riverbank erodibility.

To estimate river bank erosion, measurements of critical shear stress and the erodibility coefficient are of utmost importance. The critical shear stress (τ_c) is the maximum shear stress produced by running water, beyond which soil starts to be eroded. Generally, the soil erosion rate for the cohesive riverbank or riverbed is directly proportional to the surplus shear stress (Partheniades, 1965; Hanson, 1990a, 1990b; Hanson and Temple, 2002).

$$\varepsilon_r = K_d(\tau_a - \tau_c)^a \tag{1}$$

where ε_r is the rate of erosion in (ms^{-1}), K_d is the detachment coefficient (cm^3/N-s), τ_c represents the critical shear stress in Pascal, and a refers to the exponent usually assumed to be 1. While τ_a is the developed hydraulic shear stress ($\tau_a = \gamma_w RS$, here γ_w is the specific unit weight of water, R_h is the hydraulic radius,

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and S is the average channel slope (Daly et al., 2015). Erosion occurs (ε_r) only when the developed hydraulic shear stress is higher than the critical shear stress. The determination of soil erodibility parameters (τ_c and K_d) of riverbank soil is a complex task (Grissinger, 1982).

Extensive research has been carried out on the erosion parameter of soil samples, analyzing several soil parameters like soil structures, clay content, soil moisture content, clay mineralogy, and biochemical features of the river (Grissinger, 1982). It is challenging to assess erodibility parameters because of the influence of several variables (Grissinger, 1982). Several methods for determining erosion parameters, such as flume studies, hole erosion, water tunnels, rotating cylinder tests, and submerged jet tests, have resulted in significant outcomes (Hanson and Cook, 1997; Hanson and Simon, 2001; Wan and Fell, 2004; Clark and Wynn, 2007). Shields' diagram (SD) is a widely used method for calculating the critical shear stress for homogeneous and cohesionless soils based on particle size diameter (Shields, 1936; Haan et al., 1994). Based on these experimental findings, other researchers have proposed more direct methods for estimating τ_c from various soil parameters, including plasticity index (PI), average particle size (D_{50}), dispersion ratio (D_r), and % clay (P_C) (Smerdon and Beasley, 1961), percentage of silt-clay index (Julian and Torres, 2006), and compressive strength (Kamphuis and Hall, 1983). Once τ_c is determined, K_d can be evaluated using various empirical formulae (Hanson and Simon, 2001; Wynn et al., 2004; Simon et al., 2011).

Despite the availability of various approaches, predicting riverbank erosion and identifying the most vulnerable location is challenging due to the dynamic and unpredictable nature of the river channels (Winterbottom and Gilvear, 2000). Few mathematical river models are available for estimating the rate of bank erosion. Popular models such as the Bank Stability and Toe Erosion Model (BSTEM) and the Generalized Sediment Transport Model for Alluvial River Simulation (GSTAR) have been used in predicting bank erosion problems in a river (Simon et al., 2000; Yang et al., 2005). According to Midgley et al. (2012), the BSTEM model underestimates the rate of bank erosion. However, Nardi et al. (2013) created a hybrid of bank stability approaches and hydrodynamic models to anticipate vulnerable locations and estimate erosion rates. The former has a relatively high degree of inaccuracy. In contrast, the second is too hard to apply because it requires substantial data variables to calibrate and validate these models, which are often nonexistent in developing countries. Therefore, the high precision in determining the erodibility parameter in-situ experiments is advantageous. A submerged Jet erosion test (JET) device is an innovative field method developed by (Hanson, 1990b) that enables greater adaptability to diverse soils and climatic conditions. The submerged jet test is preferable to the flume test because it is performed manually on the whole riverbank without determining the sample preparation. Many researchers, including Hanson and Cook (1997, 2004) and Daly et al. (2013), have recommended using jet test findings to compute the erodibility parameters (τ_c and k_d). A detailed explanation of the submerged jet apparatus and testing procedure is further described (Hanson and Cook, 1997; Hanson and Simon, 2001; Daly et al., 2013). Recent research with this apparatus reveals the critical shear stress τ_c and erodibility coefficient k_d ranges for various study sites. Hanson and Simon (2001) found, after completing 83 jet experiments on river beds of highly erodible soft soil in the Middle west of the United States, that τ_c can vary from 0 to 401 Pa and k_d is between 0.001 to 3.76 (cm^3/N-s). Karmaker and Dutta (2011) investigated the erosion parameters of different locations along the Brahmaputra in India, showing ranges of 0.1 to 100 Pa for τ_c and 0.520 to 11.29 cm^3/N-s for k_d. Semmad and Chalermyanont (2018) conducted a process-based riverbank retreat assessment along the U-Tapao River basin of Thailand; erosion parameters τ_c and k_d of the eroded bank soils varied from 4.42 to 20.92 Pa and 2.51 to 39.91 cm^3/N-s respectively. However, in an alluvial river bank, the properties of the soil particle size vary from place to place. The main variation of soil particles is the silt-clay content, which is crucial for identifying fluvial erosion and mass failure of soil (Darby et al., 1996). The main drawback of the JET erosion test is that it cannot estimate the whole amount of river bank erosion. Even so, this test can be employed to determine the soil erodibility of the alluvial river at a particular site. It is possible to model the processes of bank erosion using soil erodibility measurements in order to estimate the overall bank erosion.

The Barak River is one of the major rivers in the northeast region of India, known for its dynamic and meandering nature that flows through the alluvial plains of the Barak Valley in southern Assam. The Barak River was selected as the study area because it experiences severe bank erosion every year due to the high stream flow and sediment transport during the flood period. The river undergoes many changes through spatial and temporal indications of the shifting of the river course and causing large-scale erosion in the river. Furthermore, various locations along the Barak River have documented considerable bank shifting, a significant safety concern in the region. A recent study on centerline channel shifting and erosion studies shows that this river has been shifting its course in the right direction towards downstream (Annayat and Sil, 2020a). Despite all the visible changes in the river Barak, a comprehensive erosion study of the Barak River basin by an in-situ study like (JET Apparatus) has not been conducted. The literature research revealed that most bank erosion studies utilize remote sensing and GIS. Nevertheless, geospatial technology does not consider soil erodibility parameters. Therefore, to analyze the riverbank's hydraulic and soil erodibility parameters, the present study aims to understand the riverbank erosion process by studying the variation of the in-situ erodibility parameter along the composite riverbanks of an alluvial river Barak. Thus, the detailed aim of the study is outlined below.

To analyze river bank erosion (fluvial erosion) by estimating the variation of the erodibility parameter of the alluvial section of the Barak River using in situ submerged JET Apparatus.

To determine the annual riverbank erosion and identify the riverbank locations that are more vulnerable to erosion.

2. Material and Methods

2.1 Study Area

The study area considered in the present work is the Barak River. It is the second largest river in North-East India and Assam, with a length of 130 kilometers and a drainage area of 24,000 sq. km, as shown in Fig. 1. It is the most crucial river basin in North-Eastern India, with a population of 2.98 million people. It starts in the Japvo mountain range in the Manipur hills and flows south through hilly slopes to Tipaimukh, near Mizoram and Assam. At last, it flows into Bangladesh, where it splits into two rivers, Surma and Kushiyara (Deb and Sil, 2019). The river runs mostly over the alluvial plains of the Barak valley of Assam before reaching the Bay of Bengal via Bangladesh. The study area in Assam runs from upstream Fulertal Ghat to downstream Bhadarpur Ghat. In the last 30 years, there have been five significant floods: 1986, 1991, 2004, 2007, and 2022. The river exhibits several flood waves alongside the monsoonal response, which depends on the basin's annual average monsoonal rainfall. The region's average annual rainfall is around 2,400 – 4,000 mm, which accounts for more than 80% of annual precipitation and occurs between April to October (Choudhury and Ullah, 2014). The bed gradient of the Barak River is relatively flat, ranging from 1:10,000 to 1:20,000 from upper to lower reach (Jain et al., 2007). The average width of the Barak River is approximately 380 m (Annayat and Sil, 2020b). In this study, ten sites were chosen along the bank of the Barak River (see Fig. 1). Three sites are situated in the upstream part of the Barak River, namely Sonai, Sonabarighat, and Nagatilla. Two sites are located in the middle part of the Barak River, Krishnagar and Tarapur Nathpara. The remaining sites are located in the lower portion of the Barak, named Srikona-Surtara, Pherighat Rajnagar, Katakhal, Kalinagar, and Panchgram.

2.2 Methodology

2.2.1 Measurement of Erosion Parameters

The soil erosion parameters can be experimentally determined using an in situ Submerged Jet erosion apparatus for cohesive soil. Hanson (1990b) designed the device; the device uniformly distributed a circular jet through the nozzle at a uniform velocity, imparting shear stress in the soil bank. Accordingly, the generated eroded depths are measured, and their time profiles are used to calculate the erosion parameters (τ_c & k_d). Critical shear stress τ_c tells us when the soil will start eroding, and the erodibility coefficient k_d tells us how fast we can expect that soil to erode once it is actually eroding. Estimates of the soil erodibility parameters have been developed by various scholars. Hanson and Cook (1997, 2004) and Hanson (1990b) developed a mathematical

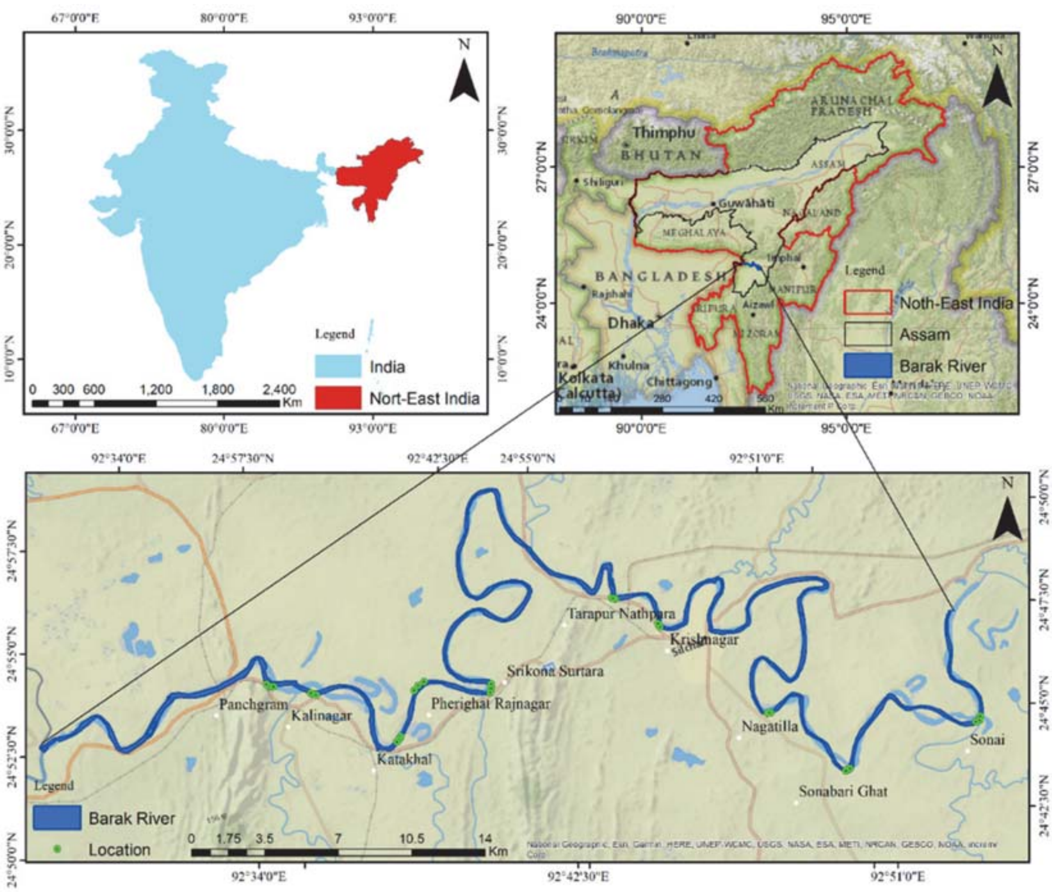

Fig. 1. The Barak River of North-Eastern India and Locations of Ten Field Sites (circles) at Which JET Tests Were Conducted

procedure to direct an estimate of τ_c and k_d by fitting a hyperbolic logarithm equation to the scour depth vs. time, whereas erodibility coefficient k_d was determined by fitting the scoured data to the surplus shear stress equation (Eq. (1)). The critical stress (τ_c), is determined when the rate of scouring is identical to zero at the equilibrium scour depth (J_e).

$$\tau_c = \tau_0\left(\frac{J_P^2}{J_e^2}\right), \tag{2}$$

where $\tau_0 = c_f \rho_w U_i^2$ is referred to as the maximum shear stress induced at the jet nozzle due to the flow velocity (Pa), C_f represents the coefficient of friction, its average value for turbulent flow conditions is approximately 0.00417 (Beltaos and Rajaratnam, 1974; Hanson and Cook, 2004), ρ_w refers the fluid density, $U_i = \sqrt{2gh}$ defines the velocity of the jet nozzle, g stands for the acceleration of gravity, and h is the difference of the pressure head. $J_P = C_d d_0$ is the core length from the jet orifice (cm), d_0 is the diameter of the jet nozzle, and C_d is the diffusion constant, with reported values ranging from 5.8 to 7.4 and an accepted average of 6.2 (Beltaos and Rajaratnam, 1974). Imagine that the jet test is conducted over a considerable amount of time. In this hypothetical situation, the scour hole might get deep enough to reach the equilibrium depth, which is the point at which the rate of downward erosion ($Er \rightarrow 0$) tends to zero. One of the challenges in calculating the equilibrium scour depth (J_e) is that reaching equilibrium could take between a few hours to days (Blaisdell et al., 1981), and most field operations do not run tests long enough to obtain this condition. Therefore, the Blaisdell solution (BS) approach was developed to calculate soil erodibility parameters from JET test results. Blaisdell et al. (1981) suggested a hyperbolic logarithm Eq. (3) to calculate the equilibrium scour depth (J_e), the standard form of a hyperbolic equation.

$$(f - f_0)^2 - A^2 = X^2, \tag{3}$$

where A is defined as the rate of semi-transverse and semi-conjugate axes of the hyperbola function. $f = \log\left(\frac{J}{d_0}\right) - x$, $x = log\left[\frac{U_o t}{d_0}\right]$ and $f_0 = \log\left(\frac{J_e}{d_0}\right)$. By estimating the scour depth value based on plotting the graph between f versus x, the coefficients f_0 and A can be estimated using a Microsoft Excel solver, and then the required equilibrium ($J_e = d_0 10^{f_0}$) depth can be determined. In Excel solver, the Generalized Reduced Gradient (GRG) nonlinear method is used to determine the equilibrium depth of the scour hole by continuously minimizing the search of the spreadsheet with the initial value of coefficient (constraints) A = 0.5 and f_0 = 0.5. It has the option to choose from different initial values, increase the number of trials, or continue the search once J_e is obtained by the value of f_0. The critical shear stress (τ_c) is then determined. Whereas the k_d is calculated by fitting the scour data to the surplus shear stress equation based on the estimated scour depth, time, the predefined value of τ_c, and the non - non-dimensional time function, the detailed explanation was given by (Hanson and Cook, 2004); hence, it is not explained here.

2.2.2 In-Situ Measurement of JET Test

The experimental setup and test framework adopted in the present study of the in-situ submerged jet test are illustrated in (Fig. 2). This study conducted 40 in-situ submerged jet experiments at ten locations along the Barak River from upstream to downstream

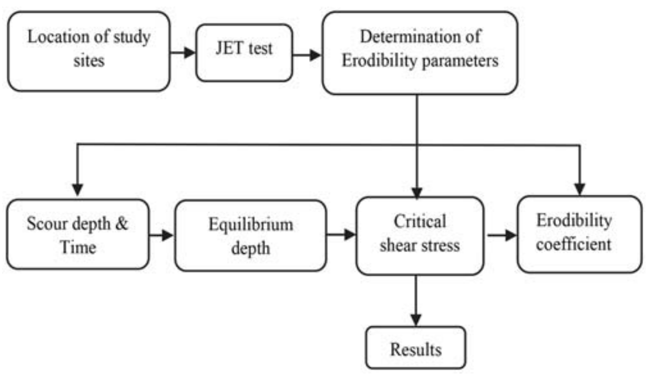

Fig. 2. Flow Chart of the JET Test

Fig. 3. Examples of Submerged JET Test Being Performed in the Bank of Barak River

during the mid-winter season of 2020 to 2021 at the low flow level (Figs. 1, see 3). At each location conducted, four submerged tests: twelve tests were performed in the upstream area (Sonai, Sonabarighat, and Nagatilla), eight in the middle stretch (Krishnagar and Tarapur Nathpara), and the remaining tests in the downstream area (Srikona-Surtara, Pherighat Rajnagar, Katakhal, Kalinagar, and Panchgram). The required site was chosen based on critical banks, accessibility, and the most flood-prone areas. Erodibility parameters (τ_c & k_d) are measured in situ using submerged JET. Before performing the test, it must be ensured that the soil consists of clay or silty soil, as tests cannot be conducted on the sand (Karmaker and Dutta, 2011). Before installing the jet-test device, the top of the surface layer must be cleaned. Each test was conducted for 45 minutes, during which pressure head differentials and scour depth data were collected at 5-minute intervals throughout the observation period.

2.2.3 Soil Testing

Disturbed soil samples were collected near the locations where the jet experiments were performed. For each test site, approximately 200 cm^3 of soil samples were collected, and all the soil samples were oven-dried for 24 hours before for analysis of an index property of the soil. The mean particle size distribution (D_{50}) was determined using sieve analysis according to the "IS 2720-4 (1985)". Soil samples less than 75 µm were analyzed using the hydrometer approach to calculate the percentage of silt-clay content (%SC) as per IS standard 2720-part 4. River bank soil Atterberg limits refer to the soil's liquid limit, plastic limit, and plasticity index as determined by ASTM D4318 (2005). Around the study sites, the river has some sand bars and vegetation cover on the banks of the Barak River.

In the present study, we compare the critical shear result with four empirical relationships based on soil index values given through Eq. (4) – (7). These include plasticity index (PI), average particle size (D_{50}), dispersion ratio (D_r), and % clay (P_C) (Smerdon and Beasley, 1961), based on the laboratory flume test results highlighted below.

$$\tau_c = 3.541 \times 10^{-28.10 D_{50}} \tag{4}$$

$$\tau_c = 0.49 \times 10^{0.018 P_C} \tag{5}$$

$$\tau_c = 0.16 (PI)^{0.84} \tag{6}$$

Julian and Torres (2006) proposed an empirical Eq. (7) to determine τ_c from the percentage of silt-clay contents (%SC).

$$\tau_c = 0.1 + 0.178(SC) + 0.00281(SC)^2 - 2.34 \times 10^{-5} \times (SC)^3 \tag{7}$$

Although there are no direct relationships between soil erodibility coefficient (Hanson and Temple, 2002), there are a few empirical approaches for determining k_d if τ_c is known. Such empirical relationships between k_d and τ_c, which are frequently power laws, were developed based on jet test results (Hanson and Simon, 2001; Wynn et al., 2004) as illustrated in Eqs. (8) and (9). Karmaker and Dutta (2011) studied the erosion parameters of several locations in India along the Brahmaputra River and reported jet test results that k_d is linked to τ_c, as given in Eq. (10).

$$k_d = 0.2\, \tau_c^{-0.5} \tag{8}$$

$$k_d = 3.1\, \tau_c^{-0.376} \tag{9}$$

$$k_d = 3.16\, \tau_c^{-0.185} \tag{10}$$

In which τ_c represents the critical shear stress (Pa) and K_d represents the detachment coefficient (cm^3/N-s).

2.2.4 Estimation of Annual Bank Erosion

Measurement of the developed shear stress is necessary to determine the annual bank erosion. It is developed because of the hydraulic shear force applied by the running water on the bank surface. The developed shear stress (τ_a) for each part of the streambank was computed using Eq. (11) (Leutheusser, 1963)

$$\tau_a = 0.76 \rho g d S\,, \tag{11}$$

where τ_a is referred to as the developed hydraulic shear stress (Pa) at a particular water depth,d is the height of the water from the top of the water level (m), ρ is denoted as the water density (kg/m^3, g stands for gravity (m/s^2), and S represents the EGL line's channel slope (energy gradient line). We calculated the annual bank erosion at ten locations where the jet test was performed. All the erodibility parameters for the particular banks were estimated, and the annual bank erosion was estimated annually for each riverbank site by a form of following the surplus shear stress equation.

$$\varepsilon = K_d(\tau_a - \tau_c)^1 \times \Delta_t\,, \tag{12}$$

where Δt represents the cumulative time for river erosion

In order to calculate annual bank erosion, the erosion rate was multiplied by the number of bankfull discharge days observed in a given year for fluvial erosion, which is the cumulative time for river erosion. Under these conditions, it is assumed that the discharge that forms in the river is the bankfull discharge (Chang, 1988). In this assessment, the river has to be considered a bankfull condition when its capacity is 90% or more. Based on the stage record data, the average annual number of bankfull discharge days was estimated for all ten locations. Stage record data have been collected from the local gauging site at Silchar. Local surveys and historical stage records in the Barak River show the presence of multiple flood events along the monsoonal change, which depends on the average monsoonal rainfall of the watershed every year.

2.2.5 Satellite Data Analysis

In this study, time-based satellite imagery analysis was performed to investigate the actual river bank erosion at the selected reach of the Barak River. The Landsat images with 30 m resolution of the Barak River representing the years 2000 and 2020 are obtained from the United States Geological Survey (USGS) for analysis. The 2020 image, captured by Landsat 8 (OLI), was taken on

Table 1. The Detailed Soil Properties Test Results from the Ten Study Sites

Site	Lat, long	Median size (D_{50}) mm	Pc (% of clay)	SC (% of silt-clay)	Bulk unit weight $\gamma\left(\frac{KN}{m^3}\right)$	Bank material
Sonai	24.744,92.873	0.053	14.13	52.93	17.45	CL
Sonabari Ghat	24.749, 92.841	0.077	34.5	65.3	18.68	CL
Nagatilla	24.784,92.815	0.102	7.98	47.21	16.89	CL
KrishnaNagar/Malugram	24.8357,92.781	0.046	45.5	78.3	19.22	CL
Tarapur Nathpara	24.8537,92.7658	0.23	5.38	15.66	19.2	SM
Srikona Surtara	24.8331,92.6961	0.016	60.15	80	18.2	CH
Pherighat Rajnagar	24.845,92.6632	0.015	17.62	53	17.25	ML
Katakhal	24.8267,92.6475	0.056	11.28	48.5	17.5	CL
Kalinagar	24.857,92.6185	0.031	17.3	61.3	18.4	CL
Panchgram	24.8684,92.5993	0.26	4.45	14.62	20.5	SM

CL- low plasticity clay, SM- silty sand, CH- high plasticity clay, ML-low plasticity silt

February 22, 2020, at 4:18 AM UTC, while the 2000 image captured by Landsat 5 (ETM^+), was taken on February 13, 2000, at 10:18 AM UTC. Additionally, the flow conditions at the time of image capture were characterized by low to moderate river flow levels, typical for the mid-winter season in the study area. The raw images were then processed using a UTM projection scheme, with WGS84 used as the datum and ellipsoid. For each location, the riverbank edge and channel centerline were digitized along the length of the Barak River. Assessment of riverbank erosion is conducted using the transect method. The river reach was split into three sections for the analysis of observed annual bank erosion: upstream (Sonai, Sonabarighat, and Nagatilla), middle (Krishnagar and Tarapur Nathpara), and downstream of Barak (Srikona-Surtara, Pherighat Rajnagar, Katakhal, Kalinagar, and Panchgram). The bank erosion of a river is calculated from the centerline of the river. The 2000 river centerline is used as a baseline for measuring river bank erosion, and ten digitized bank locations were projected onto the 2020 image. From the centerline to the bank sites, a number of transect lines were constructed, and then the lengths of those transects were measured. At each transect, the bank erosion was determined by taking the length of the new transect and subtracting it from the length of the preceding transect.

3. Results and Discussion

This section presents the soil profile analysis at the riverbank, followed by the variation of soil erodibility parameters and their link to riverbank erosion. The results from the in-situ test and river stage record data assess the annual bank erosion of the alluvial river Barak. Furthermore, the experimental jet test results compare the different empirical equations and time-based satellite images to identify the erosion-vulnerable sites along the Barak River.

3.1 Soil Profile

The analysis of the soil samples shows that the soil close to the banks of the Barak River is both fine-grained (high plasticity clay, low plasticity clay, and low plasticity silt) and coarse-grained (silty sand), according to the Unified Soil Classification System (ASTM, 2017). Most of the soil sample consists of clay, silt, and a small proportion of gravel, which is the same as (Annayat and Sil, 2020b). This type of soil profile is common, usually found on the alluvial river banks where the floodplain is frequently inundated (Karmaker and Dutta, 2011). Within the study reach, the material of the riverbed and riverbanks does not differ significantly, with an average particle size D_{50} of 0.25 mm (Annayat and Sil, 2020b). The detailed laboratory test results from the ten study sites are presented in Table 1.

3.2 Variation of Soil Erodibility Parameters

To determine the variance of soil erodibility parameters (τ_c and K_d), jet tests were conducted at ten different sites along the Barak River to identify their dependence on location. Each testing location was set up similarly to ensure a uniform testing environment. The relative frequency observed for τ_c and K_d at each site provides an additional perspective on erosion resistance. In Fig. 4, the relative frequency of τ_c and K_d likely indicates the percentage of occurrences of erodibility parameter within the total dataset. The result of the τ_c shows that the soils tested along the riverbank range between 0.1 and 100Pa. At the two location sites, Panchgram and Tarapur Nathpara, nearly 50% of critical stress values are < 1 Pa, and 100% are within the 0.1 – 10Pa range. However, at Krishna Nagar and Srikona Surtara, 100% of the τ_c Values of > 10 Pa indicate the most resistance to erosion. Whereas the remaining τ_c values data fall in the range from 1.0 to 10 Pa. In the case of K_d,the test result data lie between 0.1 – 10 cm^3/N-s. The lower the value of K_d, the higher the resistance to erosion. According to these results, Sonai, Tarapur Nathpara, and Panchgram riverbank materials are the least resistant to erosion compared to other locations. The data analysis also suggests that the erosion resistance of Barak's riverbanks varies significantly. As observed at the Panchgram and Tarapur Nathpara locations, the most erodible

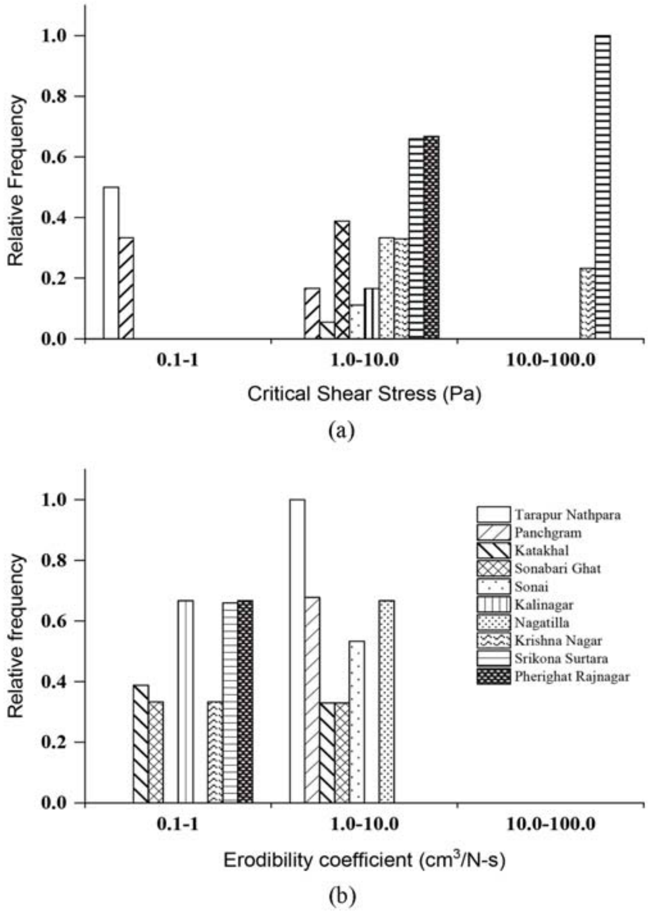

Fig. 4. Relative Frequency Distribution of τ_c: (a) K_d, (b) for Submerged JET Test Results of Riverbanks

bed materials, with τ_c close to 0.01 to 0.1 Pa and K_d as high as 5.44 cm^3/N-s. These banks eroded rapidly despite low pressure from the submerged jet. The most resistant bank materials were identified in the Krishna Nagar and Srikona Surtara sites, with the maximum τ_c recorded being 55 Pa, while the lowest recorded K_d was 0.68 cm^3/N-s. Data analysis P-test was conducted to test the location dependency variation of erosion parameters. The results indicate that the erodibility parameters are susceptible to local conditions, as the p-values for both cases are very low, τ_c P-value 0.08 and K_d P- value 0.01. This indicates that the erosion parameters can vary significantly from one location to the next. Therefore, it is necessary to determine the local erosion parameters of the soil to estimate the riverbank erosion.

The results of the tests conducted on the riverbank demonstrate an inverse correlation between the critical shear stress and erodibility coefficient (Fig. 5), where soils with a low τ_c have a high K_d and soils that have a high τ_c have a tendency to low K_d. Some similar trends were observed by Wynn et al. (2004), and Karmaker and Dutta (2011) discovered a similar power correlation between these two variables. Based on the jet test analysis, we have found that the K_d can be estimated as a function of τ_c.

$$K_d = 3.23\,\tau_c^{-0.269} \tag{13}$$

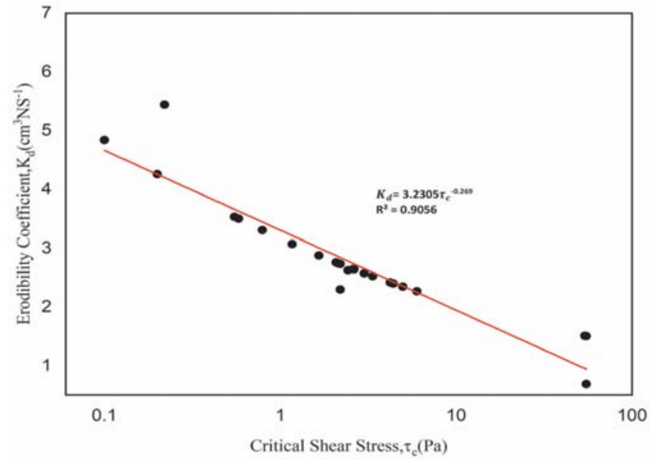

Fig. 5. Relationship between τ_c and K_d as Obtained from the Submerged JET

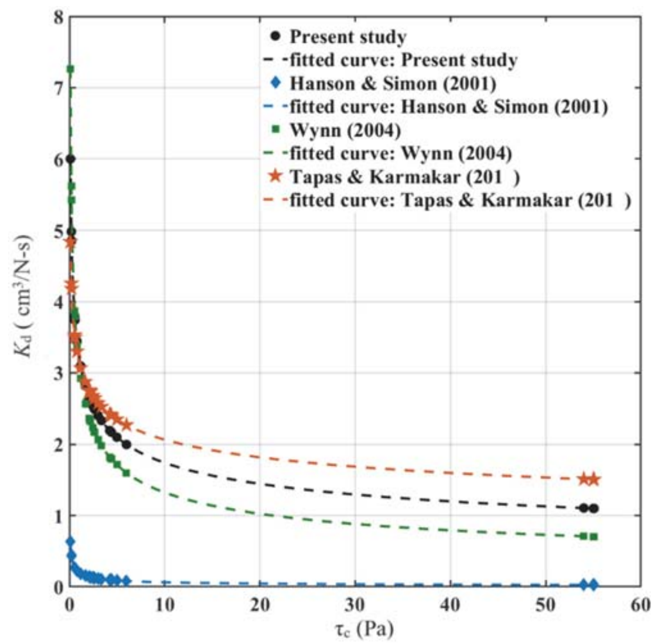

Fig. 6. A Comparison of τ_c – K_d Relationships Derived from JET Data and Other Empirical Method

In a multiple linear regression analysis, it was determined that the independent variables showed a strong relationship with τ_c. Several combinations of selected independent variables were employed to develop the best-fit model. In this scenario, the robust regression model is applied to the linear Equation with a good correlation with $R^2 = 0.90$. The relationship between τ_c and K_d obtained from the submerged JET was compared to the relationship derived by Hanson and Simon (2001), Wynn et al. (2004), and Karmaker and Dutta (2011) in Fig. 6. A comparison reveals considerable differences in regression coefficients; this might be because Hanson and Simon (2001) conducted their tests on the riverbed. In contrast, the current study was conducted on the alluvial part of the river bank. It is possible that riverbeds may be more resistant to erosion since they are usually immersed and thus less subject to subaerial processes. Wynn et al. (2004) observed a lower correlation, which indicates that vegetation cover in the river bank offers significant resistance to erodibility at the testing site. Karmaker and Dutta (2011) and the present study show a similar trend because both tests were conducted on the alluvial river. The performance of fitted K_d from relationship runs for all locations considered was relatively similar to the measured K_d. The test followed the 1:1 trend line by submerged jet, as shown in Fig. 7. However, due to river course changes, the erodibility coefficient of river soil varies from location to location. Consequently, assessing the K_d value in the field is recommended, while the fitted K_d value can be used for approximate estimation.

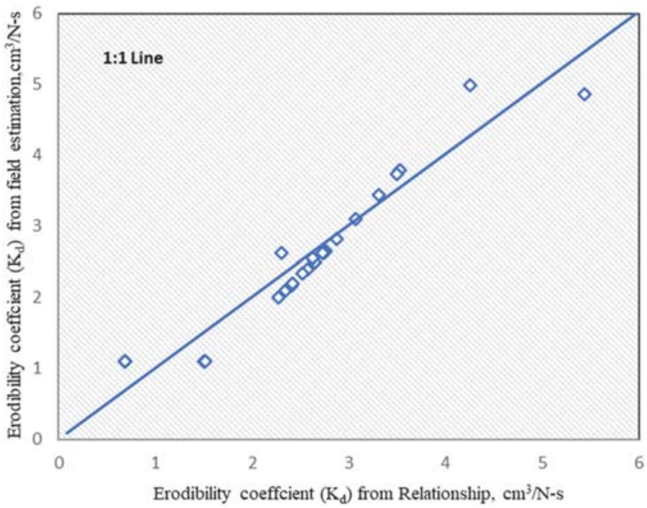

Fig. 7. Comparison of Fitted K_d from the Relationship and the Measured K_d from Field Estimation by the JET Test

The critical shear stress established by submerged JET testing is compared to three empirical formulas based on the percentage of clay, average particle size (D_{50}), and % SC content. The results are displayed in Table 2. The Comparison of the data demonstrates that using D_{50} and % Clay methods provides poor estimates of τ_c. Since all these methods were focused on lab tests of nearly homogenous remoulded soils, they were all dependent on a single soil parameter. Based on the % SC approach, estimation produces almost close to the relative median value as obtained by jet tests, while the τ_c values determined by the submerged jet test were quantitatively lower than the % SC estimates because the vegetation coefficient was taken into account (ranging from 1 to 19.2). According to Clark and Wynn (2007), the % SC approach cannot measure the actual critical shear stress because the quality of the water influences soil erodibility. Because it was performed in the field, the submerged JET erosion apparatus had relatively high variability, which likely represented the spatial variation in

Table 2. Measurements of the Critical Shear Stress, Median, and Ranges for Various Approaches

		Smerdon and Beasley (D_{50})	Smerdon and Beasley (% Clay)	Julian and Torres (2006) %SC	Jet Test (Present study)
τ_c (Pa)	Median	1.257	0.591	2.68	2.515
	Maximum	1.817	0.976	9.05	55.07
	Minimum	0.799	0.308	1.20	0.1

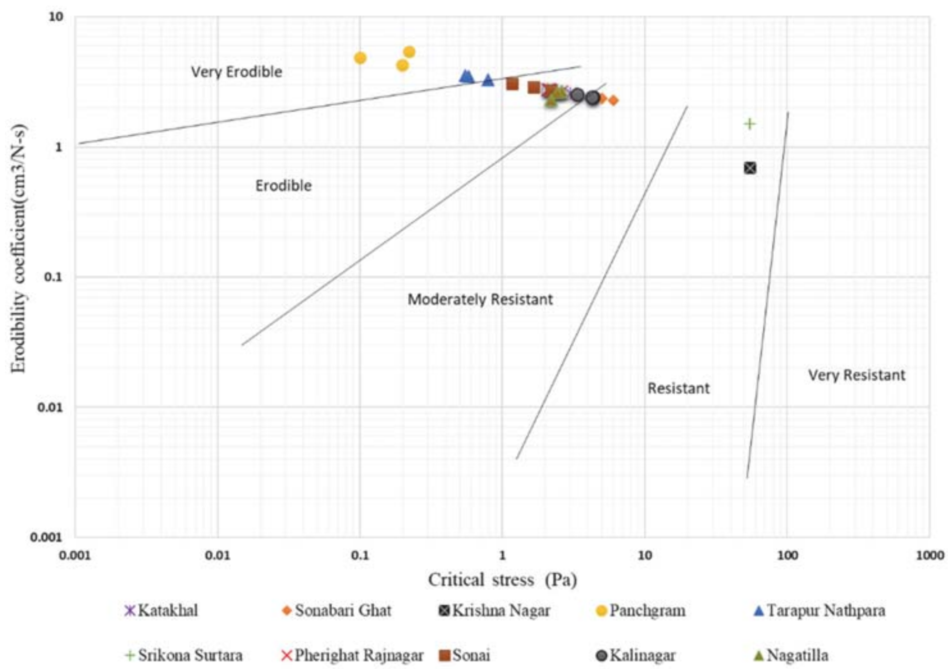

Fig. 8. Erodibility Classification Obtained from In-situ JET Test for the Selected Locations for the Study Area

soil structure and its physical and chemical properties. For this reason, the JET test performed better estimation under field conditions.

3.3 Identifying Erosion-Vulnerable Sites

In order to classify the resistant or erodible nature of the river bank a scatter plot is developed (Fig. 8) considering erodibility coefficient (K_d) and critical shear stress (τ_c) parameters, which were categorised into very erodible, erodible, moderate resistance, resistance and very resistance. It was observed that the riverbanks in Panchgram and Tarapur Nathpara are very erodible. In contrast, the river banks in Katakhal, Sonai, Nagatilla, and Rajnagar Pherighat are susceptible to erosion. The erosion rate at the river bank was very erodible due to high hydraulic shear stress with low τ_c and high erodibility coefficient value. Accordingly, Sonabari Ghat and Kalinagar banks fell into the erodible to moderately resistant categories. On the other hand, Krishna Nagar and Srikona Surtara exhibit low hydraulic shear stress and erodibility coefficient, indicating they are in the resistant zone. The probable reason for this fluvial resistance of the river bank materials changes in space and time is caused by the wetting and drying phases. Resistance of fluvial erosion is usually evaluated at a particular time; however, because of the wetting-drying phases and weathering processes, the measured τ_c and K_d can change significantly over time (Daly et al., 2015).

3.4 Annual Bank Erosion

At ten locations (e.g., Sonai, Sonabarighat, Nagatilla, Krishnagar, Tarapur Nathpara, Srikona-Surtara, Pherighat Rajnagar, Katakhal, Kalinagar, and Panchgram), where the jet test was performed, we calculated the annual bank erosion. According to the analysis of stage records for all locations, an average of 25 near-bankfull days were observed per year. The median values of critical shear stress and erodibility coefficient were used at different locations. The average bankfull depth close to the bank was determined using historic stage record data. Details of the fluvial erosion computation and the various parameters used for the erosion estimation are given in Table 3. The resultant annual river bank erosion was classified into three different erosion classes based on the local observations and previous research papers by (Annayat and Sil, 2020a): Resistant (< 1m), moderate erosion (1 – 20 m), and high erosion (> 20 m). In Krishna Nagar and Srikona Surtara, with the current bank full depth flow and erodibility parameter, there is almost no bank erosion based on estimates of annual bank erosion. Because bank materials in which the critical shear stress exceeds the developed shear stress produce a negative value of bank erosion, which is regarded as zero bank erosion. The data also revealed that the bank erosion rates in Panchgram, Tarapur Nathpara, and Sonai are highly erodible, with rates of 44.98, 31.31, and 31.08 m per year, respectively. In comparison, the other locations are in the moderately erodible category. However, these estimations are based on the number of bankfull discharge days and bankfull depth in a given year, which may vary from location to location. The average annual erosion rate of the Barak River ranges from 0.54 to 86 m/ year, as reported by (Annayat and Sil, 2020a).

Measured annual riverbank erosion was then compared with the yearly observed riverbank erosion obtained from time-based satellite images from 2000 to 2020. It is suspected that a giant flood that occurred in 2004 and 2007 altered the path of the Barak River, as seen in satellite imagery. The analysis of satellite images from 2000 to 2020 indicates that riverbank shifting occurs at all sites. The average maximum annual bank erosion was recorded upstream of Sonai and Sonabarighat (~272 m and ~398 m, respectively) and downstream of Kalinagar and Panchgram (~436 m and ~243 m, respectively). The bank erosion observed at sites Kalinagar and Panchgram were closely similar. Due to the proximity of these locations, soil characteristics and hydraulic conditions are anticipated to remain relatively high. The least amount of erosion occurred at Srikona Surtara, Pherighat Rajnagar, and Khatakhal, which could be because these locations are located downstream of the Barak River, where a less steep slope is to be expected. This lower slope would lower boundary shear stress and reduce the possibility of fluvial erosion. However, large erosion occurred at Panchgram, located downstream from Srikona Surtara, Pherighat Rajnagar, and Khatakha, which might be caused by several other factors. The bank soil of this site was silty sand (SM) with less effective cohesion, resulting in high

Table 3. Details of the Yearly Bank Erosion for Each Location in the Barak River

Location	No. of Bank full discharge days, T_t	Average river slope, S	Bankfull depth close to the riverbank, d(m)	τ_c (Pa)	k_d From field estimation, cm^3/N-s	Erosion rate (ε)	Yearly bank erosion E_Y (m)	Yearly Average erosion range (Local observation)
Sonai	25	1 in 9000	8	1.637	2.89	1.43904E-05	31.08	Highly Erodible
Sonabari Ghat		1 in 9000	8	5.12	2.34	3.55513E-06	7.69	Moderate erodible
Nagatilla		1 in 9000	7	2.416	2.52	7.04844E-06	15.22	Moderate erodible
Krishna Nagar		1 in 10000	9.5	55.07	0.687	-3.17507E-05	0	Resistant
Tarapur Nathpara		1 in 9000	6.5	0.64	3.44	1.44979E-05	31.31	Highly erodible
Srikona Surtara		1 in 11000	9.5	54.69	1.507	-7.05629E-05	0	Resistant
Pherighat Rajnagar		1 in 11000	7	2.28	2.71	7.96952E-06	17.21	Moderate erodible
Katakhal		1 in 10000	9	2.426	2.69	1.15572E-05	24.96	Erodible
Kalinagar		1 in 10000	9	3.983	2.45	6.70563E-06	14.48	Moderate erodible
Panchgram		1 in 10000	6	0.1733	4.844	2.08283E-05	44.98	Highly erodible

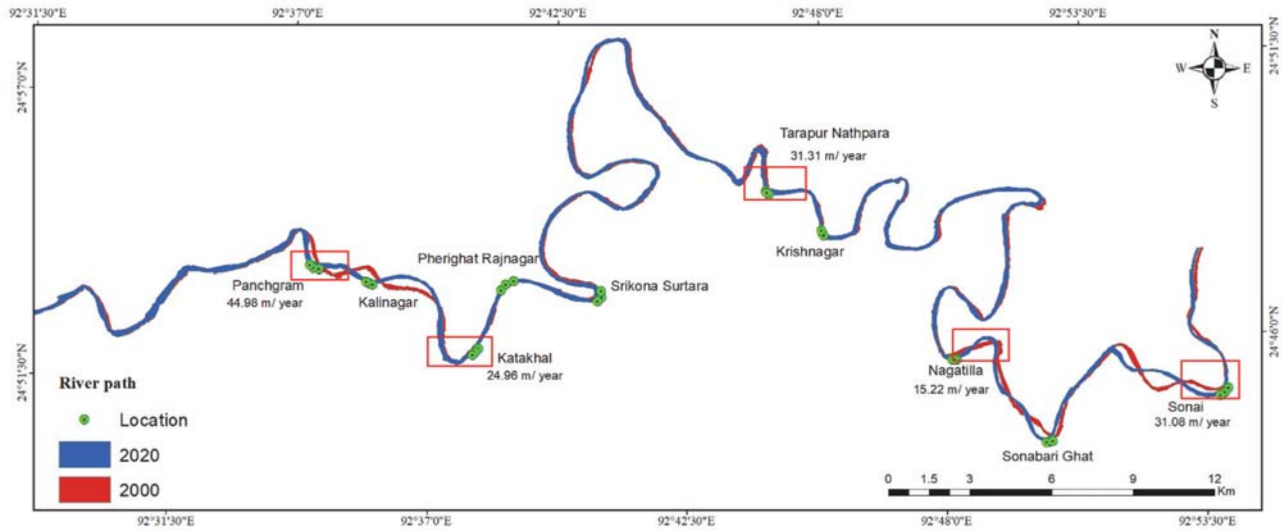

Fig. 9. Location Map of the Riverbanks Which are Vulnerable to Erosion Based on In-Situ Test

bank failure potential and, correspondingly, high bank erosion (see Table 2). In addition, the site is located in the outlet of a small catchment, which is the confluence point to the Barak River. This probably results in the formation of an underground porous channel that flows from the bank side towards the river, causing additional erosion in that area. The analysis also shows that the river bank at higher erosion sites (i.e., Sonai, Sonabarighat, Kalinagar, and Panchgram) gradually took a concave shape from 2000 to 2020, as depicted in Fig. 9. Most of the time, concave banks cause secondary flows caused by both curvature and turbulence, which change the flow fields, bank structure, and ultimately leading to further erosion (Camporeale and Perona, 2007; Papanicolaou et al., 2007).

The vulnerability map of river bank erosion sites is depicted in (Fig. 9). The vulnerability map shows that only a few sites, like Sonai, Tarapur Nathpara, Katakhal, and Panchgram, are the most susceptible to erosion relative to the other river sites in the context of in situ river bank erosion. Various factors influence riverbank erosion, such as the height of the inundated river bank, bankful discharge, riverbank slope, soil structure, and embankments close to the river channel (Winterbottom and Gilvear, 2000). In our analysis, we found some areas that were found to be vulnerable even though there was no center-line change, and there were also converse cases. As we mentioned earlier, various factors affect bank erosion. Additionally, the erodibility of bank materials fluctuates over time due to wetting/drying cycles and subaerial processes, leading to significant variations in τ_a and k_d (Daly et al., 2015). Moreover, as the erosion progresses, the riverbank may gradually erode towards the lateral direction, causing spatial changes in bank materials and further affects the τ_a and k_d values. Apart from this, based on the JET test findings, hydraulic shear stress and soil erodibility factors are essential for assessing riverbank erosion. The results obtained by the observed average centerline shift along the Barak River between 2000 and 2020 and the measured bank erosion matched the locations reasonably well. Thus, the current studies in situ bank erosion estimation can be used to identify vulnerable river sites.

4. Conclusions

This paper studies the river bank erosion and vulnerability assessment in a highly dynamic and meandering stretch of the Barak River in northeast India, using an in-situ approach. A total of Forty in-situ submerged JET tests were performed at ten locations to determine the soil erodibility parameters (i.e., critical shear stress and erodibility coefficient) of the composite riverbanks along the river. The upper reach of the Barak River up to Badarpur Ghat in Assam was considered for the study area. The results show that the spatial variation of the erodibility parameters in the river banks varies significantly, with the magnitude of critical shear stress (τ_c) and erodibility coefficient (K_d) of the composite river bank soils ranging from 0.1 to 55 Pa and 0.1 to 10 cm^3/N-s, respectively. The correlations between k_d and τ_c derived from JET data closely follow the relationship established by Karmaker and Dutta (2011) reported for this type of alluvial river. The study found that the erodibility coefficient can be estimated as a function of critical shear stress with a satisfactory relationship ($R^2 = 0.90$). The analysis of erosion-vulnerable sites based on the JET test showed that the soil could be classified as very erodible to moderately erodible, which is highly vulnerable to erosion. In addition, the upper reach of the river was found to be more erodible than the lower reach due to the highly developed shear stress (τ_a) and erodibility coefficient (K_d) value. At the study sites, annual river bank erosion was estimated using measured erodibility parameters and stage record data. Data reveals highest annual bank erosion was recorded at Panchgram, Tarapur Nathpara, and Sonai, with rates of 44.98, 31.31, and 31.08 m per year, respectively. However, no erosion rate was recorded in Krishna Nagar and Srikona Surtara, which indicates their erosion-resistant nature. The measured bank erosion rate using the erodibility parameter was compared to the satellite imagery map for the time period 2000 to 2020. Based on this study, it is recommended that the qualitative assessment of annual river bank erosion for these types of alluvial soil submerged jet erosion should be considered. The results of the in-situ jet tests using the excess shear stress approach are more reliable in predicting erosion rates than the empirical method and are also helpful in identifying river bank locations that are more vulnerable to erosion. This can also help with the implementation of effective plans and programs to increase river protection activity in the designated area along the Barak River. However, seepage erosion, riverbank stability, and sediment loading should be considered for a more accurate estimate of annual bank erosion.

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