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A proposed method of bank erosion vulnerability zonation and its application on the River Haora, Tripura, India

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ABSTRACT

In this paper a new RS-GIS based simple method has been proposed for estimating bank erosion. This method does not need intense field investigation and can provide erosion vulnerability zonation for the entire river. The method uses eight parameters, i.e., rainfall erosivity, lithological factor, bank slope, meander index, river gradient, soil erosivity, vegetation cover, and anthropogenic impact. Meteorological data, GSI maps, SRTM DEM (30-m horizontal resolution), LISS III (23.5-m resolution), and Google Images have been used to determine rain erosivity, lithological impact, bank slope, meander index, river gradient, vegetation cover, and anthropogenic activities. Soil map of the NBSSLP (National Bureau of Soil Survey and Land-use Planning, India) has been used for assessing soil erosivity index.

By integrating the individual values of those six parameters out of those eight parameters (the first two parameters remained constant for the particular study area), a bank erosion vulnerability zonation map of the River Haora, Tripura, India (23°37′–23°53′ N. and 91°15′–91°37′ E.) has been prepared. The values have been compared with the existing BEHI-NBS method of 60 spots and also with field data of 30 cross sections (covering the 60 spots) taken along a 51-km stretch of the river within Indian Territory, and we found that the estimated values are matching with the existing method as well as with field data. The whole stretch has been divided into five hazard zones, i.e. very high, high, moderate, low and very low hazard zones; and they are cover 5.66, 16.81, 40.82, 29.67, and 9.04 km, respectively.

1. Introduction

Bank degradation is the result of a process that combines the erosive power of water (Bentrup and Hoag, 1998) and the effect of gravity. In addition, channel enlargement, bank instability, degradation of physical habitat, and numerous other geomorphic responses accelerate the process of bank erosion (Hammer, 1972; Arnold et al., 1982; Booth, 1990; Booth and Henshaw, 2001; Jacobson et al., 2001). Bank erosion is a severe problem to any fluvial system as it can generate up to 90% of the total sediment yield from a catchment (Olley et al., 1993; Prosser and Winchester, 1996; Wallbrink et al., 1998; Wasson et al., 1998). It is also considered a hazard because it causes loss of lives and properties. The Haora River, which is the lifeline of the Agartala City of Tripura, India, experiences severe bank erosion in several parts of its course.

Prediction of the location and the extent of river bank erosion continues to be difficult despite the testing of a range of approaches and methods (Sandra and David, 2000). Several worldwide methods exist for estimating bank erosion. Among them, some of the well known and widely used methods are mentioned in Table 1.

Most of these methods (Table 1) are either extensively field based or require highly advanced technology (PEEP method, test of a method to calculate near-bank velocity and boundary shear stress etc.). Moreover, these methods are unable to produce a zonation map for the entire stretch of any river. Other GIS-based methods, where prediction can be done from open source satellite images (Klaassen and Vermeer, 1988; Bhakal et al., 2005; Das and Saraf, 2007; Kummu et al., 2008; Sarkar et al., 2012), are applicable for the large rivers only. Therefore high resolution satellite images (which are very expensive) are necessary for the prediction of bank erosion of a small river (like the River Haora, having a length of 61.2 km). As a result, bank erosion of small rivers is poorly understood and thus poorly integrated into management strategy (Wang et al., 1997).

Thus, the main objective of this paper is to propose a new GIS-based method for preparing zonation maps of bank erosion. This zonation has been done by considering eight parameters: i.e., (i) rainfall erosivity, (ii) lithological factors, (iii) slope of the river bank, (iv) meander index of each curve of the river, (v) river gradient (longitudinal), (vi) soil erodibility factor of the bank, (vii) vegetation cover of the bank, and (viii) anthropogenic factors present along and across the river. The main

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Table 1
Summary and method of different existing models for estimating bank erosion.

Model	Methods	References
Graft	Erosion probability could be determined for any given cell by taking into account its distance laterally in the upstream direction to the active river channel, and a value representing flood magnitudes for the given period	Graft (1984), Sandra and David (2000)
Bank shifting	Superimposing the river banks of different time periods together and measuring the gap between them.	Gilvear and Winterbottom (1992), Gilvear et al. (1994, 1999), Gilvear and Winterbottom (1998)
Bank erosion	$BE = 0.016Q_{1.58}^{0.60}$ where BE is the bank erosion rate in metres of recession per year, and Q1.58 is the discharge (m^3/s) of the 1.58-year recurrence interval flood event, assumed to represent bank-full discharge	Rutherfurd (2000), Prosser et al. (2001)
Photo Electronic Erosion Pin (PEEP)	Quasi-continuous data on the magnitude, frequency and timing of the individual erosion and deposition on the river banks	Lawler (1991, 1992a,b), Lawler and Leeks (1992), Lawler (1993a,b), Lawler et al. (1997)
Experiment	Subsurface bank erosion has been investigated for vertical banks by considering a sandy erodible layer overlaid by a clayey one under uniformly distributed constant overhead pressure	Imanshoar et al. (2012)
Bank material strength	Using erosion pins to large-scale studies using aerial photos and maps	Thorne (1981)
Numerical analysis	Investigating bed-deformation and bank line shifting in 2D planform in a moving boundary fitted-coordinate system, and a new formulation of nonequilibrium sediment transport is introduced to reproduce the channel processes.	Nagata et al. (2000)
Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS)	BEHI evaluates properties of stream banks related to stability; NBS evaluates channel flow conditions and how they affect bank stability. Together, BEHI and NBS are utilized as independent variables in a series of regression equations that predict annual lateral bank retreat.	Rosgen (1996, 1999, 2001a,b), Nieber et al. (2008)

advantage of this method is that all parameters can be estimated from secondary data, maps and images, and require less field investigation.

2. Regional setting

Haora River is one of the major rivers of the West Tripura District. It originates from the western flank of the Baramura Range and flows through the Sadar subdivision of Tripura to meet with the Titas River in Bangladesh (located between the latitudes of 23°37′ N. and 23°53′ N. and between longitudes of 91°15′ E. and 91°37′ E.) (Fig. 1). The river flows west and drains at basin areas of 457.97 km^2 (SOI Topographical Maps, 1932). The total length of the river is 61.2 km, in which 52 km is flowing within the Indian Territory. The proposed method has been applied only on the Indian part of the Haora River (marked as AB in Fig. 1). The river is primarily rain fed, and a major part of the river is flowing through the alluvial soil belt, which is prone to erosion.

3. Materials and method

The 1932 Survey of India (SOI) topographical maps and 2009 Google images have been used for the demarcation of the Haora River basin and the present flow path of the river. Rainfall data has been collected from the Meteorological Department, Tripura. Several secondary maps, including soil and lithological maps, have been collected from the National Bureau of Soil Survey and Land Use Planning (NBSSLP) and from the Geological Survey of India, respectively. River slope gradient has been measured from a 30-m horizontal resolution SRTM digital elevation model (DEM). Meander curve, vegetation cover, and other parameters of the bank have been measured from the 2005 LISS III satellite image and from 2009 Google images.

3.1. Zonation mapping of bank erosion vulnerability

For the preparation of bank erosion vulnerability zonation of the Haora River, 15 m on either side of the water's edge are considered as active bank zones. This demarcation has been done on the basis of maximum extension of bank erosion that can be noticed within the entire stretch, and it will be different from river to river.

3.1.1. Rain erosivity (R) factor

Soil erosion is closely related to rainfall through the combined effect of detachment by raindrops striking the soil surface and by the runoff (Mkhonta, 2000).

Therefore, the following formula (Eq. (1)) has been used for estimating annual and seasonal R factors that was developed by Singh et al. (1981) in Indian context.

$$\text{Annual R-factor } R_a = 79 + 0.363 * P \tag{1}$$

where, P = annual rainfall in mm.

Risk of bank instability is found to be higher in the rainy days having high rainfall intensity with a number of lean days before because during lean periods the moisture of soils is drying up (Thorne et al., 1998). As a result of that, the cohesive power of soil is getting reduced. Any sudden rainfall with relatively higher intensity is leading the banks prone to erosion.

For the calculation of rainfall erosivity, the following equation has been introduced:

$$\text{Rainfall erosivity } R = \frac{R_a \times \sum_{k=0}^{n} (L_d \times R_i)}{R_d} \tag{2}$$

where R_a = annual R factor in mm; L_d = number of lean days (a maximum 20-day limit has been considered within which soil can be dried up) before a rainy day (days are considered as rainy days when there is at least 10 mm of rainfall) (Bhattacharyya, 1993), R_i = rainfall amount of that particular day (if rainfall occurs continuously for several days, the average amount of those days should be considered); R_d = total number of rainy days in a year.

In the case of the Haora River basin, there is only one rain gauge station for which the rainfall erosivity factor for the whole basin remains constant.

3.1.2. Lithological factor

Lithological factor is also considered as an important factor because the materials along the river banks determine the resistivity of it (Twidale, 2004). Thus, the bank material along the river up to the