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Drainage Basin Morphometry and its Relation to Erosion Susceptibility in the Barakar River Basin, Jharkhand and West Bengal

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Abstract: *Fluvial systems are extremely sensitive to the prevailing conditions of litho-structure and tectonics. Such geomorphic systems swiftly respond to any change in the external conditioning factors in the form of morphological adjustments. Fluvial morphometric parameters are therefore, studied all over the world in order to ascertain the intensity of geomorphic processes operating in the basin. Traditionally topographic maps were employed to quantitatively evaluate these attributes. However, the method is tedious and unsuitable for the application to large and multiple basins. Since the advent of high-resolution Digital Elevation Models (DEMs), a large number of drainage basins have been studied with respect to their morphometric attributes. The present study has used these attributes (relief, surface, shape and drainage texture) for predicting the erosion susceptibility of the Barakar river basin in India. The Shuttle Radar Topographic Mission (SRTM) DEM of 30 m resolution have been used in the analysis. Erosion susceptibility was calculated by employing the Multi-Criteria Decision Making (MCDM) technique. Among a variety of MCDM techniques, the popular Analytical Hierarchy Process (AHP) was used. The primary difference between the traditional AHP techniques is that the relative importance of each parameter was ascertained on the basis of the multi-component Principal Component Analysis (PCA) technique. This implies that instead of taking only one PC, six PCs were considered with a cumulative explained variance of 96.624%. The relative importance of each parameter was determined on the basis of the loading ratios of the various parameters under multi-component PCA. Finally, AHP-based erosion susceptibility maps were weighed based on their explained variances (obtained from PCA for individual component) and the final map was displayed on the basis of spatial variation of the erosion susceptibility in the Barakar drainage basin.*

Introduction

Fluvial erosion is a fundamental geomorphic process which is governed by numerous extraneous variables such as lithology, structure and tectonics. Variations in these variables will be manifested by the rivers, both at the reach as well as the basin-scale, in the form of morphological adjustments. Therefore, one approach of ascertaining this response is by quantitatively determining the various morphological attributes of a drainage basin. These attributes, collectively referred to as drainage basin morphometry, have been widely employed to gauge the varying response of the rivers to lithology, climate and tectonics (Horton, 1932; Horton, 1945; Strahler, 1956, 1957; Gregory and Walling, 1968). However, there has been a notable shift in the methodological approach in recent years.

Traditional topographical maps have now been replaced by high-resolution Digital Elevation Models (DEMs) such as SRTM, ASTER, etc. (Sengupta, 2015). DEM-based drainage basin morphometry has found a wide range of applications such as erosion susceptibility (Kadam *et al.*, 2019; Asfaw and Workineh, 2019; Prabhakar *et al.*, 2019), flash flood hazard (Mesa, 2006; Angillieri, 2008; Bhat *et al.*, 2019), watershed hydrological regime (Sreedevi *et al.*, 2013; Rawat and Mishra, 2016; Bezinska and Stoyanov, 2019) and control of litho-structure and tectonics (Kuhni and Pfiffner, 2001; Rebai *et al.*, 2013; Kale *et al.*, 2014).

Assessing and estimating the status of erosion undergone in a watershed is often a prerequisite in the domain of integrated watershed management. It is pertinent to mention here that the actual amount of erosion undergone by a drainage basin is difficult to compute as this requires a continuous monitoring of both the suspended and the bed loads (Singh *et al.*, 2008). Several previous studies have used these morphometric parameters as proxies to determine the spatial difference in the degree of erosion within the basins (Prabhakaran and Jawahar Raj, 2018; Kadam *et al.*, 2019 and the references therein). This process is predominantly index-based, employing a large number of attributes which calls for the application of Multi-Criteria Decision Making (MCDM) techniques in this domain. Among a host of MCDM techniques, the Analytical Hierarchy Process (AHP) is extremely popular in earth sciences (Kachouri *et al.*, 2015; Haidara *et al.*, 2019; Das *et al.*, 2020 and the references therein). This model, devised by Saaty (1980), is essentially based on the relative importance of a number of parameters, which determines the weightage assigned to these parameters. The process of weight-determination is fundamentally based on experts' opinion which often differs from each other (Mistri and Sengupta, 2020). Therefore, this study attempts to reduce the variety of problems and ambiguities associated with the AHP by proposing the multi-component Principal Component Analysis (PCA) into the existing domain of AHP. The Barakar basin in the states of Jharkhand and West Bengal in eastern India has been considered as a case study.

Study area

For the present study, the Barakar basin in eastern India has been considered (Fig.1). This basin is apparently sandwiched between two dams viz. Tilaiya (24°19′21″N; 85°30′58″E) and Maithon (23°48′9″N; 86°48′33″E). Encompassing an area of about 6,159 km^2, the area may be divided into two minor sub-basins viz. Barsoti (W-E orientation) and the Usri (flowing in the N-S direction) besides fifteen medium or small streams. The Barakar river flows from west to south-east originating from the Padma in Hazaribag district of Jharkhand. The river Barakar is the main embranchment of the river Damodar. The total length of the river is 225 km. It traverses through the districts of Hazaribag, Giridih and Dhanbad in the state of Jharkhand and Paschim Bardhaman district in West Bengal (Ghosh and Mistri, 2015). The river was selected for the study because it is the principal tributary of the Damodar river, which is clearly recognised to be flowing through a rift valley (Kundu *et al.*, 2011). However, the status of the Barakar river is still unresolved as to whether it occupies a separate rift valley or not. Therefore, this river basin was selected in order to characterise the basin with respect to its erosion potential so as to assess whether the spatial variation in erosion susceptibility will give a clue to this unresolved question.

This river bears the typical characteristics of a seasonal river. In the rainy season, the level of discharge and rate of stream power becomes high, the height of water level reaches around 14–17 m from riverbed, and in summer season, the amount of water contained in the river is very low, with a height of about 1 m from bed level.

The basin is underlain by ancient rocks of the Precambrian age marked by acute surface fractures, cracks, lineaments exposed at a few places on the surface. The upper reach of the river is on the offshoots of the Chotanagpur plateau with a series of low-lying hill ranges and dams like Pareshnath hills and Tilayia and Maithon dams, respectively.

The surrounding hills ranging in elevation from 91 m to 1374 m form a rolling topography. The average annual rainfall across this region is around 1525 mm, with more than 80% of the rainfall occurring between June and September. The amount of soil cover in the whole region is very thin composed of loose gritty, sandy, reddish material formed by weathering of bed rock. The soils are mainly of the inceptisols or alfisols type (Biswas and Pani, 2016).

Materials and methods

Database

The basic database for this research comprised the 30 m resolution SRTM DEM data which was downloaded from the Earth Explorer website. This dataset has been regarded to be superior to other freely-available DEM datasets due to its finer resolution (30m), the advantage becoming more prominent while detecting drainage lines and extracting the drainage network of a basin (Das *et al*., 2016).

The pits or data gaps in the DEM were filled and the flow routines were allotted by the D8 algorithm. This algorithm routes the flow of one pixel into any one of the eight neighboring pixels, based on the direction of the steepest slope (O'Callaghan and Mark, 1984). Using the Flow Accumulation

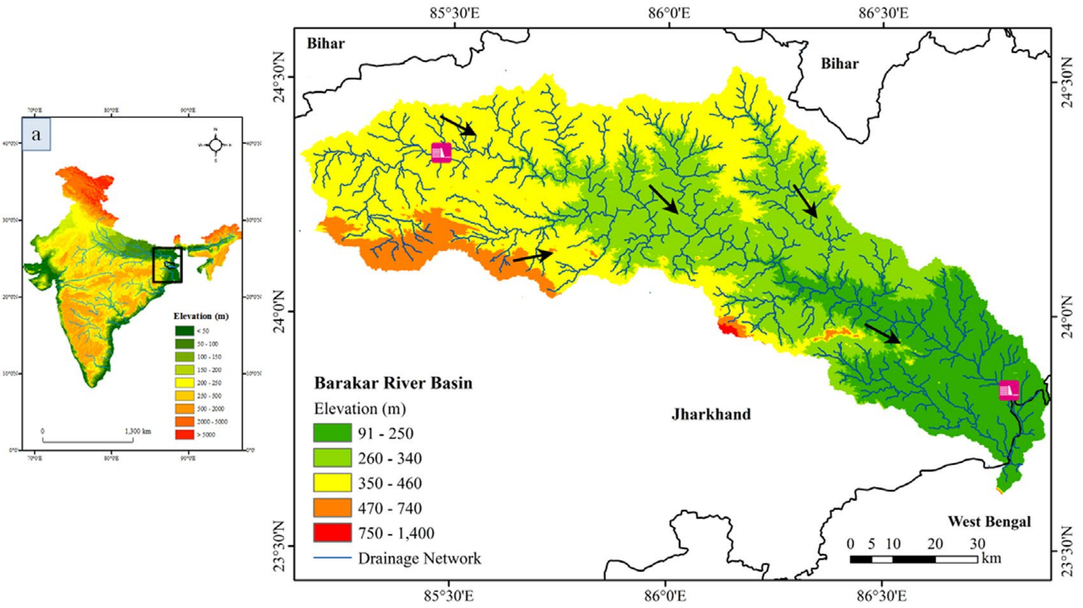

Figure 1. Location of the studied basins a) Digital Elevation Model (DEM) of India showing the location of the Barakar drainage basin (represented by a black box). (b) Barakar drainage basin with various ranges of elevation, where blue lines represent the river Barakar and its tributaries. The red triangle represents the source and blue triangle represent the confluence points of Barsoti and Usri with Barakar main channel at Dalangi (24°13'19"N, 85°51'41"E) and Maheshpur (24°04'05"N, 86°21'55E), respectively. Flow directions are shown by black arrows and pink symbols represent Tilayia and Maithon dams.

Command of the Hydrology Extension in the Spatial Analyst Tools in ArcGIS, the drainage accumulation raster was created. A threshold of 100 pixels in the Flow Accumulation raster was taken in order to generate the stream network. Overlay of the extracted drainage network to the Survey of India (SoI) topographical maps of 1:50,000 scale was also carried out for verification. This was followed by the extraction of the watershed of the studied basins for further analysis (Fig.2).

Calculation of morphometric parameters

The next step involved calculating the drainage morphometric parameters in ArcGIS. Attributes namely relief (relative relief, dissection index and hypsometric integral), surface (slope, curvature), drainage texture (drainage density, stream frequency, constant of channel maintenance, length of overland flow, ruggedness number and infiltration number), hydrological (topographic wetness index and stream power index were calculated from the standard formulae postulated by previous workers (Table 1).

Normalisation and fuzzification of the parameters

In order to account for the differences in units and range of values of each parameter, the absolute values were converted into dimensionless fuzzy numbers (Boender *et al.*, 1989; Burrough *et al.*, 1992). These range from 0 (low membership) to 1 (high membership). Fuzzy memberships are very popular methods of normalization (Abdul Rahaman *et al.*, 2015; Haidara *et al.*, 2019 and the references therein).

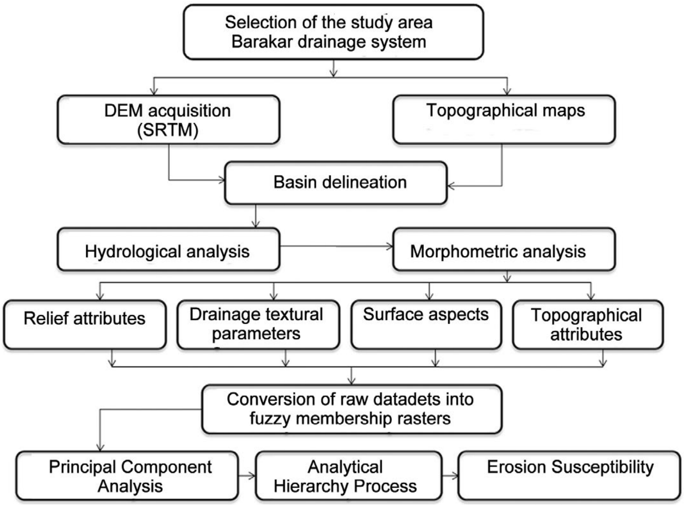

Figure 2. Flow-chart showing the methodology adopted for the study.

Table 1. Formulae used for calculating morphometric parameters. The abbreviations of each parameter are denoted in the parentheses.

Sl. no.	Morphometric parameter	Formula	Variables	Reference
1	Relative relief (Rr)	$Rr = H_{max} – H_{min}$	H_{max} = Maximum elevation and H_{min} = Minimum elevation	Strahler (1956)
2	Dissection index (DI)	$DI = Rr / H_{max}$	Rr = Relative relief and H_{max} = Maximum elevation	Nir (1957)

Sl. no.	Morphometric parameter	Formula	Variables	Reference
3	Hypsometric integral (HI)	$HI = (H_{mean} - H_{min}) / (H_{max} - H_{min})$	H_{mean} = Mean elevation of the basin, H_{min} = Minimum elevation of the basin and H_{max} = Maximum elevation of the basin	Pike and Wilson (1971)
4	Slope(θ)	1st derivative of DEM surface		Evans (1980)
5	Curvature (Cv)	2nd derivative of DEM surface		Evans (1980)
6	Drainage density (D_d)	$D_d = L_u / W_a$	L_u = Total length of all the streams in the basin, W_a = basin area	Horton (1945)
7	Stream frequency (S_f)	$S_f = N_u / W_a$	N_u = Total number of all streams, W_a = basin area	Horton (1945)
8	Constant of channel maintenance (CCM)	$CCM = 1/D_d$	D_d = Drainage density	Schumm (1956)
9	Length of overland flow (LOF)	$LOF = 1/D_d \times 2$	D_d = Drainage density	Horton (1945)
10	Infiltration number (IN)	$IN = D_d \times S_f$	D_d = Drainage density S_f = Stream frequency	Faniran (1968)
11	Ruggedness number (R_n)	$R_n = (Rr \times D_d) / 1000$	Rr = Relative relief, D_d = Drainage density	Melton (1965)
12	Topographic wetness index (TWI)	$TWI = \ln [A_s / \tan(\theta)]$	A_s = Specific catchment area derived from the accumulation matrix, θ = Slope in radians	Moore *et al.* (1991)
13	Stream power index (SPI)	$SPI = \ln [A_s \times \tan(\theta)]$	A_s = Specific catchment area derived from the accumulation matrix, θ = Slope in radians	Moore *et al.* (1991)

For the process of terrain erosion to occur, several factors operate in tandem. It has been mentioned earlier that all such factors were considered before performing Multi-Criteria Decision Making (MCDM) - based terrain susceptibility mapping. Factors such as relative relief, slope, curvature, hypsometric integral, dissection index, drainage density, stream frequency and infiltration number are expected to be favourable for erosion and increase in such factors will be reflected by a corresponding augmentation of the process of erosion. The MS Large Membership Function was applied to the rasters of such parameters in an ArcGIS environment. This may be mathematically represented as (Luo and Dimitrakopoulous, 2003)

$$f(x) = \begin{cases} 1 - \frac{bs}{x - am + bs}, & x > am \\ 0, & \text{otherwise} \end{cases}$$

..... Equation 1

where, f(x) is the fuzzy membership function of the attribute x, m = arithmetic mean of the attribute x, s = standard deviation of attribute x, a = mean multiplier (taken as 1) and b = standard deviation multiplier (taken as 1). This function is monotonically increasing which implies that as the value of x increases, f(x) also increases and vice versa.

The MS Small Membership Function was then applied to the parameters which are negatively related to erosion such as topographic wetness index, length of overland flow and constant of channel maintenance as per the following mathematical function: (Luo and Dimitrakopoulous, 2003)

$$f(x) = \begin{cases} \frac{bs}{x-am+bs}, & x > am \\ 0, & \text{otherwise} \end{cases}$$

….. Equation 2

The notations in Equation 3 are the same as that of Equation 2. The MS Small Membership Function is characterised by monotonic decreasing nature i.e., with an increase in the value of x, the magnitude of f(x) decreases and vice versa.

Multi-criteria-based Erosion Susceptibility Assessment

The process of erosion is a multi-criteria problem that can be summarised in a generic model as follows:

$IES = f(x_1, x_2, \ldots x_n)$ .....Equation 3

In this equation, IES is the Index of Erosion Susceptibility and $x_1, x_2, x_3 \ldots\ldots x_n$ are the independent parameters determining erosion susceptibility (Boender *et al.* 1989).

Due to the fact that erosion is governed by a multitude of factors, MCDM models have become especially useful in this domain. The Analytical Hierarchy Process (AHP), which was introduced by Saaty (1980), has found enormous application as a MCDM technique in erosion susceptibility and sub-basin prioritisation (Abdul Rahaman *et al.*, 2015; Sadhasivam *et al.*, 2020). The fundamental process involves a non-parametric scaling (1to 9) of the respective factors varying according to their relative importance. Then pairwise comparison was applied before assigning relative weights to different parameters. So, the success of an AHP exercise is largely dependent on the consistency of the pairwise comparison. This is verified with the help of the Consistency Ratio (CR) given in Equation 4.

$CR = CI/RI$ ..... Equation 4

where, Consistency Index (CI) is calculated from the formula $(\lambda maxn) / (n–1)$, numerator being the weight sum derivative of the AHP-based pairwise comparison matrix, n is the number of criteria and RI represents the Random Index generated for a pair wise comparison matrix taking ‘n’ criteria.

The process of assigning relative weights to all the parameters in AHP becomes quite cumbersome and ambiguous as this is dependent on an expert’s opinion and they may not match with each other (Macharis *et al.*, 2004). This limitation can be minimised by applying the Principal Component Analysis (PCA) in the AHP. There are numerous publications wherein PCA has been employed in earth sciences (Mather and Doornkamp, 1970; Magner and Brooks, 2008 and the references therein). The SPSS software was employed to perform the PCA by extracting the values of individual parameters from 50 equally spaced points covering the whole basin. All the previous papers have taken a single component (the 1st PC) in the analysis. In the analysis of morphometric attributes of the Barakar river basin it is revealed that only 41% of the explained variance is explained by the 1st PC (Table 2). So, 6 PCs were considered in this study with a cumulative explained variance of 97%. Generally, while building models by PCA, the explained variance should be very high, preferably above 95% (Wallis, 1965). Ratios of the loading values for each PC was used to estimate the relative importance of each parameter. These importance values were then assigned to the AHP algorithm for deriving the weightage of each parameter for individual PC and cumulated. So, six rasters of AHP-based erosion susceptibility were obtained for the six PCs. The next step involved weightage of the individual AHP rasters with respect to their Explained variances (Table 2). For example, the 1st Component had an explained variance of

Table 2. Results of the Principal Component Analysis of the individual parameters. $^{a}L_k$ = Loading score on the kth Component $^{b}E_k$ = Explained variance (%) for the kth Component. For notations of parameters, refer Table 1

Parameters	$L1^a$	$E1^b$	$L2^a$	$E2^b$	$L3^a$	$E3^b$	$L4^a$	$E4^b$	$L5^a$	$E5^b$	$L6^a$	$E6^b$
Rr	0.106	41.45	0.815	24.15	0.499	19.63	0.018	5.55	0.189	4.70	0.154	1.64
θ	0.517		0.440		0.65		0.093		0.015		0.161	
CCM	0.875		0.147		0.323		0.169		0.234		0.120	
DI	0.029		0.833		0.406		0.241		0.169		0.014	
Cv	0.538		0.155		0.604		0.500		0.069		0.112	
HI	0.417		0.499		0.532		0.440		0.027		0.215	
TWI	0.592		0.552		0.511		0.248		0.058		0.109	
SPI	0.592		0.552		0.511		0.248		0.058		0.109	
LOF	0.875		0.147		0.323		0.169		0.234		0.120	
R_n	0.556		0.76		0.217		0.127		0.020		0.101	
D_d	0.903		0.089		0.222		0.055		0.222		0.139	
I_N	0.904		0.154		0.269		0.107		0.100		0.039	
S_f	0.685		0.235		0.321		0.012		0.589		0.144	

0.4145 (41.45%). Similarly, the second component had an explained variance of 0.2416 (24.16%). Therefore, the 1st component based AHP raster for erosion susceptibility was weighted to a factor of 0.4145 and the second component based AHP raster was assigned a weight of 0.2416. This process was continued for all the six-component based AHP rasters. They were then summed up to derive the final erosion susceptibility of the Barakar basin (Eq. 5)

$$IES = \sum_{i=1}^{n} EVi \times FAHPi \quad \text{.... Equation 5}$$

where, IES = Index of Erosion Susceptibility, EVi = Explained variance of the ith component and FAHPi = Fuzzified Analytical Hierarchy Process raster obtained for the ith component.

Equation 5 can be expanded for the Barakar basin in the form of Equation 6.

$$Es = [(FAHP1 \times 0.4145) + (FAHP2 \times 0.2416) + (FAHP3 \times 0.1913) + (FAHP4 \times 0.0555) + (FAHP5 \times 0.0470) + (FAHP6 \times 0.0164) \quad \text{.... Equation 6}$$

Results and discussions

This paper takes into account 13 morphometric parameters viz. relief (relative relief, dissection index and hypsometric integral); surface (slope, curvature), drainage texture (drainage density, ruggedness number, stream frequency, length of overland flow, infiltration number and constant of channel maintenance) and hydrologic (topographic wetness index and stream power index).

Relief attributes

The geomorphic process of fluvial erosion is primarily determined by gravity. Relief attributes bring the question of gravity-induced potential energy into geomorphometric analysis. Relief attributes such as relative relief, dissection index, hypsometric integral, etc. are, therefore, used across the globe as indicators of erosion potential

Relative relief (Rr)

Defined as the mathematical difference between the highest and lowest points in an areal unit, relative relief gives an impression about the morphologic units in a terrain besides being an indicator of the intensity of erosional processes operating within a basin (Kuhni and Pfiffner, 2001). Generally, increase in the relative relief is associated with an augmentation of erosional process. In the studied basin, this parameter ranges from 30–994 m. By and large, the basin is characterised by relatively lower values of Rr. Only about 10% of the area depicts comparatively higher values. The basin is characterised by lower values of Rr with the north-eastern part of the Barakar basin displaying significantly higher values of relative relief (less than 10% of the area). Here the river cuts across a series of low-lying hill ranges (Pareshnath hills), regarded to be off-shoots of the Chhotanagpur plateau. Also, in the upper reaches of the Barsoti river in the western part, such areas of moderate relative relief are encountered (Fig 3a). The lower part of the basin displays no major abnormality with the relative relief being less than 40 m. This suggests that depositionary environment is prevalent.

Dissection index (Di)

The degree of erosion undergone by a basin is called the dissection index, a ratio between relative relief and maximum elevation (Nir, 1957). The value of DI ranges from 0 to 1, with values close to 1 representing elevated rates of erosion. DI for the Barakar basin ranges from 0.07 (extremely low dissection) to 0.77 (high dissection). High DI is encountered in the entire western domain of the Barakar basin, coinciding with the areas of high relative relief (Fig. 3b). The upper domain, predominantly displays very low values of DI, implying modest rates of erosion.

Hypsometric integral (Hi)

Hypsometric integral (HI) refers to the area below the hypsometric curve (or the area height relationship) and ranges from 0 to 1. The intensity of erosional processes operating within a basin is positively related with the HI. The average HI for the Barakar basin is 0.372, suggesting modest erosion rates. Areas in the eastern and north-western part of the basin display HI values significantly higher than the average HI (Fig. 3c). Elevated values of HI in the western part of the basin are expected considering the fact that Rr and DI are higher in this part. However, in the north-western part of the basin, intense erosion is suggested by higher HI values. But it appears that erosion is much subdued over this region because of the relatively lower values of Rr and DI. High HI values in the region may be associated with higher elevation.

Surface attributes

Surface attributes viz. slope, aspect and curvature refer to the 1st order derivatives from the DEM of an area. For this study only the parameters of slope and curvature were considered. Aspect was ignored because the data is categorical.

Slope (θ)

Slope or gradient represents the ratio between the elevation differences between two points on the earth's surface to the corresponding ground distance between those two points. High slopes are generally characterised by greater amount of geomorphic works of erosion and transportation. In this study, the slope map of the Barakar river basin was obtained from the SRTM DEM (30 m resolution) in an ArcGIS environment. Even a cursory examination of the spatial variation in slope across the basin (Fig. 4a) reveals a more or less, similarity with the spatial variation in relative relief. It appears that the presence of hill-ranges in the western part of the drainage basin has played a part in increasing the slope in such areas. The rest of the areas in the whole

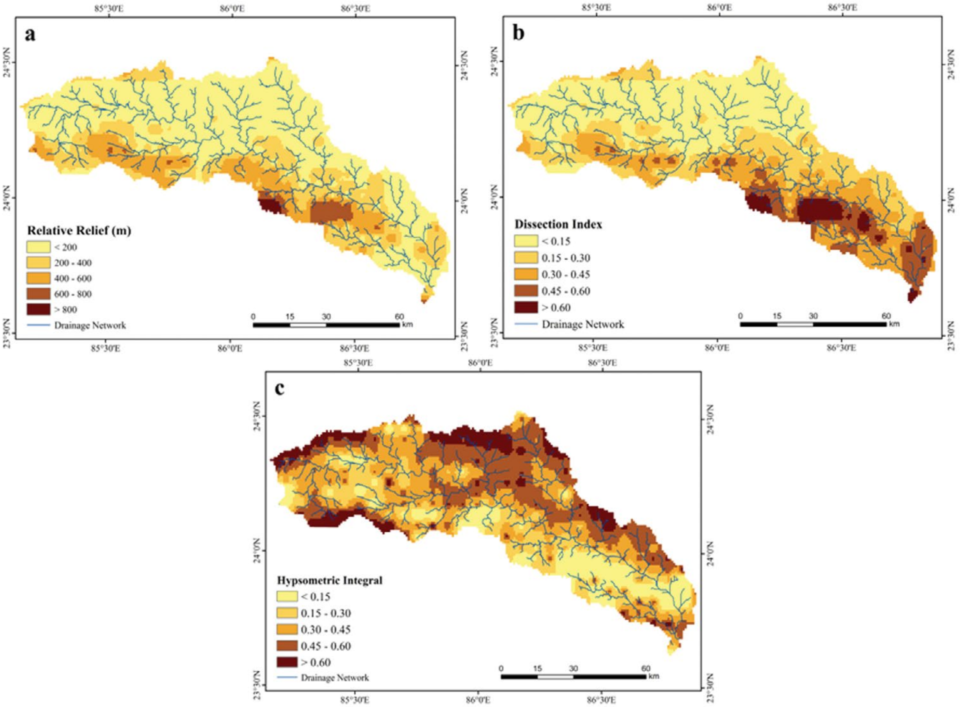

Figure 3. Spatial variation in the relief morphometric parameters of the Barakar drainage system a) Relative relief b) Dissection index c) Hypsometric integral.

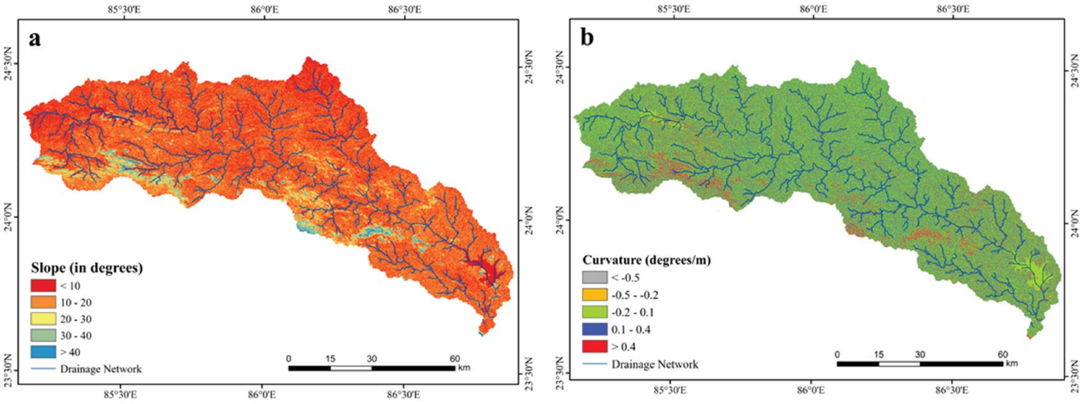

Figure 4. Barakar drainage system: Variation in the surficial morphometric parameters a) slope b) curvature.

domains display relatively modest values of slope, with the eastern and northern domains displaying very low slopes (0° to 2.03°).

CURVATURE

The rate of change of slope is expressed in degrees/ 100m is known as Curvature (Goudie, 2004). Surfaces are categorised as concave, convex or rectilinear based on whether the curvature is positive or negative or zero. Concave areas are associated with negative curvature implying gradual decline of slope downstream. This is a typical characteristic of an area undergoing little erosion.

Convex areas are regarded to be manifestations of topographic abnormality, where the slope increases downstream.

Rectilinear surfaces are characterised by zero curvature. In the studied basin, the curvature, by and large, is negative with some areas of positive curvature found somewhere in the western domain (Fig 4b).

Drainage textural parameters viz. drainage density, constant of channel maintenance, ruggedness number, stream frequency, length of overland flow and infiltration number indicate the degree of landscape dissection by the drainage network. The formulae for calculating these parameters are outlined in Table 1.

Drainage density (D_D)

Drainage density (D_d) is defined as the ratio between the lengths of all streams in a drainage network to the area. This measure is a direct measure of the stream power and efficacy of various erosional processes operating within a basin (Gregory and Walling, 1968). High values of D_d indicate greater capacity of the fluvial processes and imply greater erosional regime and vice versa. In the Barakar drainage system, drainage density appears to be very high in the north-western and region (2.40–3.19 km km^{-2}) and it is low at the eastern domain. This explains the relatively lower rate of dissection in the eastern domain which has been observed previously (Fig. 5a).

Constant of channel maintenance (CCM)

The reciprocal of drainage density is known as constant of channel maintenance i.e., the area of a basin surface needed to sustain a unit length of stream channel. It is inversely related to erosion. This parameter shows the highest value in the eastern domain, the area where very low drainage densities are encountered (Fig. 5b).

Stream frequency (S_F)

This is the ratio of the number of streams of all orders in a basin to its area (Horton, 1932). The effects of Dd and Sf on erosion are similar. Unlike drainage density, no spatial pattern is noticeable in the variation of stream frequency (Fig. 5c). This parameter ranges between 17.52 to 64.98 km^{-2} approximately.

Length of overland flow (LOF)

The length of flow of the rain water over the ground surface before it gets concentrated

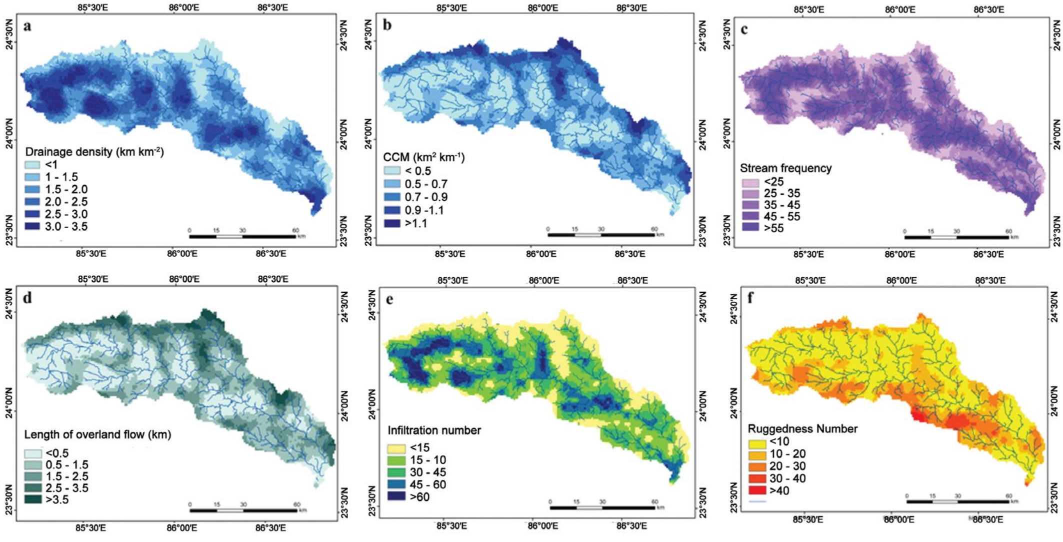

Figure 5. Maps showing the spatial variations in the drainage textural parameters a) Drainage density b) Constant of channel maintenance c) Stream frequency d) Length of overland flow e) Infiltration number f) Ruggedness number

in definite stream channels (Horton, 1945) is called LOF and is computed as one half of the reciprocal of drainage density. Smaller value of LOF denotes high runoff promoting high erosion, and vice versa. This fact is typically exemplified in the Barakar Drainage System, which displays higher LOF in the north and eastern domain, suggestive of lower erosion (Fig. 5d).

Infiltration number (IN)

Infiltration number (IN) of any watershed is defined as the product of drainage density and stream frequency (Faniran, 1968). So, it can be stated that IN is directly proportional to the drainage density and stream frequency. The Barakar basin is no exception and high values of IN coincide with higher values of Dd (Fig. 5e)

Ruggedness number (RN)

The product of relative relief and drainage density of a region is called ruggedness number and is generally positively associated with the erosional status (Melton, 1965). The regions displaying higher R_n values will be characterised by elevated erosion rates and rugged topography. In the Barakar basin, the highest R_n values are observed in the eastern part. The lower domain of the basin displays least R_n values (Fig. 5f).

Hydrological Attributes

Hydrological response of a watershed to a rainfall event largely determines the ongoing process of erosion. It is generally recognised that areas of flow convergence are characterised by diminishing erosion and vice versa. The possibility of flow convergence and divergence is governed by two main factors viz. slope and specific catchment area (a measure of potential water flux). With the availability of high-resolution DEMs, the topographical attributes could be quantified by various wetness indices (Moore *et al.*, 1991). These indices have been calculated for the Barakar drainage basin so as to understand the spatial variation in the hydrologic response in the watershed.

Topographic wetness index (TWI)

Topographic wetness index tries to quantify the control of local topography on the hydrological processes operating within a basin. This parameter is considered to be primarily responsible for variation in the rate of geomorphic processes operating within the basin (Beven and Kirkby, 1979; Moore *et al.*, 1991). This parameter is negatively correlated with erosion. The individual rasters of slope and flow accumulation (proxy for specific catchment area) were undergone mathematical operations (Refer Table 1 for equation) to derive the TWI for the studied

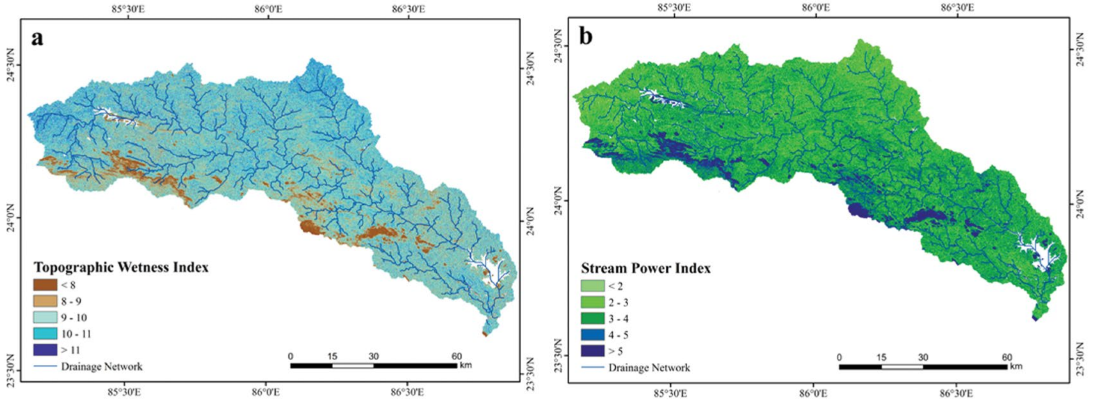

Figure 6. a) Topographic wetness index b) Stream power index of the Barakar basin. The areas marked shaded in white represent the dam areas

basin. In the western domain of the basin (Fig. 6a), the TWI is the minimum whereas the highest TWI is observed in the northern part of the basin, corresponding with the areas of low slopes. This is expected since TWI tends to be inversely related with slope and intensity of erosion. Therefore, in the north and eastern domain, the erosion process appears to be minimal.

STREAM POWER INDEX (SPI)

In areas where discharge data is not available, the SPI is often taken as a proxy to quantify the stream power. This parameter tends to increase in areas under intense erosional regime (Moore *et al.*, 1991; Chen and Yu, 2011). In the studied drainage system, the SPI displays high values in the western part and in the middle domain of the basin (Fig. 6b). This reiterates the fact that the Western and middle domain is under intense erosional regime.

Multi-Criteria Decision Making (MCDM) and Index of Erosion Potential

The process of sub-aerial erosion is governed by a multitude of factors. As it is known that the exact quantification of the process of erosion is unfeasible, one has to depend on a number of proxy parameters for assessing the intensity of erosion being undergone in a drainage basin. morphometric attributes comprise one such popular proxy parameter. Considering these parameters in isolation may result in oversimplification and the obtained results may not produce the real scenario. Application of MCDM techniques in this realm enables amalgamation of a large number of factors into a single platform. One of the prime considerations before performing such kind of exercise is to assign weights to different parameters, the values which are dependent on the relative importance of each factor. Among a host of different MCDM techniques, the Analytical Hierarchy Process (AHP) has emerged to be popular in the field of earth science (Abdul Rahaman *et al.*, 2015). The model, based on a pairwise comparison matrix (Saaty, 1980) has faced some criticism because of greater chances of ambiguous weight selection (Mistri and Sengupta, 2020). Especially the pertinent question 'How much is one parameter more important than other?' introduces further complexities to the problem. This confusion was somewhat addressed by performing the multi-component Principal Component Analysis (PCA) prior to the AHP exercise. Six Principal Components (PCs) were extracted with a cumulated explained variance of about 97% and the ratios of the loading values were used for assigning the relative importance of each parameter. Each PC was treated separately in this exercise. Next the component wise AHP was calculated to derive the relative weightages of each parameter. Thus, instead of one AHP, there were six AHP-based maps for each of the six individual PCs. Table 2 reveals that infiltration number (IN) with a loading value (LV) of 0.90 is apparently the dominant factor in the first PC, with an explained variance of 41.45 %. Next in importance include drainage density (LV = 0.90), length of overland flow (LOF) and constant of channel maintenance (CCM) (LV = 0.88) and then followed by stream frequency (0.69), stream power index (0.59), and topographic wetness index (0.59). The parameters viz. hypsometric integral (LV = 0.42), relative relief (LV = 0.11), dissection index (LV = 0.03) accounted for the least of the variations in the dataset (Table 2). AHP based importance scale was constituted by employing the LV ratios of each parameter. For example, the LV of infiltration number is 0.904 whereas the LV of drainage density is 0.903. The ratio between the two LVs was 1.001 which was approximated to the nearest integer as 1 because AHP has no scope for fractional rank scores. Similarly, the ratio

Table 3. Pairwise comparison matrix under Analytical Hierarchy Process (AHP) for 1st Principal Component. For parameter notations, refer, Table 1. The final weight of each parameter (in percentage) after the pairwise comparison is shown in the last column.

Parameters	IN	D_d	LOF	CCM	S_f	SPI	TWI	R_n	Cv	θ	HI	Rr	DI	Weights (%)
IN	1	1	1	1	1	2	2	2	2	2	2	9	9	12.1
D_d	1	1	1	1	1	2	2	2	2	2	2	9	9	12.1
LOF	1	1	1	1	1	2	2	2	2	2	2	8	9	11.9
CCM	1	1	1	1	1	2	2	2	2	2	2	8	9	11.9
S_f	1	1	1	1	1	1	1	1	1	1	2	7	9	9.3
SPI	1/2	1/2	1/2	1/2	1	1	1	1	1	1	1	6	9	6.9
TWI	1/2	1/2	1/2	1/2	1	1	1	1	1	1	1	6	9	6.9
R_n	1/2	1/2	1/2	1/2	1	1	1	1	1	1	1	5	9	6.8
Cv	1/2	1/2	1/2	1/2	1	1	1	1	1	1	1	5	9	6.8
θ	1/2	1/2	1/2	1/2	1	1	1	1	1	1	1	5	9	6.8
HI	1/2	1/2	1/2	1/2	1/2	1	1	1	1	1	1	4	9	6.3
Rr	1/9	1/9	1/8	1/8	1/7	1/6	1/6	1/5	1/5	1/5	1/4	1	4	1.5
DI	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/4	1	0.9

between the LV of ruggedness number (0.56) and Slope (0.52) was taken as 1 whereas the exact score was 1.075. This procedure was employed for all parameters for obtaining the Nine-Point Scale of Saaty (1980). The AHP process was then performed and the results are outlined in Table 3. As expected, the most relevant factors governing the process of sub-aerial erosion in the Barakar basin include IN (12.1%) and D_d (12.1%), LOF (11.9%) and CCM (11.9%). Relief, surface and hydrological morphometric parameters appear to be secondary factors as compared to the drainage textural parameters as per the 1st PC (Table 3). The same procedure was followed for other five PCs.

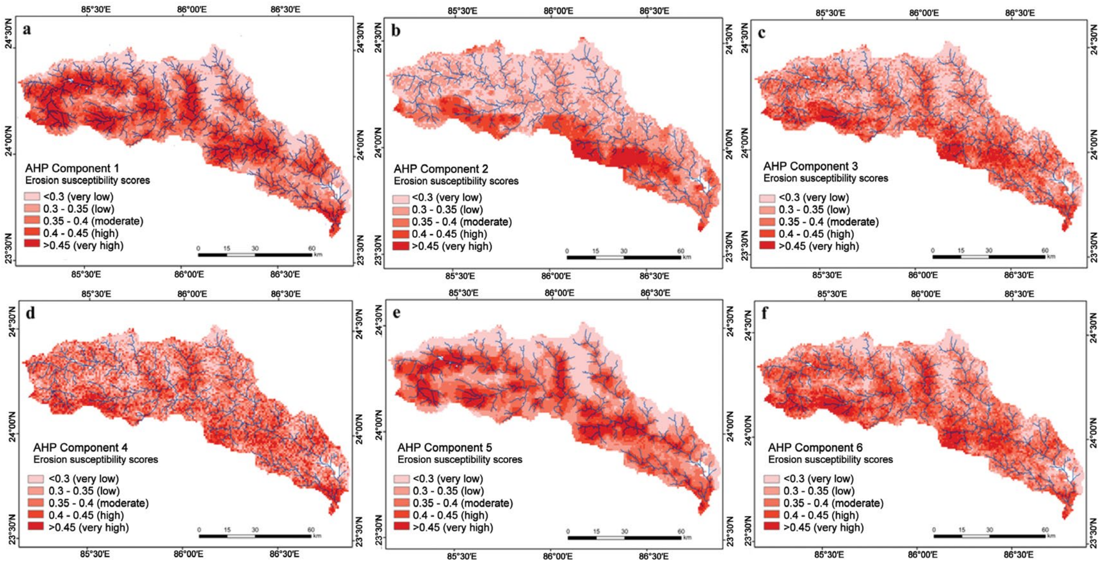

Figure 7 AHP-based erosion susceptibility maps of the Barakar drainage system with respect to Principal Component (PC) a) PC1 b) PC2 c) PC3 d) PC4 e) PC5 f) PC6

Finally, the importance scores (in %) were converted to decimals and the weightage for each individual parameter in each component was assigned (Table 4). These weightages were given to the rasters of morphometric parameters in ArcGIS and summed up to extract the component-based erosion susceptibility maps (Fig. 7 a–h).

Weightages were assigned to each AHP-based component rasters in accordance with their explained variance (Table 2) to derive the Index of Erosion Susceptibility (IES) of the Barakar river basin (Fig. 8). Careful scrutiny of the map gives an indication that the Barakar basin is predominantly characterised by moderate to high values of IES. This is especially observed in the southern part of the basin. Most of the relief aspects such as relative relief, dissection index, and hypsometric integral and surface attributes are found to be higher in the southern part as compared to the northern part.

Conclusion

The present study was carried out in order to ascertain the terrain erosion susceptibility of the Barakar drainage basin using the 30 m resolution SRTM DEM and MCDM approach. Among a myriad of AHP techniques, this study has employed the well-documented Analytical Hierarchy Process (AHP) on various basin morphometric parameters. However, the methodology followed in this study differs from conventional AHP techniques, which take into consideration the opinion of the experts in a particular field. The differing views of the experts have usually differed from each other, thereby inviting criticism (Macharis *et al*. 2004). This study has, therefore, integrated the multi-component PCA into the AHP technique while establishing the functional relationships among the contributing factors of erosion. Consideration of more than one component becomes significant in studies involving natural phenomena as the first PC rarely explains much of the variation. Therefore, this study proposes the use of multi-component PCA before assigning relative importance of each parameter in the AHP pairwise comparison matrix.

The final map of the index of erosion susceptibility generated from the multi-component AHP has been displayed in Fig. 8. The Index of Erosion Susceptibility (IES) reveals that, by and large, the values of IES are below 0.5. As per the methodology and data normalisation techniques adopted in this study, it may be assumed that IES values close to 1 are suggestive of intense erosion.

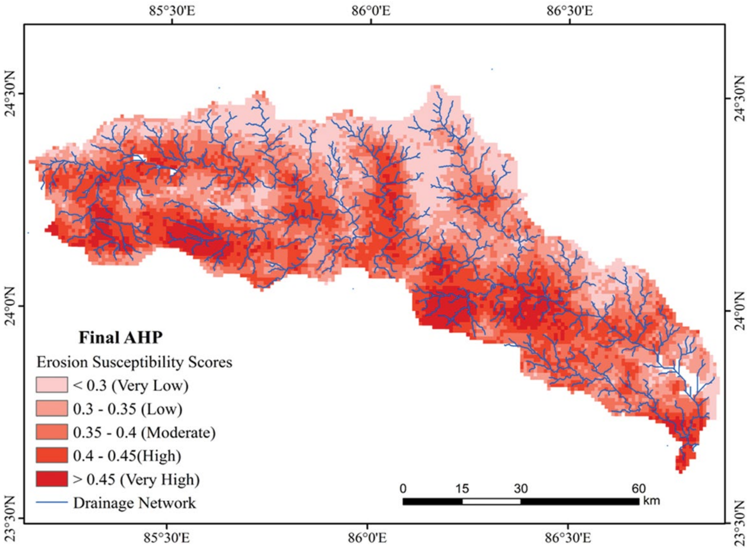

Figure 8 Final Principal Component-weighted AHP-based erosion susceptibility map of the Barakar drainage basin.

However, the fact that most of the areas display IES below 0.5 implies that erosion is, more or less, subdued in the Barakar basin of eastern India. However, some areas in the south are characterised by comparatively higher values as compared to the north. The southern part of the basin is in the vicinity of the Pareshnath hills, regarded to be an offshoot of the Chhotanagpur plateau. Most of the relief morphometric parameters viz. relative relief, dissection index and hypsometric integral as well as the slope, curvature, drainage density and stream frequency tend to increase from north to south. The parameters which are negatively associated with erosion i.e., topographic wetness index shows the reverse trend, i.e., decreases from north to south. This depicts the regional trend in erosion susceptibility (increase from north to south) in the studied river basin. Another important characteristic of the Barakar river basin is that it is elongated to a considerable extent in the W–E orientation. However, the morphometric parameters as well as the index of erosion susceptibility do not exhibit any W–E changing pattern. In other words, the magnitude of erosion susceptibility does not change much from west to east. This gives an impression that there is not much change in the geological conditions along the elongated basin in the W–E direction. Therefore, there is a possibility that the basin may have been formed in the past due to the presence of one or more E–W trending faults and fault-lines. The possibility of the river occupying a rift valley in the past cannot be discounted considering the fact that the neighbouring Damodar river occupies a rift valley (Mukherjee and Ghose, 1999; Kundu *et al.* 2011). This possibility needs further investigation but one inference which cannot be denied is that even if the Barakar river had been controlled by faults and lineaments in the past, these faults are not active in the Holocene. This is evidenced by extremely subdued rates of morphometric parameters and erosion susceptibility throughout the basin.

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