Multivariate erosion risk assessment of lateritic badlands of Birbhum (West Bengal, India): A case study

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Each geomorphic hazard involves a degree of risk which incorporates quantification of the probability that a hazard will be harmful. At present, the categorization of sub-watersheds into erosion risk is considered as the fundamental step to conserve the soil loss. Development of badlands over the laterites of Birbhum district is an indicative of excessive soil loss in the monsoonal wet-dry type of climate. Slope erosion and channel erosion have generated huge amount of sediment from the small watersheds during intense monsoonal rainfall (June–September). The adjoining areas of Rampurhat I Block, Birbhum (West Bengal) and Shikaripara Block, Dumka (Jharkhand) have lost the lateritic soil cover at a rate of 20–40 ton/ha/year (Sarkar *et al.* 2005). In order to estimate the progressive removal of soil particles from the gully-catchments of the above-mentioned area, different morphometric parameters, soil parameters, hydrologic parameters and empirical models are employed. Side by side, the study is carried out to categorize the gully-catchments into different magnitude of erosion risk using several multivariate statistical techniques.

1. Introduction

Fluvial erosion is the composite result of several hydro-geomorphic processes (e.g., overland flow, rill and gully erosion) whereby debris, soil and rock materials are loosened or dissolved and removed from any part of the earth's surface (Kirkby 1969a; Stoddart 1969). In general, 'soil erosion' is a two-phase process consisting of the detachment of individual particles from soil mass (by rainsplash erosion) and their transport by erosion agents such as running water (overland flow). When sufficient energy is no longer available to transport the particles, deposition occurs (Morgan 2005). Soil erosion is a function of erosivity (i.e., potential ability of falling raindrops to detach soil particles) and erodibility (i.e., the degree to which soil particles is susceptible to erosion by water) (Hudson 1984). As the raindrops, rills and gullies are the chief agents of catchment erosion or suspended sediment yield; the early phase of soil erosion study should incorporate the quantitative basin-oriented or catchment-oriented approach (Chorley 1969; Jha and Paudel 2010). Then to control the erosion or to take erosion protection measures, the fundamental step is to assess the present severity or risk of catchment erosion through the hydro-geomorphic quantitative expressions and thematic maps. A geomorphic hazard, like soil erosion, involves a degree of risk, the elements at risk being land property, loss of top-soil, soil infertility and the environment (Bell 1999; Blinkov and Kostadinov 2010). 'Risk' involves quantification of the probability that a hazard will be harmful and the tolerable degree of risk depends upon what is being risked, soil conservation being much more important than land utilization (Bell 1999). 'The assessment of erosion hazard' is a specialized form of land resource

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evaluation, aiming categorization or ranking of land areas and catchments of the study area into regions of low to high erosion risk zones based on selected hydrologic, geomorphic and soil parameters (Sarkar *et al.* 2005). Side by side, analyzing the regional climatic pattern, rainfall erosivity, overland flow and using several multivariate statistical techniques, we have identified sequentially those influencing parameters or factors which enhance significantly the catchment erosional processes of area under study and at last we have prepared the catchments' priority for soil conservation (in terms of controlling the factors of soil erosion).

2. Methodology

Erosion risk assessment always demands an interdisciplinary approach connecting the disciplines of hydrology, geomorphology and pedology (Gerrard 1981; Jha and Kapat 2009). It stresses predominantly on the quantitative method, incorporating the statistical and mathematical equations to analyse phenomena. The present study includes three principal processes – empirical observations, recording of data and quantitative interpretation. The adopted methodology is clearly represented in a flowchart (figure 1). The ultimate aim of this study is to recognize those catchments of gullies where the soil productivity, land uses and land covers are threatened by excessive soil loss by water. To reach that goal the following objectives are taken into consideration:

- Understanding the geo-environmental settings of the study area which influence both rainfall erosivity and soil erodibility;
- Analyzing statistically the relations of hydrogeomorphic parameters with erosion of selected catchments;
- Multivariate analysis of those parameters to identify the dominant or principal parameters and relative clustering of catchments in terms of components' scores; and
- Classifying the sample catchments from low to high erosion risk and mapping the potential erosivity and soil erosion of the study area.

Here the catchments or drainage basins of 2nd and 3rd order and slope facets are taken as an ideal geomorphic unit. The study area is subdivided into 17 catchments for the detailed erosional study. In the pre-field session, topographical sheet (72 P/12/NE, 1979), District Resource Map of Birbhum District (Geological Survey of India 2001), climatic data of India Meteorological Department and Irrigation and Waterways Department of West Bengal, satellite images (LANDSAT and IRS), SRTM data (2006), numerous literatures, bulletins and reports are collected. The spatial information is stored in Geographic Information System (GIS) and the thematic maps are prepared using GIS software (ArcGIS 9.2 and 21st Century GIS). The

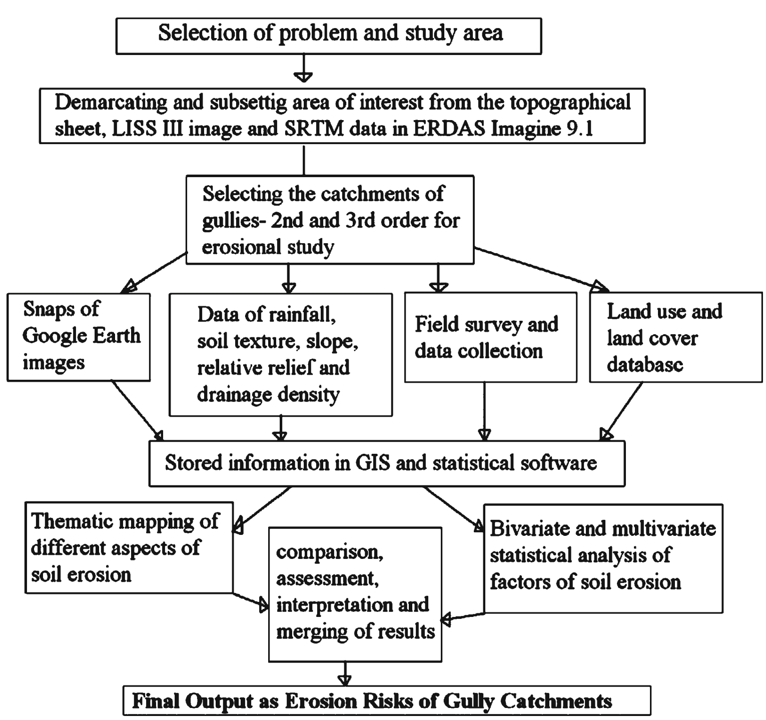

Figure 1. Flow chart of methodology adopted in this study.

different statistical analysis (e.g., linear and curvilinear regression, correlation, principal component analysis, cluster analysis and multiple regressions) is done in Microsoft Excel 2003 and SPSS 14.0 softwares.

The selected study area (65.84 km^2) is situated between the adjoining area of western Rampurhat, I Block of Birbhum district, West Bengal and eastern Shikaripara Block of Dumka district, Jharkhand. The study area is located at 5 km west of Rampurhat railway station, near Baramasia bus-stop. The latitudinal extension ranges from 24°10′N to 24°13′N and longitudinal extension ranges from 87°39′E to 87°45′E (figure 2). It is the lateritic elevated interfluve portion (mean relief of 56 metre) of Brahmani (north) and Dwarka (south) rivers. The laterites and lateritic soils of Cainozoic Era are found here over Rajmahal Trap–Basalt of Jurassic to Cretaceous Period (Hundy and Banerjee 1967; Sarkar *et al.* 2007). The detrital laterites are occurred here in loose concretions as gravels and pebbles and these are generally derived from weathered primary high-level laterites by fluvial processes and are deposited far from their source of origin (Rajmahal Highlands). Laterites are generally underlain by lithomergic clays which is more prone to tunnel erosion (soil piping) (Jha and Kapat 2009).

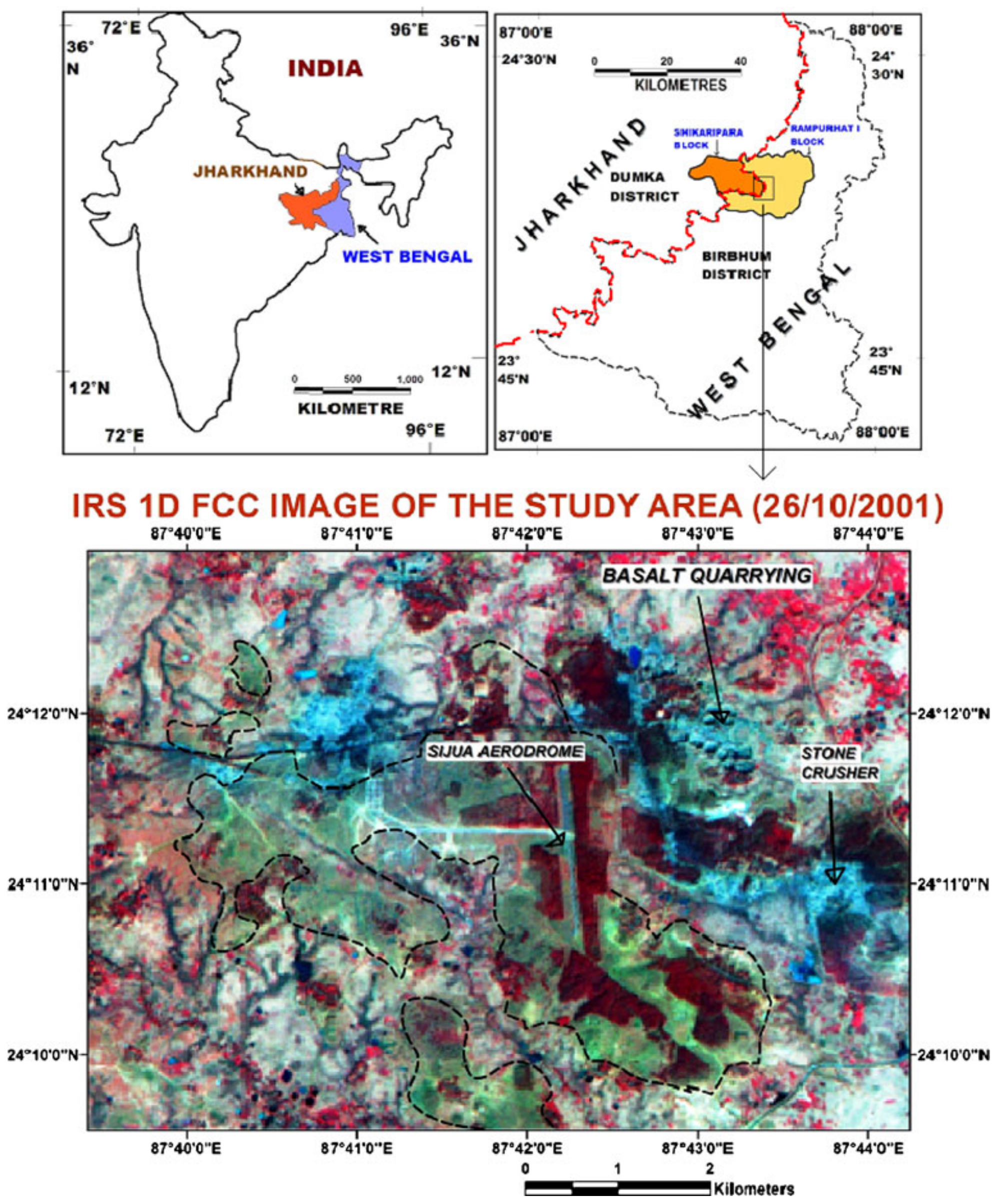

Figure 2. Location map of the study area.

3. Severity of soil erosion and role of climatic variables

The movement of water on catchment occurs in two ways to enhance soil loss (Abrahams 1964; Morisawa 1985):

(1) Rainfall on the surface of a watershed can be removed by infiltration into the soil or rock, by sheet flow over the surface/or by flow through a system of rills, gullies or stream channels; and
(2) The sub-surface water may remove material in solution or suspension as it flows, resulting in a subsurface system of 'pipes'. Piping (or sapping) may eventually result in open rills or gullies when the roofs of these tunnels collapse.

Based on the topographical sheet (1979), IRS 1D LISS III image (2001), Google Earth (2007) and field survey (2010), the current geographical area of forest, degraded lateritic land and stone quarrying are 3.95, 16.23 and 2.9 km^2, respectively. From the recurrent field investigations, following important facts regarding magnitude of erosion risk have come into light.

(i) The severity of erosion can be understood by the appearances of numerous rills and gullies, exposure of tree roots, pedestal erosion, pinnacle erosion, bare soil cover, barren waste land, tunnels and surface crusting (figure 3);
(ii) Monsoonal wet-dry type of climate has high seasonal regime which influences laterisation and soil loss (McFarlane 1976);
(iii) Due to high erodibility of lateritic soil (20–40 t/ha/y), deforestation, morum and stone quarrying, low water holding capacity (<50 mm/m), low clay content (<25%) and organic carbon (<1.5%) of soil favour surface and sub-surface erosion;
(iv) Rainsplash erosion is more effective in the upstream deforested area of catchment than overland flow;
(v) Horton overland flow and saturation overland flow both occur in heavy showers of summer thunderstorms and monsoon and it transports downslope clay and silt from topsoil and leave the coarse sand and gravels in upslope (Kirkby 1969b);
(vi) Breaks in vegetation cover, bareness of soil, local irregularities on slope, surface run-off, etc. develop rills and gullies at some distance from the water divide and the system of rills becomes true drainage net by abstraction and micropiracy (Parsons 2005);
(vii) Diversion of the overland flow into large rill increases its erosive and grading ability and that rill may become enlarged enough to be called as a gully. Though gully heads are formed by saturation overland flow, collapsing of tunnels and soil slumping; and
(viii) Such a gully in turn develops rills on its valley walls which by the processes of micropiracy and cross-grading become tributaries (figure 3a).

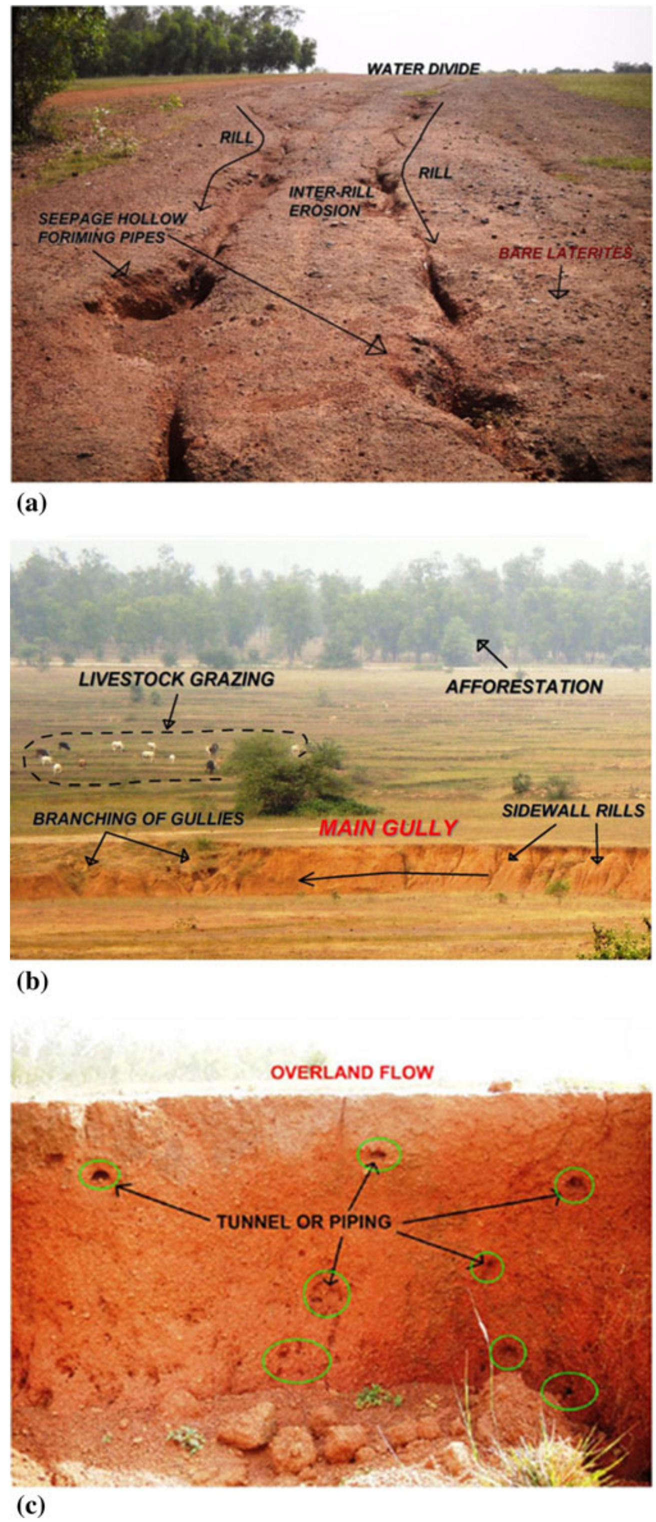

Figure 3. Photographs showing (**a**) rill and inter-rill erosion, (**b**) gully erosion and (**c**) tunnel erosion on laterites at western part of Bhatina village, Rampurhat.

Table 1. *Summary of land sculpturing activities in different seasons.*

Climatic phenomena	Effects on landform and soil loss
1. Seasonal variation of temperature (about 15°–19°C)	Encourage various processes weathering, like block disintegration, formation of cracks and joints
2. High temperature range (max. 45°C and min. 9°C)	Lowering soil moisture and ground water table, loosening of soil particles, drying up of surface soils, reduction in soil cohesiveness
3. Seasonal rainfall (from mid-June to 1st week of September)	Weathered products are removed or accumulated to yield ferruginous soils, laterisation process becomes active
4. Short phases of heavy downpour within monsoon season	Development of badland topography – rainsplash erosion, sheet erosion, rill and gully erosion, gully piping, mass wasting at gully headwall and sidewall, bareness of soil cover

Source: Sen *et al.* (2004), p. 213.

The climate of the study area has been identified as sub-humid and sub-tropical monsoon type, receiving mean annual rainfall of 1420–1437 mm. According to the scheme of Chorley *et al.* (1984), the study area is identified as 'Tropical Wet-Dry Savanna Morphogenetic Region' where the chief dominant pedo-geomorphic processes are mod-max chemical weathering, moderate physical weathering, mod-max mass wasting, max pluvial erosion, mod-max fluvial processes (sheet wash, rainsplash, rill and gully erosion-badlands), and laterisation (Cooke and Doornkamp 1987). The monsoonal and cyclonic rainfall (maximum intensity of 21.51–25.51 mm/hr) is the most forceful climatic variable operative in this typical lateritic badland, causing excessive erosion through rainsplash, overland flow and sub-surface flow. According to Sen *et al.* (2004), there are two seasonal stages of annual soil erosion (table 1). (1) Surface preparation stage of winter (December–February) and summer (March–May) and (2) the active surface erosion stage (mid June–October).

4. Catchment-wise annual rainfall erosivity and aggressiveness

Erosivity data may be used as an indicator of regional and temporal variations in erosion potential to pinpoint areas of high risk or vulnerability of erosion (Boardman *et al.* 2009). Soil loss is closely and directly related to rainfall partly through the detaching power (kinetic energy of raindrops) striking the bare soil surface and partly

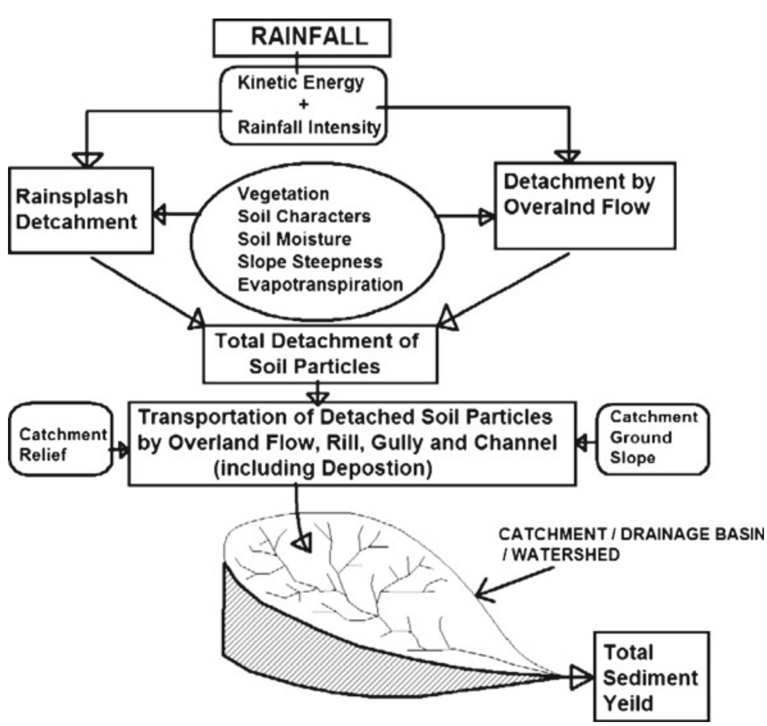

Figure 4. Simplified model of total soil loss by water from a gully-catchment.

through the contribution of rain to surface and subsurface run-off (Morgan 2005). Due to low-cohesiveness of lateritic soil and prolonged dryness of topsoil (November–May), the study area is much more vulnerable to rainsplash erosion than overland flow in intensified monsoonal showers. In inter-rill areas, the dominant mechanism of sediment detachment is that of raindrop impact (Parsons 2005). The whole system of soil loss of a watershed is provided as model in figure 4. To estimate the annual rainfall erosivity we have taken the average value of Roose's rainfall erosivity index (1975) and Morgan's mean annual rainfall erosivity (1974). To quantify the potential rainfall erosivity, we have employed the effective rainfall which is the actual portion of rainfall over surface after rainfall interception by vegetation. After getting the rainfall erosivity value, annual rainfall detachment of catchments (table 2) is derived by the formula of Morgan (2001). The expressions are as follows:

From (Morgan 2005), mean annual rainfall (in mm) = R and effective rainfall (P) = R $(1 - A)$ where A is the proportion of rainfall interception (0–1) by vegetation.

From Roose (1975), mean annual rainfall erosion index in mg mm $ha^{-1}h^{-1}$.

From Morgan (1974), mean annual rainfall erosivity (KE>25)

I_{30} (75 mm h^{-1} – maximum value recommended by Wischmeier and Smith 1978).

From Morgan (2001), rainfall detachment rate (kg m^{-2} year $^{-1}$) = K KE 10^{-3}, where K is the soil detachability index (g J^{-1}).

The result suggests that 2nd order catchments of 2a, 2b, 2e, 2f, 2g, 2h and 3rd order catchments of 3a, 3d and 3h are very much susceptible to splash erosion (figure 5). Alongside, the annual rainfall detachment rate of soil particles ranges from 1.40 to 18.12 kg m^{-2} $year^{-1}$. Again we have found that the catchments of loamy and clay loam soils are more prone to rainfall detachment.

Rainfall aggressiveness index (potentiality of rainfall to yield sediment from a watershed) is $\sum p^2/P$ (Arnolds 1980; modified form of Fournier index 1960), where p is the monthly rainfall (mm) and P is annual rainfall (mm) (Morgan 2005; Parsons 2005). The high value of $\sum p^2/P$ 232.14 and 277.33 for the years 1960 and 2008, respectively denotes a strong seasonal climatic regime with a dry season during which the plant cover decays (Morgan 2005). According to Douglas (1976), the prediction of erosion rates still rely on climatic parameters, few of which are more satisfactory than Fournier's (1960) general empirical equation embodying p^2/P, basin relief (H) and basin area (S) (Cooke and Doornkamp 1987). The temporal variation (1960–2006) suggests that there are increasing trend of catchment-wise sediment yield (figure 6a and 6b).

$$\text{Log D.S.} = 2.65 \log p^2/P + 0.46 \log H^2/S - 1.56,$$

where D.S. is the sediment yield in ton km^{-2} $year^{-1}$ and H^2 is coefficient of massivity.

5. Catchment-wise overland flow and erosion risk

The estimation of overland flow has provided an idea of volume or depth of water required for erosion and transportation in a drainage basin (Chow 1964; Chow *et al.* 1988). It has been found that overland flow of sample catchments is very much positively correlated with proportion of bare soil cover (0.91), constant of channel maintenance-index of watershed erodibility (0.46) and effective rainfall (0.82), and negatively correlated with actual to potential evapotranspiration ratio (−0.95), effective hydrological depth of soil (−0.92), ratio of soil detachment rate and transport capacity of flow (−0.53) and subsurface flow (−0.94), respectively.

The main erosional and transportation factor is the surface run-off of watershed which is more active on vegetation-free slopes (Kirkby 1976). With increasing proportion of bare soil cover, the moisture content and erosion protection by vegetation are reduced in this lateritic area (McFarlane 1976). In order that with rising volume of surface run-off (after Khosla 1949), the density of gullies (number of 1st order stream per km^2, after Morgan 2005) is amplified (figure 6c). It has been found that 3rd order catchments have dense network of gullies than 2nd order catchments and the increasing volume of surface run-off (X) is positively correlated ($r = 0.82$) with gully density (Y), having increasing trend ($Y = 0.0058X + 2.34$). In the second instance (figure 6d), the low ratio of soil detachment rate and transport capacity of flow (H/G) means maximum loss of soil cover from catchment (because of high transportation capacity of overland flow) which is depicted here also (figure 7b). H/G ratio (Y) is exponentially and negatively correlated ($r = -0.53$) with catchment-wise overland flow (X), having decreasing trend ($Y = 506.33X^{-1.68}$).

6. Multiple regressional analysis of sediment yield (SY) and sediment delivery ratio (SDR)

Soil erosion is the first step in the sedimentation process which consists of fluvial erosion, transportation and deposition of sediment. A fraction of

Table 2. *Estimating catchment wise rainfall erosivity, detachment rate of soil and erosion risk.*

Catchment	Effective rainfall (mm)	Roose's index (A)	Morgan's KE index (B)	Mean annual rainfall erosivity index (A + B/2)	Annual kinetic energy of effective rainfall (J m^{-2})	Dominant soil texture (USDA)	Annual rate of soil particle detachment by rainfall (kg m^{-2} $year^{-1}$)	Erosion risk
2a	1190	10292	165272	92929	24053	Sandy loam	16.83	High
2b	1135	9820	127270	73455	24843	Sandy loam	17.39	High
2c	1092	9447	97265	58080	20257	Sandy clay loam	2.02	Low
2d	1233	10665	195276	108303	21497	Sandy clay loam	2.14	Low
2e	1135	9820	127270	73455	19320	Clay loam	13.52	Moderate
2f	1062	9186	76260	47316	15121	Sandy loam	10.58	Moderate
2g	1108	9584	108262	63715	15930	Sandy loam	11.15	Moderate
2h	1080	9335	88259	53465	17916	Clay loam	12.54	Moderate
3a	1154	9981	140271	80117	25894	Sandy loam	18.12	High
3b	1151	9956	138267	79090	23750	Sandy clay loam	2.37	Low
3c	1145	9907	134265	77039	20287	Sandy loam	2.02	Low
3d	1078	9322	87264	52955	21488	Sandy loam	15.04	High
3e	1059	9161	74256	46289	14049	Sandy clay loam	1.40	Low
3f	1065	9211	78258	48339	13830	Sandy loam	9.68	Moderate
3g	1124	9720	119266	69353	16469	Sandy clay loam	1.64	Low
3h	1122	9708	118263	68840	19568	Sandy loam	13.69	High
3i	1095	9472	99263	59103	20005	Clay loam	14.01	High

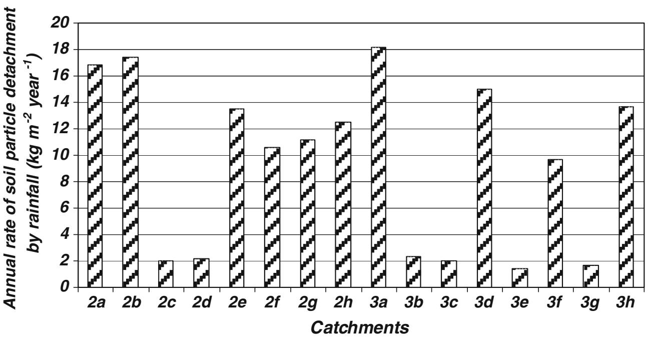

Figure 5. Diagram showing the catchment-wise annual rate of soil detachment by rainfall.

lateritic soil passes through overland flow, rills and gullies contributes to sediment yield of catchment while some of them deposit in water channels (i.e., gully floor) (Rousseva *et al.* 2000). Sediment yield (SY) and sediment delivery ratio (SDR) are the measure of potential erosion that takes place in a watershed, minus storage and quantifies the rate of sediment exported out of the local erosional system (Bell 1999; Wan and Sangchyoswat 2010). If we can estimate the maximum potentiality of catchments' SY and SDR, then we can rank those sample catchments into erosion risk category. Here, two predictive equations of SY and SDR are applied regionally and those equations are significantly depended on basin morphometric properties, rainfall, basin run-off, soil characters and land uses.

Douglas (1976) formulated a widely acclaimed equation of sediment yield where the numerator represents the erosive influence of rainfall and the denominator represents the vegetation-protection factor. The equation is as follows (Cooke and Doornkamp 1987):

$$E = 1.631(0.03937\,P)^{2.3} \Big/ \Big[1 + 0.0007\,(0.03937\,P)^{3.3}\Big]$$

where E = suspended sediment yield (m^3 km^{-2} year^{-1}) and P = effective precipitation in mm (that part of the precipitation which produces surface run-off, after rainfall interception).

Using the above empirical equation, we have found the catchment-wise sediment yield rate and prepared a sediment yield map for the study area (figure 7). The map suggests that centrally located catchments yield more sediments and its value decreases towards south-east and north-west direction.

Again we have employed another empirical equation of sediment yield measurement using land use and hydro-geomorphic data. Universal Soil Loss Equation (USLE) estimates only sheet and rill erosion, it is necessary to incorporate the erosion by surface run-off (Wischmeier and Smith 1972; Stone and Hilbon 2000). Then combining USLE and modified USLE, Williams and Berndt (1972) have intended to quantify the sediment yield of watershed, including run-off volume and peak run-off rate. The equation is expressed as follows (Wischmeier and Smith 1978; Parsons 2005):

$$\mathrm{SY} = 11.8\,(\mathrm{Q}\,\mathrm{q_p})^{0.56}\ \mathrm{K\,C\,P\,LS}$$

where SY = sediment yield of monsoonal period (ton km^{-2}), Q = run-off volume of monsoon period

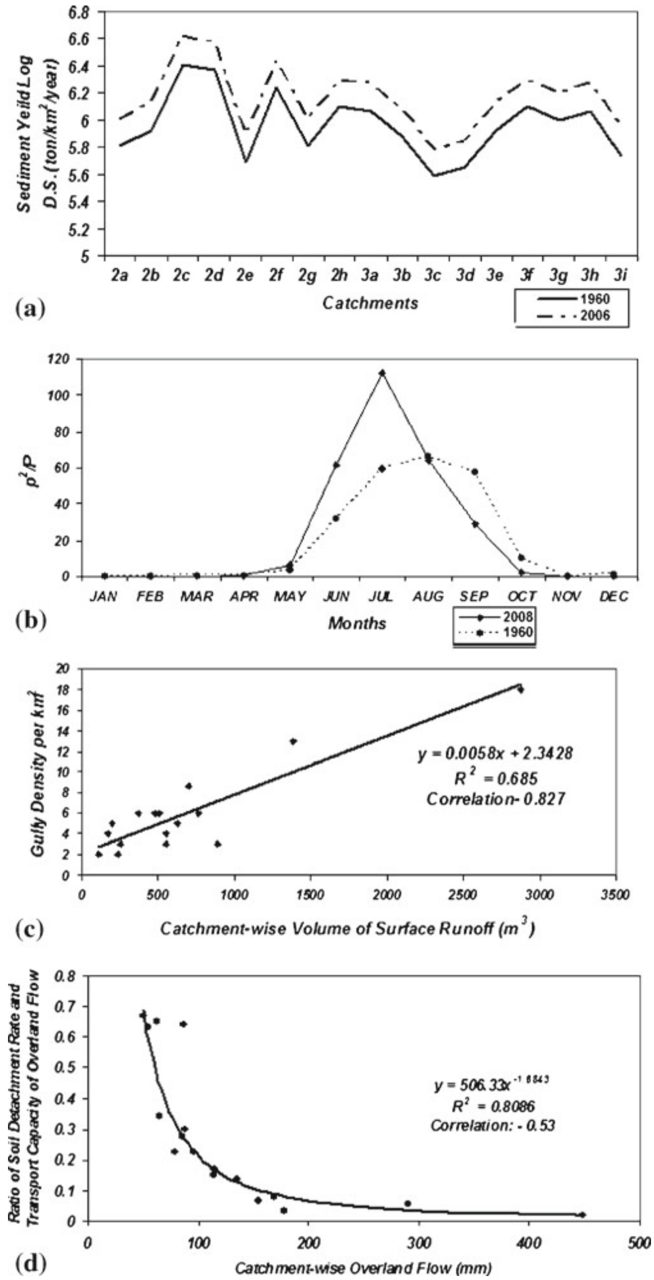

Figure 6. Diagrams showing (**a**) increasing sediment yield of catchments, (**b**) month-wise rainfall aggressiveness from the year 1960 to 2008, (**c**) increasing density of gully with rising volume of catchment surface run-off, and (**d**) decreasing ratio of soil detachment rate and transport capacity of flow (maximum soil loss) with increasing catchment overland flow.

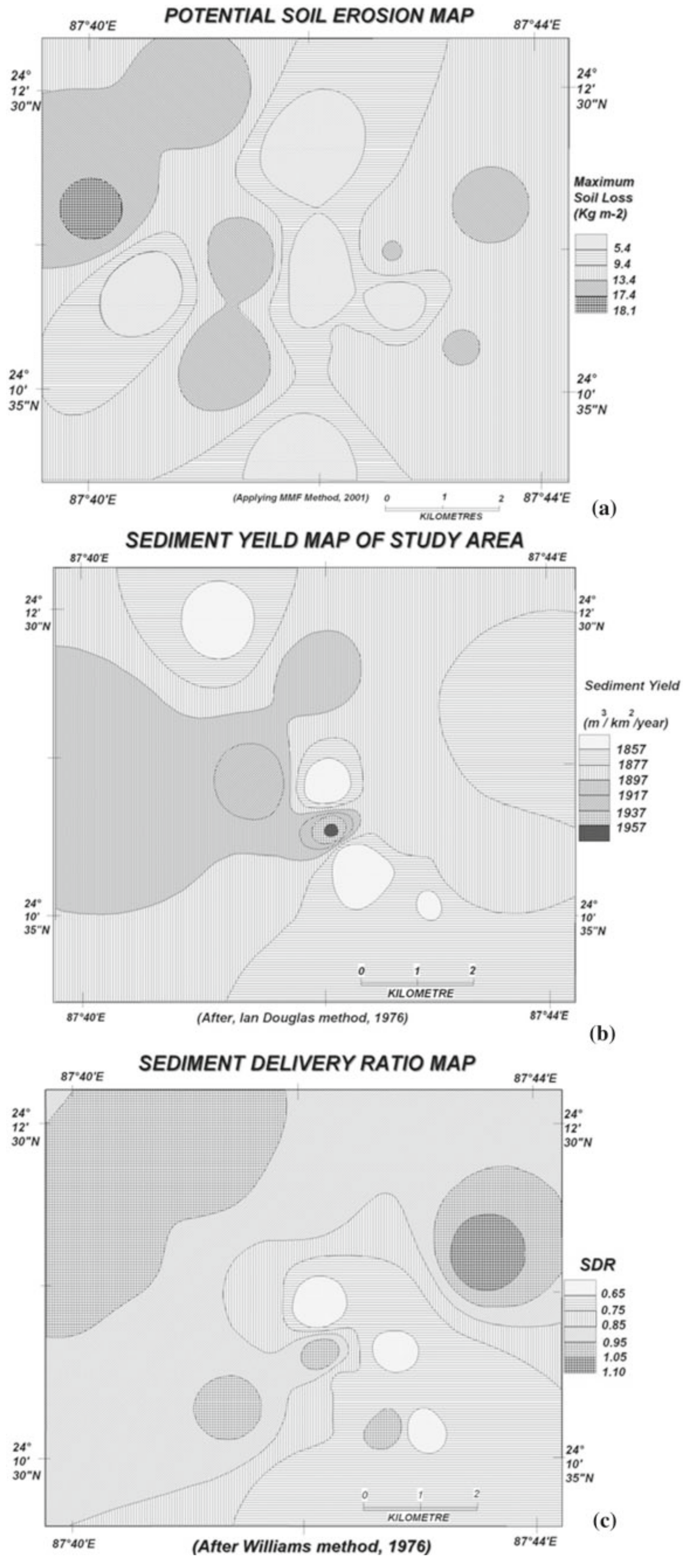

Figure 7. Maps showing (**a**) the total maximum potential soil loss (combination of rainsplash detachment and overland flow detachment) of the study area using Morgan's method (2001), (**b**) potential sediment yield of the study area and (**c**) sediment delivery ratio on the basis of catchments' individual values.

Table 3. *Extracting multiple linear regression of sediment yield (SY) of catchments.*

Multiple regressional equation	Unstandardized coefficients					
	a	b (Q_p)	c (GD)	d (SED)	e (H)	f (LR)
SY = a + bQ_p + cGD + dSED + eH + fLR	47.938	9.844	6.478	0.891	6.073	67.525

of catchments (m^3), q_p = peak run-off rate in monsoon of catchments (m^3 s^{-1}), K = soil erodibility factor of USLE, C = crop factor of USLE, P = conservation factor of USLE and LS = slope-length or topographic factor of USLE.

It has been found that monsoonal SY (after Williams and Berndt 1972) is significantly correlated (Pearson's product moment correlation, r) with the monsoonal peak discharge (Q_p, $r = 0.95$), gully density (GD, $r = 0.77$), soil erosion density (SED, $r = 0.36$), basin relief (H, $r = 0.41$) and leminscate ratio (LR, $r = -0.58$) of the sample catchments of this lateritic terrain. As a whole, the study area has mean SY of 191.93 ton/km^2, mean Q_p of 26.72 m^3/s, GD of 6/km^2, and SED of 31.58 km/km^2. From the analysis we have prepared a multiple regressional equation (table 3) $SY = -47.938 + 9.844Q_p + 6.478GD - 0.891SED - 6.073H + 67.525LR$. The multiple regression estimates that 2a, 2b, 2c, 3a, 3b, 3c, 3d and 3i catchments have high potentiality of sediment yield in the heavy monsoon period (June to September).

Sediment delivery ratio (SDR) is the ratio between sediment yield and gross erosion per unit area above a measuring point. SDR is expressed as a percent and represents the efficiency of the catchment in moving soil particles from the areas of erosion to the point where sediment yield is measured. According to Williams (1977), SDR (figure 9b) is estimated as follows (Wischmeier and Smith 1978; Morgan 2005):

$$SDR = 1.36610^{-11}\,(DA)^{-0.0998}\,(ZL)^{0.3629}\,(CN)^{5.444}$$

where DA = drainage area in km^2, ZL = relief-length ratio in metre km^{-1}, CN = curve number of run-off (Chow *et al.* 1988).

Table 4. *Extraction of three principal components of selected variables of catchments and their relative dominance.*

Variables	Source	PC1	PC2	PC3
Effective rainfall (mm)	Morgan (2005)	**0.87655**	0.27468	0.16832
Run-off coefficient	Chow (1964)	**0.94351**	0.219	0.01179
Overland flow (mm)	Kirkby (1976)	**0.94351**	0.219	0.01179
Subsurface flow (mm)	Kirkby (1976)	**−0.9335**	−0.2226	−0.147
Rainfall erosivity	Morgan (2005)	**0.74697**	−0.1466	0.02439
Actual to potential evapotranspiration (E_t/E_o)	Morgan (2005)	**−0.9597**	−0.2443	−0.0119
Effective hydrologic depth of soil in metre (EHD)	Morgan (1987)	**−0.9436**	−0.0752	−0.1432
Soil moisture (R_c)	Kirkby (1976)	**−0.9784**	−0.1774	−0.0713
Proportion of bare soil cover		**0.83233**	0.34317	0.02285
Crop factor	Morgan (2005)	**0.81808**	0.35882	0.05174
Ratio of soil detachment rate and transport capacity of flow (H/G)	Morgan (2005)	**−0.6891**	−0.1321	−0.2089
Surface run-off volume in m^3	Khosla (1949)	0.34096	**−0.7637**	0.42739
Monsoonal peak discharge m^3/s	Kirkby (1976)	0.34096	**−0.7637**	0.42739
Drainage density D_d	Horton (1945)	−0.4196	**0.61991**	0.4312
Length of overland flow L_g	Horton (1945)	0.47545	−0.2545	−0.3716
Constant of channel maintenance (C)	Schumm (1956)	0.56804	−0.501	−0.4429
Gully density/km^2 (GD)	Morgan (2005)	0.10729	**−0.7316**	**0.57561**
Soil erosion density/km^2 (SED)	Morgan (2005)	−0.1571	−0.3804	**0.71779**
Catchment relief in metre	Chorley (1969)	−0.0147	−0.2748	**0.74574**
Relief/length ratio	Chorley (1969)	−0.2682	**0.72738**	0.40221
Maximum valley-side slope θ_{max}	Melton (1958)	−0.2692	0.42018	**0.61325**
Mean ground slope of catchment S_g	Chorley (1969)	−0.2544	**0.64594**	0.30978
Leminscate ratio	Chorley *et al.* (1984)	−0.2493	**0.91359**	0.0622
Eigen value		9.848671	5.182548	3.049189
% of Variance		42.82031	22.53282	13.25734
Cumulative variance %		42.82031	65.35312	78.61047

From the sediment delivery ratio map (figure 7), we have found that the delivery of sediment is decreasing from north-west to south-east direction whereas western and central portions of the study area have generated maximum sediment yield. From the result it can be predicted that 2nd order catchments of 2a, 2b 2d and 3rd order catchments of 3a, 3b, 3c, 3d and 3i have generated high value of SDR (0.85–1.10) in respect of hydro-geomorphic parameters. So those areas of catchments should be protected from soil detachment and sediment transportation.

7. Factor analysis and categorization of erosion risk

In multivariate analysis of geomorphic phenomena, often volumes of data having many variables are analysed amidst the problem of multidimensionality. Multidimensionality is signified by a condition wherein groups of variables often move together and one reason for this is that more than one variable may be measuring the same driving principle governing the behaviour of the system (Singh 2007). According to Kothari (2009), the factor analysis is a multivariate technique to find out something more fundamental among interdependent variables or latent which creates the commonality.

Though rainfall detachment and detachment by overland flow are the main source of sediment yield of catchment, both of them are controlled by numerous climatic, hydro-geomorphic and pedologic variables of catchment (Shrestha 1997; Boardman *et al.* 2009). So to reduce the number of variables into few factors or components and to detect structure in the inter-relationships among variables we have employed principal component analysis (PCA) which is a method of factor analysis. The principal components (PC) as whole form an orthogonal basis for the space of the data (Gregory 1977; Singh 2007). Considering 20 variables of 17 sub-catchments (2nd and 3rd orders), we have extracted the principal components in such a fashion that first PC accounts for the largest amount of total variation in the data (table 4). The importance of each component is expressed by its eigen values. The higher the eigen value, the more important is the component because of the largest number of inter-correlated dominant parameters (Singh 2007; Kothari 2009). Transforming the first and second PC into prinsscores and then into Z-scores, we have standardized and categorized the sample catchments into susceptibility of fluvial erosion in relation to dominant hydro-geomorphic variables (Doornkamp and King 1971; Gregory 1977). Alongside, discriminate analysis is used to understand the association and separation of the catchments from each other based on Z-scores. The main purpose of discriminate analysis is to cluster the groups of catchments which are discriminated from other groups based on scores of erosion risk.

We have chosen 20 important variables which inter-relatedly contribute their negative and positive effects on the whole system of catchment denudation. Extracting three principal components

Table 5. *Transforming the 1st and 2nd principal components to individual catchments' prinsscores, Z-scores and their ranking of erosion risk.*

Gully-catchment	Prinsscore PC 1	Prinsscore PC 2	Total score	Rank (high to low erosion risk)	Z-score$_1$	Z-score$_2$
2a	2001.58	−735.44	2737.02	**3**	1.300	−0.855
2b	2002.14	−726.97	2729.11	**2**	1.302	−0.802
2c	1618.3	−536.61	2154.91	**6**	0.045	0.382
2d	1765.76	−546.14	2311.9	**4**	0.528	0.323
2e	1575.02	−574.7	2149.72	**9**	−0.097	0.145
2f	1223.03	−411.45	1634.48	**14**	−1.250	1.161
2g	1298.05	−435.62	1733.67	**13**	−1.004	1.010
2h	1440.71	−494.76	1935.47	**10**	−0.537	0.642
3a	2092.82	−782.95	2875.77	**1 (Highest)**	1.599	−1.150
3b	1926.2	−706.78	2632.98	**5**	1.053	−0.676
3c	1736.93	−962.3	2699.23	**15**	0.433	−2.267
3d	1737.8	−674.71	2412.51	**7**	0.436	−0.477
3e	1152.04	−430.91	1582.95	**17 (Lowest)**	−1.482	1.040
3f	1124.08	−371.32	1495.4	**16**	−1.574	1.411
3g	1347.05	−469.68	1816.73	**12**	−0.843	0.798
3h	1583.35	−575.24	2158.59	**8**	−0.069	0.142
3i	1651.8	−731.25	2383.05	**11**	0.154	−0.829

we have cumulatively explained 78.61% of total variance, having three eigen values 9.84, 5.18 and 3.04, respectively. The three principal components uniquely dominated the system are as follows:

- **PC 1:** Mainly climatic and hydrologic variables drive strongly the denudation system of catchments; effective rainfall, run-off coefficient, overland flow, rainfall erosivity, bare soil cover and crop factor positively influence the system; whereas sub-surface flow, E_t/E_o, EHD, R_c and H/G negatively influence the system.
- **PC 2:** Mainly geomorphic variables, *viz.*, leminscate ratio, catchment ground slope, relief/length ratio and gully density drive system; though run-off volume and monsoonal peak discharge have an effect in the motion of system.
- **PC 3:** Again geomorphic variables, *viz.*, gully density, SED, catchment relief and θ_{max} drive the denudation system positively.

Based on the summation of prinsscores of PC1 and PC2, we have ranked the gully-catchments (table 5) into high to low erosion risk which are positively correlated with potential sediment yield rate of the sample catchments (figure 8).

Based on the dendogram of catchments' prinsscores (similarity coefficients), we have obtained at least four clusters of catchments. Then from the discriminate analysis of Z-score$_1$ (Z_1) and Z-score$_2$ (Z_2) we have categorized the four groups of catchments (figures 9 and 10) on the basis of individual performance of hydro-geomorphic variables (table 5). So those groups have unique property of erosional system in this lateritic terrain and the priority of soil conservation should be given on this basis. Groups B and A have high risk of soil erosion than two other groups, so the catchments of Gr. A and Gr. B should get main concern

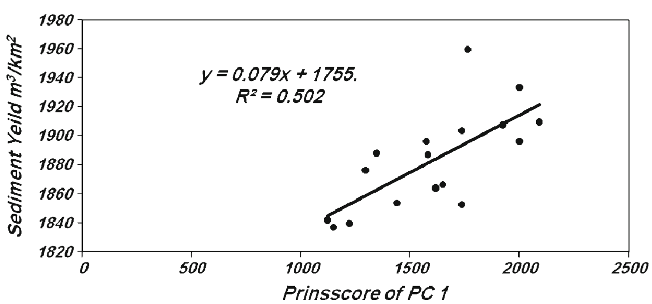

Figure 8. The postive linear trend line is established between catchment-wise prinsscore of PC1 (x) and potential sediment yield of catchments (y).

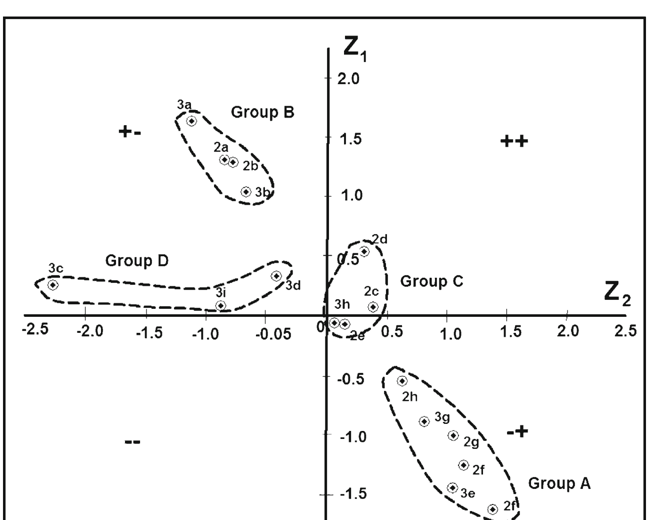

Figure 9. Discriminate analysis showing four clusters of catchments on the basis of Z scores.

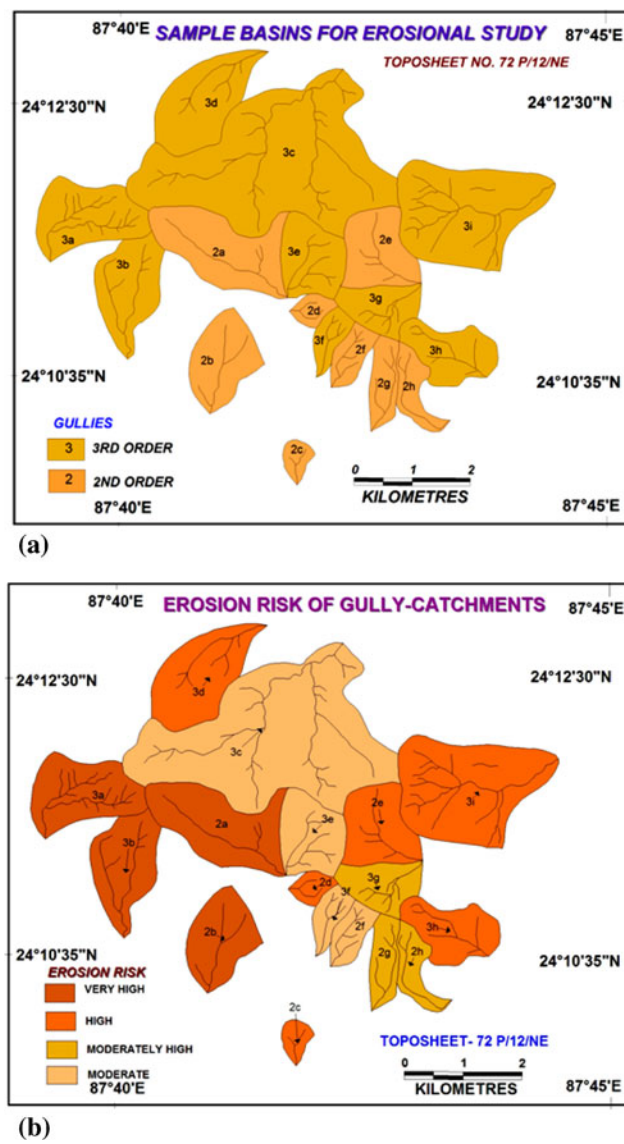

Figure 10. Maps representing (**a**) sample gully catchments of 2nd and 3rd orders and (**b**) categorization of gully-catchments into erosion risk.

Table 6. *Categorizing risk and priority of catchments on the basis of erosional properties.*

Group	Catchments	Mean overland flow (mm)	Mean potential erosion (kg/m^2)	Mean SDR	Mean SY (ton/km^2)	Mean gully density/km^2	Priority rank (risk)
A	2c, 2d, 2e, 3d, 3h, 3i	130.28	10.11	0.87	149.78	6.50	II (High)
B	2a, 2b, 3a, 3b	237.82	16.24	0.94	182.71	8.33	I (Very high)
C	2f, 3c, 3e, 3f	53.17	7.23	0.67	43.05	5.00	IV (Moderate)
D	2g, 2h, 3g	82.86	8.46	0.67	145.26	7.33	III (Moderately high)

for soil conservation and for minimization of dominant hydro-geomorphic variables (table 6). Therefore, each individual group is treated as unique conservational measures to minimize the effect of dominant variables and to maximize the resistance of soil.

8. Conclusion

The diagnostic survey and multivariate analysis of different aspects of gully erosion of sample basins, developed in the reddish brown coloured lateritic tract of western Rampurhat I Block, have revealed the exact controlling factors of soil loss and the spatial variation of erosion. The employed methods and techniques are very much fruitful here to extract significant information from the complex data. Considering the importance of rainfall erosivity, catchment overland flow and soil erodibility, we have obtained success to incorporate the other influencing factors or components which can enhance the soil erosion of the gully catchments differentially. Comparatively, the hydrologic variables are very much influenced by the denudational system than the geomorphic variables. Understanding and estimating the potential soil erosion, sediment yield and sediment delivery ratio, at last we have identified category of sample catchments into different magnitude of erosion risk. So the multivariate analysis has produced an erosional individuality of each catchment in this small spatial unit and it can be considered as an aid for the special conservational treatment of each erosion prone catchment.

In general due to infertility, shallowness and low water holding capacity of lateritic soil and cementation of ferruginous concretions of iron oxide colloids, there is limited supply of soil moisture and limited growth of trees except shrubs, open scrub and thin grasses. These factors transform the land as degraded barren waste and dissected badlands. The other important observable factors of long-term excessive soil loss are high rainfall erosivity of short period, deforestation (due to basalt quarrying), morum quarrying, livestock grazing, elevated metal roads and long stretch of concrete basement (Sijua Aerodrome). Though, with the recent implementation of 'Bhatina Watershed Management Program' the forest cover is increased by plantation but the grass cover and newly grown plants of lateritic uplands and gully floors should be protected from grazing activity to avoid further gully expansion.

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