

Identification of soil erosion vulnerable areas in Chandrabhaga river basin: a multi-criteria decision approach

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Abstract In this present paper on delineation of soil erosion prone areas in a plateau fringe sub basin river Chandrabhaga (length: 26 km and area: 119 sq km), a tributary of Mayurakshi river, drains over lateritic tract of western Birbhum district of West Bengal. Raster based weighted linear combination (WLC) method considering six soil erosion driving parameters have been done in Arc Gis and ERDAS environments. RUSLE is used to quantify the raster based qualitative spatial erosion vulnerable model produced through WLC. This model is also tallied with pegging operation based measurement of surface lowering rates in different soil erosion vulnerable areas for validating the same. Raster based spatial model reveals that out of total basin area, 19.87 % area is extremely prone to soil erosion with a rate of 21.78 Mg/ha/year and total of 51513.86 Mg/year as derived from RUSLE based estimation of soil loss. Estimated weighted average soil erosion rate of this present basin is 9.12 Mg/ha/year. Pegging operation based measurement of surface lowering rate as well as soil loss validates the spatial scaling of soil erosion. Surface lowering rate is 2.5 mm/year in the extremely vulnerable areas followed by and highly vulnerable areas (1.1 mm/year).

Keywords Soil erosion · Raster calculator · Weighted linear combination · RUSLE · Surface lowering

Introduction

Soil is functionally a non-renewable resource; while topsoil develops over centuries, the world's growing human population is actively depleting the resource over decades. As a non-renewable resource and the basis for 97 % of all food production (Pimentel 1993), strategies to prevent soil depletion are critical for sustainable development. Significant literature exists documenting the magnitude of the soil erosion problem. Between 30 and 50 % of the world's arable land is substantially impacted by soil loss (Pimentel 1993), which directly affects rural livelihoods (Lal 1985; Kerr 1997) in addition to indirectly affecting aquatic resources (Ochumba 1990; Eggermont and Verschuren 2003), lake/river sediment dynamics (Kelley and Nater 2000; Walling 2000), global carbon cycling (Duxbury 1995; Lal 2003), aquatic and terrestrial biodiversity (Harvey and Pimentel 1996; Alin et al. 2002) and ecosystem services (Tinker 1997; Pimentel and Kounang 1998). Severe soil degradation has been documented throughout sub-Saharan Africa (Lal 1985; Pimentel 1993; Oostwoud and Bryan 2001; Lufafa et al. 2002), resulting in declining functional capacity (Zobisch et al. 1995; Gachene et al. 1997), ultimately affecting poverty and food security (Sanchez et al. 1997).

It is estimated that about 80 % of the current degradation on agricultural land in the world is caused by soil erosion due to water (Angima et al. 2003). Soil erosion is a major problem throughout the world. Globally, 1964.4 M ha of land is affected by human-induced degradation (UNEP 1997). Of this, 1903 M ha are subjected to aggravated soil erosion by water and another 548.3 M ha by wind. Average soil erosion rate in Asia is 16.6 Mg/ha/year and Asia ranks second in soil loss rate followed by South America (22.1 Mg/ha/year) (Walling and Webb

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1983). One estimate puts the loss of top soil by water action at 1200 m tones every year in India which costs Rs 12,000 crores annually (Vohra 1985). In the present century about 70 % of the total people of the world depend on agriculture. Therefore, this issue of soil loss is one of the burning topics of discussion. In India population pressure is very high (16 % of the world's population) and about 80 % of the population relies on agriculture tilling land as many time as possible and therefore, soil erosion from agricultural land is maximum. This soil loss impacted on agricultural production in very significant scale. It is estimated that India suffers an annual loss of 13.4 million tones in the production of major cereal, oilseed and pulse crops due to water erosion equivalent to about \$ 2.51 billion (Sharda et al. 2010). As per harmonized data base on land degradation, 120.72 million ha area is affected by various forms of land degradation in India with water erosion being the chief contributor (68.4 %) (Maji 2007). The National Bureau of Soil Survey and Land Use Planning (Sehgal and Abrol 1994) data show that nearly 3.7 million ha suffer from nutrient loss and/or depletion of organic matter.

Considering the importance of protecting and restoring the soil resource, it is increasingly been recognized by the world community (Lal 1998; Barford et al. 2001; Lal 2001). Sustainable management of soil received strong support at the Rio summit in 1992 and its Agenda 21 (UNCED 1992), UN Framework Convention on Climate Change (UNFCCC 1992) and Articles 3.3 and 3.4 of the Kyoto Protocol (UNFCCC 1997), the 1994 UN Framework Convention to Combat Desertification (UNFCD 1996). This attempt is not confined within summits and pacts, many a scholars have produced a good number of articles of decision value in this field addressing estimation of soil erosion by Walling and Webb (1983), Lal (2003), Lin et al. (2002), Amore et al. (2004), Lanuzaa and Paningbatan (2010) and Prasannakumar et al. (2012) vulnerability and risk of soil erosion by Milevski (2008), Boardman et al. (2009) and Sharda et al. (2013), application of geospatial techniques for estimating soil erosion Baigorria and Romero (2007), developing soil erosion based models and factor calibration for modeling by Williams et al. (1984), Flanagan and Nearing (1995), Santhi et al. (2001), Foster et al. (2003), Turpin et al. (2005), Santhi et al. (2006), Pandey et al. (2009) etc. Present river basin is majorly composed with fragile laterite soil and old lateritic alluvium. At the same time this basin is agriculturally dominated (cropping intensity is 172 %). So, addressing soil erosion issues is indispensable. In this present paper, attempt has been taken to identify soil erosion potential areas of river Chandrabhaga, a sub tributary of Mayurakshi river. Quantification of soil erosion volume and measurement of surface lowering rates etc. in different soil erosion vulnerable zones have been for validating this model.

Study sites

Chandraghaga river (length: 26 km) basin, covering an area 119 sq km, is a sub basin of Mayurakshi river system located mainly over the western plateau fringe (Chottanagpur) blocks (administrative unit) of Birbhum district namely Rajnagar, Dubrajpur and Suri. Entire basin area comes under *rarh* tract (Bagchi and Mukerjee 1983) with secondary laterite formation (Chakrabarty 1970) mainly carried by some of the rivers coming from Chottanagpur plateau (Jha 1997, Jha and Kapat 2003, 2009). Elevation of this basin ranges from 150 (at the source region) to 24 m (at confluence). Average slope, measured as per Wentworth's method (1930), is 2–3 % whereas it is <1 % in the confluence segment. Geologically 60 % of the basin area in the upper catchment is composed with granitic gneissic rock of Pleistocene age overlain by weathered coarse grain lateritic regolith and soil and 30 % of area at the lower catchment is made with newer alluvium of Holocene period (Fig. 1) (GSI 1985) (Fig. 2).

The thickness of alluvium increases toward eastern part of the basin and it ranges from 12 to 20 m and groundwater yield potentialities of aquifers from also increases eastward with a rate about 5–15 m³/h (Ray and Shekhar 2009). No such significant lineaments are existing there. The water table is moderately deep (5–10 m) with moderately high seasonal fluctuation (Mukherjee et al. 2007). Few locally confined aquifer structure are found in this basin.

Parts of the confluence area is clad with sick immature *sal* (shorearobusta) dominated forest. Two to three decades ago, parts of the upper catchment were also captured by same type of forest but it is already deforested. Most part of the basin area is dominated by agricultural land with poor qualities of soil fertility and soil moisture (during pre monsoon 8–11 %). Average annual rainfall of this basin as gauged by Suri meteorological station is 1444.432 mm. High degree of seasonality of rainfall is reflected by 82 % rainfall during the months of June to September. Rainfall analysis since 1980–2013 focused that there is no significant trend of rainfall as also indicated by linear regression model ($y = 2.137x + 5704$) and coefficient of determination ($R^2 = 0.005$). This trend is identical with the general trend of rainfall in India as estimated by many a scholars viz. Jagannathan and Parthasarathy (1973), Chaudhary and Abhyankar (1979), Kumar et al. (2005) and Dash et al. (2007) etc. reported that in all India scale there is no significant change of rainfall in last 110 years excepts few regional pockets (Sinha Ray and De 2003). Average potential evaporation of this area since 1901–2014 is 73.45 mm/year (IMD 2015).

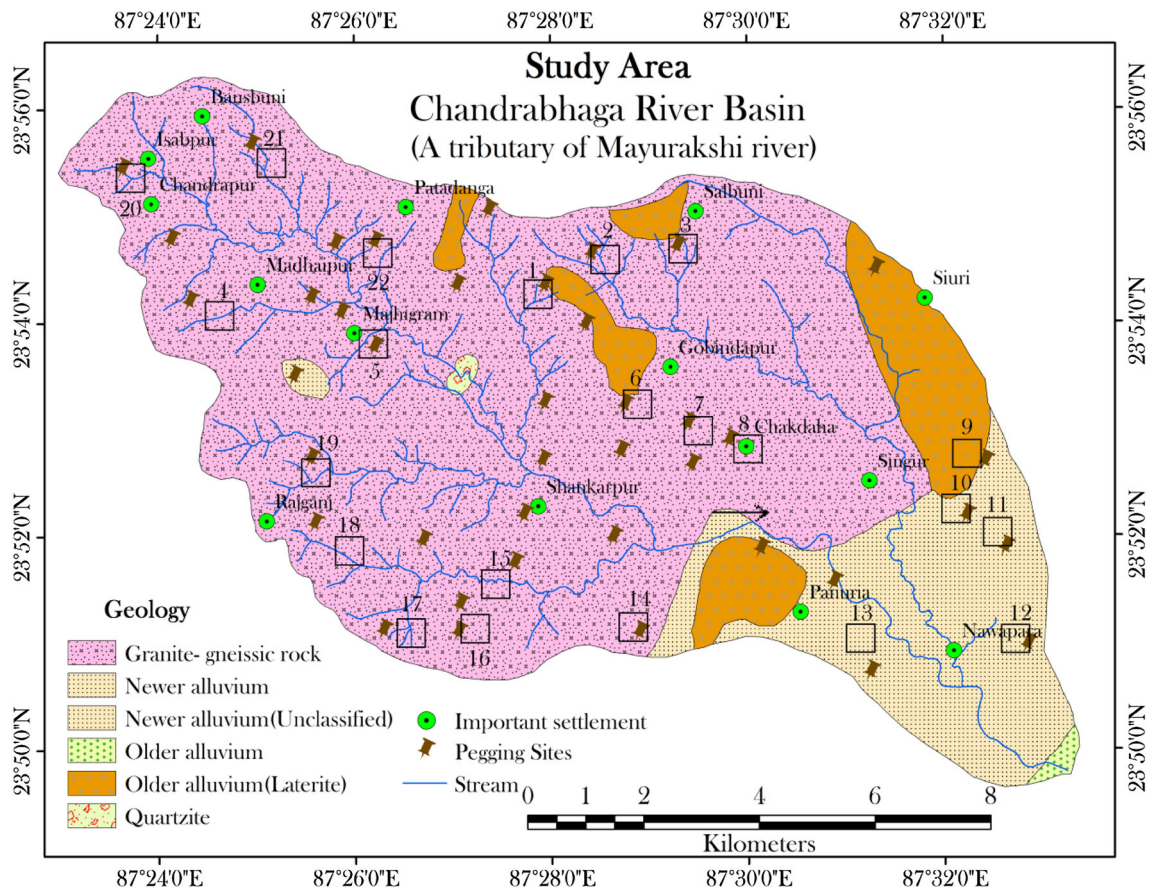


Fig. 1 Drainage network and basin over geological setting of the study area; square box indicates sites used for RUSLE; this layer created after generating spatial vulnerable soil loss model and same is then imposed on study area map

Materials and methods

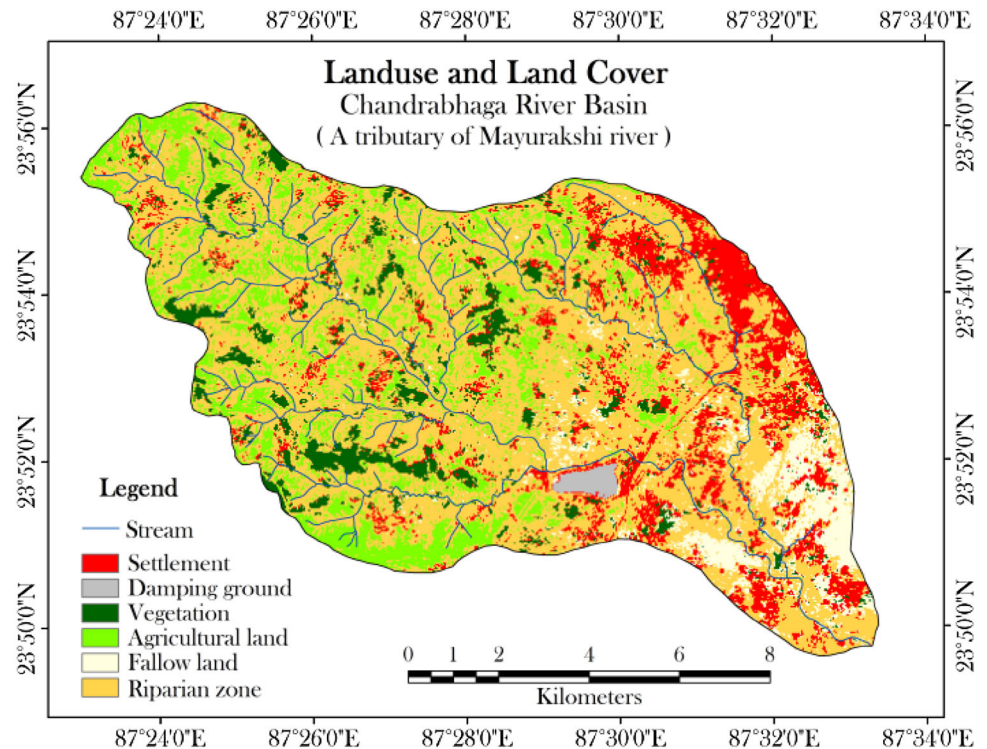
Raster based estimation of soil vulnerability analysis

In the first step, all data were registered into Universal Transverse Mercator projection northern zone 45 datum WGS 84. The base map of the study area was prepared from Survey of India (SOI) topographical maps (sheet no. 73 M/5 and 73 M/9) on 1:50,000 scale. The drainage network or stream link map for the study area were prepared from manual digitized of scanned SOI toposheets that has been used as stream link layer and stream junction prepared thereafter. The rainfall distribution map was prepared form District Planning Map, NATMO. The soil texture map was collected from the National Bureau of Soil Survey and Land Use Planning (NBSS and LUP) Regional Centre, Kolkata, India. The texture groups of soil have been integrated into GIS environment into percentage value of sand. The Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM v3, 1-arc sec) was used to create the relief zone and flow accumulation maps using spatial analyst tool in ArcGIS. The Land Use Land Cover (LULC) was prepared from

Landsat OLI image collected from US Geological Survey (USGS) Global Visualization Viewer (Path/row: 139/43). Supervised classification was done using the maximum likelihood classifier algorithm of ERDAS Imagine (v. 9.1) for LULC classification. High resolution QuickBird images available in GoogleEarth for 18th April, 2013 and 17th February, 2014 combined with field based ground control points were utilized for both training area selection and for the evaluation of map accuracy. The overall accuracy of Landsat derived LULC map is 87.6 % with corresponding Kappa statistics of 0.84. The LULC of the Chandraghaga basin is classified in six land use classes: settlement, damping ground, vegetation, agriculture, fallow land, riparian zone.

Any model for computing potential soil loss in an area must deals with a large number of variables, i.e. parameters concerning vegetation, crop management, soil, relief, slope and climate. When available spatial data are geo-referenced and can be put in the form of maps, Geographic Information Systems (GIS) allow simpler and faster data and parameter management. Therefore, GIS can make soil erosion studies easier, especially when repeated applications of similar and complex procedures are required.

Fig. 2 Landsat image based land use land cover (LULC) of Chandrabhaga river basin



For estimating soil loss, several methods and models have produced by troops of scholars. The development of Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978), Modified Universal Soil Loss Equation (MUSLE) (Williams 1975), a revised version of the empirical-based USLE the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1991, 1997), RUSLE 1.06 (Toy and Foster 1998), RUSLE1.06c (US Department of agriculture, Agricultural Research Service and National Sediment Laboratory 2003), RUSLE2 (USDA-NRCS 2008), Water Erosion Prediction Project (WEPP) (Flanagan and Nearing 1995) etc. are some land mark methods for detecting soil loss prone areas or estimation of soil loss. Another approach follows multicriteria evaluation of potential soil erosion risk zones.

For nearly two decades, a number of multi-attribute (or multi-criteria) evaluation methods have been implemented in the GIS environment for land suitability evaluation, including WLC and its variants (Carver 1991; Eastman 1997) and the analytic hierarchy process (Banai 1993). There are two fundamental classes of multi-criteria evaluation methods in GIS: the Boolean overlay operations (non-compensatory combination rules) and the weighted linear combination (WLC) method (compensatory combination rules). They have been the most often used approaches for different sorts of land-use suitability analysis (Heywood et al. 1995; Jankowski 1995; Barredo et al. 2000; Beedasy and Whyatt 1999; Malczewski 2004). These

approaches can be generalized within the framework of the ordered weighted averaging (OWA) (Asproth et al. 1999; Jiang and Eastman 2000; Makropoulos and Butler. 2005; Malczewski et al. 2003; Malczewski and Rinner 2005).

The WLC is a simple additive weighting based on the concept of a weighted average (Eastman 2006). The decision maker directly assigns weights of “relative importance” to each attribute map layer. A total score is then obtained for each alternative by multiplying the importance weight assigned for each attribute by the scaled value given to the alternative on that attribute, and summing the products over all attributes. OWA is a family of multicriteria combination procedures (Yager 1988). It involves two sets of weights: the weights of relative criterion importance and the order (or OWA) weights. Although OWA is a relatively new concept (Yager 1988), there have been several applications of this approach in the GIS environment (Asproth et al. 1999; Jiang and Eastman 2000; Mendes and Motizuki 2001; Araujo and Macedo 2002; Malczewski et al. 2003; Rashed and Weeks 2003; Calijuri et al. 2004; Makropoulos and Butler 2005; Rinner and Malczewski 2002). All those applications use the conventional (quantitative) OWA. Specifically, research into GIS, OWA has so far focused on the procedures that require quantitative specification of the parameters associated with the OWA operators.

In the present study six parameters with proper database have been selected as map layers viz. (1) slope, (2) soil

Table 1 Modes of ranking of the intra sub class of parameters and distribution of priority based weightage

Name of the attribute (j)	Highest rank indicates at 10 point scale	Logic behind	Attribute weightage (w_j) ($\sum w_j = 1$)
(1) Slope	10 rank at the highest relief class	Elevated areas usually posses greater erosion potentiality	0.2
(2) Soil texture	10 rank at highest texture class	Coarse texture indicates more propensity of soil erosion	0.25
(3) NDVI	10 rank at bare area	More canopy cover area protect soil erosion	0.2
(7) Drainage frequency	10 rank at high drainage frequency	Frequent drainage found over relatively elevated and sloppy area	0.15
(8) Rainfall	10 rank at highest rainfall zone	More rainfall strikes more erosion	0.10
(6) Proximity to stream link	10 rank near to stream	Streams command area possesses more chance of erosion as erosion vectors present there over	0.10

texture, (3) NDVI, (4) drainage frequency, (5) rainfall, (6) proximity to stream link. Among these layers initially proximity to stream link layer was in vector form. As this process executes on the basis of raster based weighted linear combination, these vector layers have been converted into raster maps using either distance mapping techniques (e.g. proximity to stream link) using spatial analyst tool in ArcGIS software or grid based raster surface like DEM (e.g. rainfall layer, drainage frequency layer, soil texture layer) in ERDAS Imagine Software. Each attribute (map layer) is categorized into ten equal classes and ranking 1–10 (adopting 10 point scale) considering the fact that greater rank will reflect greater soil erosion vulnerable zones. To fulfill this purpose, all these attributes have been reclassified into 10 classes and ranked accordingly. The logic behind ranking to intra attribute classes from 1 to 10 is described in Table 2. Weightage of each attribute has been defined subjectively (see Table 2) considering the role of those in the study area. Rank of all sub classes under each attribute is then multiplied by the defined weight of each individual attribute. This function can be presented using the following formula.

$$WLC = \sum_{j=1}^n a_{ij}w_j$$

Where, a_{ij} = ith rank of jth attribute; w_j = weightage of jth attribute.

This weighted linear combination has been done using raster calculator tool in Arc GIS environment (Table 1).

Logic behind weight distribution

For weight distribution of the selected parameters, knowledge based method of weighting following Islam and Sado (2002), Sanyal and Lu (2006), Drobne and Lisec (2009) and Mondol and Pal (2015) have been done. Total considered weight in this work is supposed to 1.

Slope drives soil erosion in positive direction and plays one of the most dominant role therefore 0.2 weight has been assigned.

Soil texture inherently determines erodibility and cohesiveness of soil. Coarse texture soil is highly fragile and in this river basin coarse textured laterite soil inspires to provide weightage of 0.25.

Drainage frequency or density is one of the dominant parameters which act as major erosion vector. Frequent drainage fuels more erosion and therefore, 0.15 weights has been given.

NDVI represents canopy area which protects soil in different ways. In general, as the protective canopy of land cover increases, soil erosion decreases (Elwell and Stocking 1976). It protects soil from direct rainfall and tightly binds soil particles. Considering its multidimensional importance much weight (0.2) is being provided.

As most of the rainfall (82 %) happens during monsoon months (June to September), rainfall intensity factor influences to provide 0.1 weight. But overall spatial variation is very low over the basin and hence, relatively less weight has been assigned.

Association of streams can positively influence soil erosion and has been assigned 0.10 weight. As it is a pedimental river basin and drained by mostly 1st and 2nd order streams so variation in this regard is meager.

Soil loss estimation framework

Along with raster based weighted linear combination method, Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1991, 1997) based soil loss has been:

$$A = R \times K \times LS \times C \times P$$

A = Soil loss

L = Slope length factor (m)

S = Slope gradient factor (%)

C = Cropping/land use management

P = Soil erosion control practice factor

LS = Length gradient factor

R is the rainfall and runoff factor by geographic location, is calculated using the following equation:

$$R = 38.5 + 0.35 \times Pr$$

Where, Pr is average annual precipitation of the study area K and LS values of the respective areas have been calculated following Robert (2000).

To quantify soil loss rate over different erosion prone areas of spatial soil loss vulnerable areas as being produced through WCL method, 22 sample sites (0.25 km × 0.25 km area each) 7 from extremely vulnerable area and 5 each from other three vulnerable areas (see Fig. 1) have been selected and these sites are distributed over the basin considering factors of dominance. Actually, these sites have been selected from spatial soil erosion vulnerability model as a separate data layer and overlaid on the map of study area to avoid another similar kind of map inserting sample sites. For estimating A value R, K, LS, C and P values for each site has been calculated as per defined method.

Measuring framework for surface lowering

Dataset for actual surface lowering rate has been taken from Ghosh (2015) and Ghosh et al. (2015) for validating soil spatial soil erosion vulnerable model. Pegging operation, since 2011–2014, on 40 sites (see Fig. 1) has been done by those scholars for calculating surface lowering rate.

Results and discussion

Individual status of the selected parameters

Before integrating all six data layers, spatial status of individual parameter can be quantized. Specifically, in each data layers percentage of area may come under potent erosion vulnerable may help to understand the nature of control on each parameter on final integrated map layer. In slope dataset, average slope variation is very negligible, but 3.14 % area with relatively greater slope (2.58–4.38 %) in the upper catchment and proximate areas of the water divide; in soil texture dataset proportion of sand greater than 60 % covers greater than 37.61 % of the basin and they are mainly concentrated adjacent to the water divide areas and gully heads areas of the basin (Fig. 3); 32.76 %

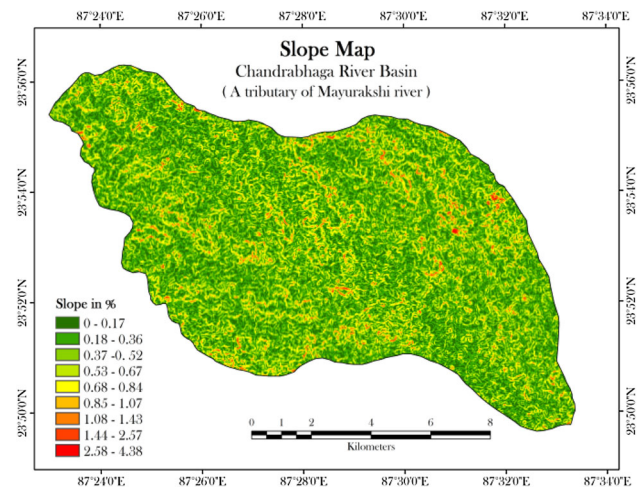


Fig. 3 Slope map shown in percentage

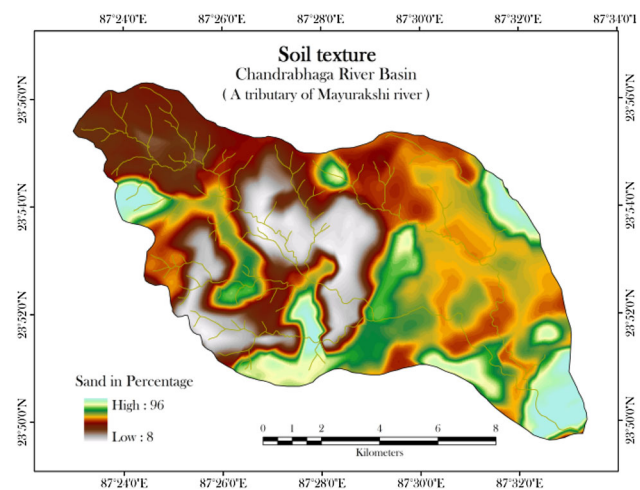


Fig. 4 Soil texture (proportion of sand)

of the basin area mainly in the upper catchment is characterized by high drainage frequency (4–8 streams/sq km) (Fig. 5); in rainfall dataset, 27.5 % area receives rainfall greater than 1400 mm annually mainly in the upper catchment (Fig. 6); in stream link proximity dataset 39.68 % area covers very proximate stream links association (Fig. 7); in NDVI dataset, 63 % area is bare and concentrated majorly within middle and lower catchment. Land use land cover (LULC) of 1985 shows that more percentage of area was covered with mainly sal forest. From all these datasets it is evident that all the potential area in each individual dataset is not concentrated in same spatial unit i.e. there is inter parameter spatial multi-directionality. Therefore, for generating final conclusion, integration of datasets is required (Figs. 2, 4, 8, 9).

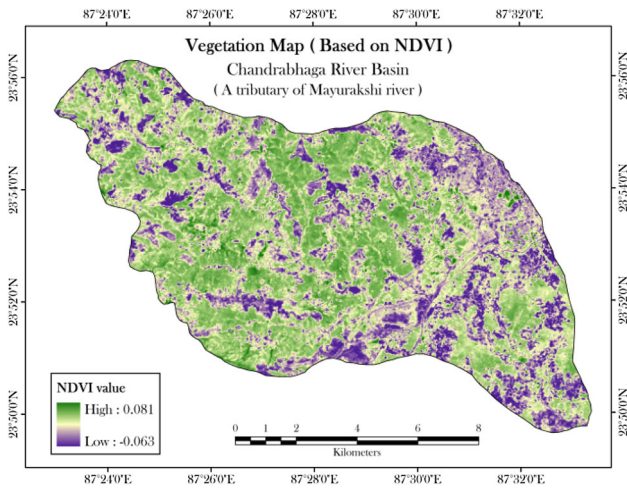


Fig. 5 Normalized differential vegetation index

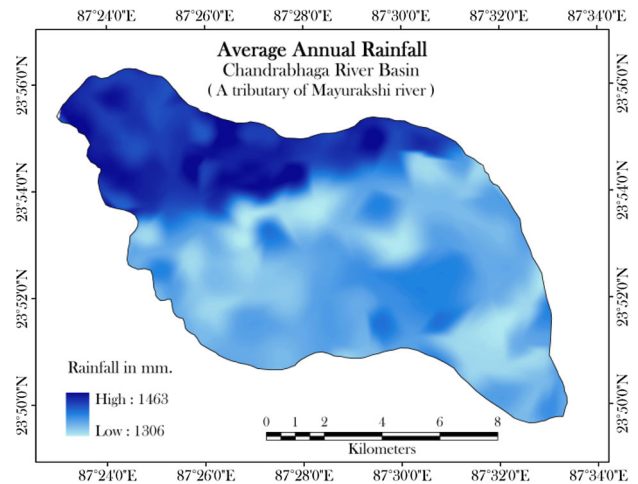


Fig. 7 Average annual rainfall

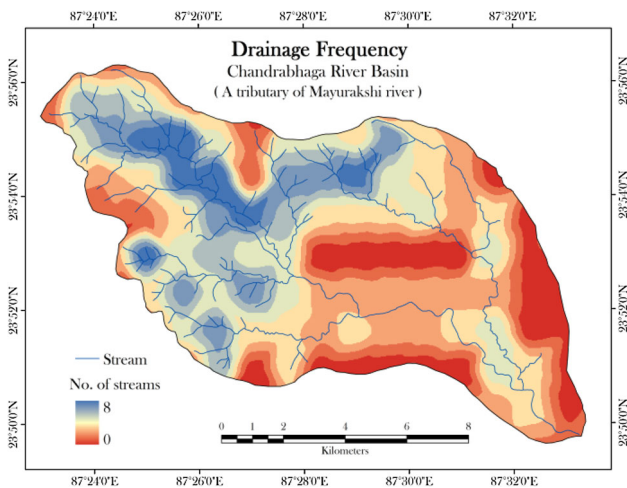


Fig. 6 Drainage frequency

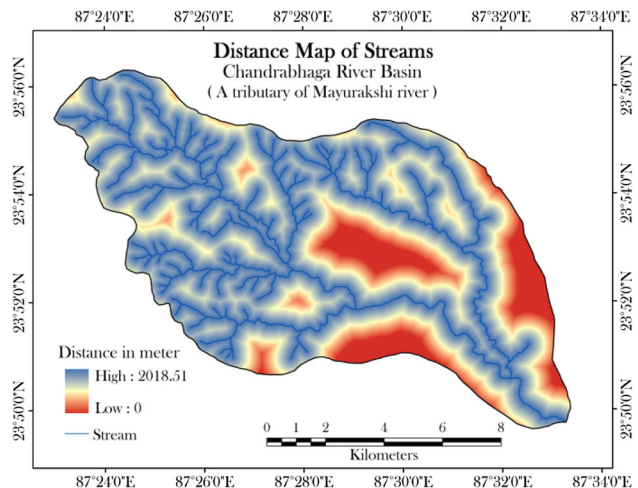


Fig. 8 Stream link proximity map

Weighted compositing of the raster datasets for delineation of potential soil erosion vulnerable areas

The vulnerability map (Fig. 10) shows the relative ranking of the erosion potential sites, generated by weighted linear combination mapping, according to the importance of concerned criteria. The vulnerability scores indicate soil erosion susceptibility. High vulnerability scores indicate that the site is highly susceptible for soil loss. According to the overall suitability score (Fig. 10) 19.87 % of the total basin area is very extremely vulnerable (score 5.66–8.0), 30.07 % is highly vulnerable (score 4.70–5.65), 23.21 % is moderately vulnerable (score 3.76–4.69), and 26.83 % is less vulnerable for potential soil erosion (see Table 2). Extremely vulnerable areas are concentrated mainly in upper and middle catchments of the basin. Sparse

vegetation, frequent gully association, coarse sand texture i.e. more proportionality of sand, association of streams explain more erosion propensity in this area. Most of the extremely erosive areas are located within granitic gneissic area with coarse lateritic fragile soil. Over the time, squeezing vegetation area (21 % loss since 1979–2014), decaying vegetation quality (lowering of NDVI value), uprooting trees etc. have highly inflated soil erosion. Lateritic soil is naturally fragile because of its inherent constraints of acidity, nutrient loss, chemical impairment, crusting, water erosion and poor water holding capacity as these are highly weathered and leached soil and enriched with oxides of iron and aluminum in tropics (Jha and Kapat 2003, 2009) and therefore the region with deep lateritic content instigates more erosion. Chemical analysis of laterite samples of this area indicates that Fe_2O_3 varies antipathetically with Al_2O_3 and the ratio of Fe_2O_3 and

Fig. 9 Raster calculator with selected parameters and their respective weightage

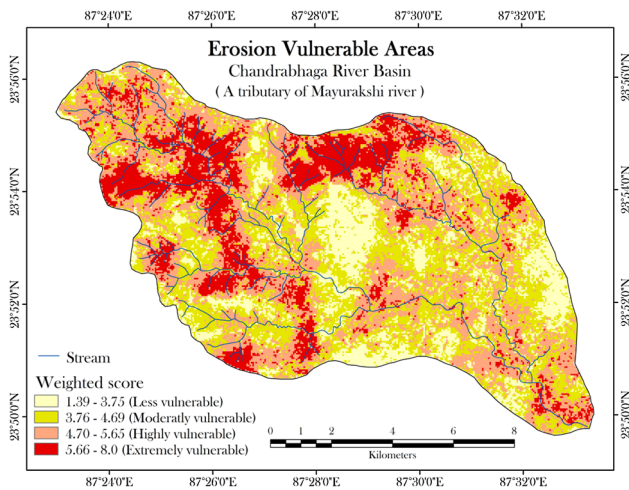
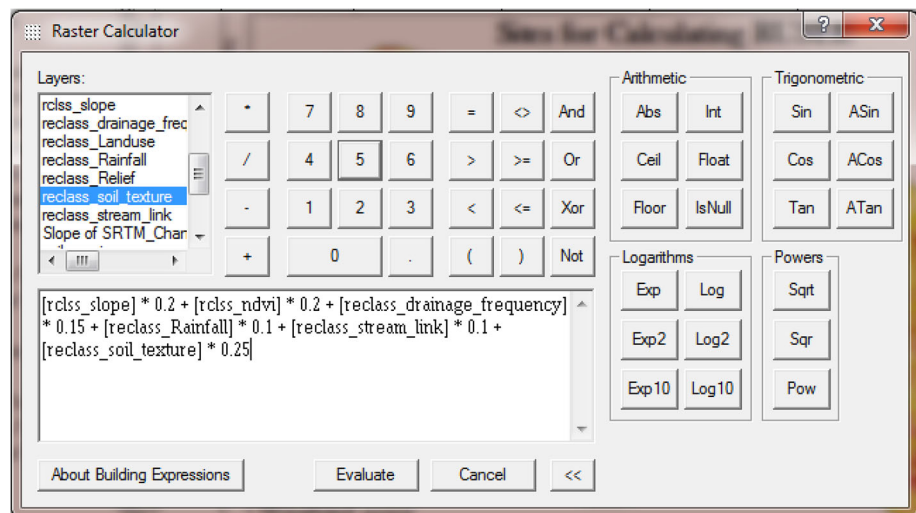


Fig. 10 Potential soil erosion vulnerable areas

Al₂O₃ is 1:0.2–1:2.01. Ti₂O₃ has a slight good and direct relationship with Fe₂O₃. The presence of anatase probably accounts for appreciable amount of TiO₃ (1.5–5.0 %) in this laterite. Such chemical composition with least biomass availability in soil is in fact highly erosive. High seasonal

variability of rainfall (Coefficient of variation = 98.04 %) encourage strong wetting and drying of soil and it often causes vulnerability of soil loss. Apart from all these, strong riling and gulling is another major vector of strong rate vulnerability of soil loss specifically in upper part of the rill and gully heads and in fat, these areas contribute more soil erosion (Kar and Bandopadhyay 1974; Bandopadhyay 1987; Jha and Kapat 2009).

Estimated soil loss

RUSLE based estimation of soil loss in different potential soil loss areas (indicated in Fig. 1) is described in Table 2. In extremely vulnerable soil loss areas, estimated soil loss is 21.78 Mg/ha/year followed by 9.45 Mg/ha/year in the highly vulnerable areas. Very minimum rate of soil erosion (2.25 Mg/ha/year) is found in 26.83 % basin area. This fact proves that overall grading as made using WLC method in Fig. 10 is down to earth. Average (spatial) estimated soil erosion is 9.12 Mg/ha/year. Total estimated annual soil loss as per this equation is 105525.9 Mg/year out of this 54.48 % lost amount is contributed by the extremely vulnerable areas (Table 2). Although this highly soil erosive

Table 2 Area under different surface water suitability zones

Suitability status	Weighted composite score	Areal extent (sq km)	% to total area	A (Mg/ha/year)	Total soil loss (Mg/year)	% to total loss	Mean surfaces lowering rate (mm/year)
Extremely vulnerable	5.66–8.0	23.65	19.8739496	21.78176	51,513.86	48.81632	2.5
Highly vulnerable	4.70–5.65	35.79	30.0756303	9.45	26,110.35	24.74307	1.1
Moderately vulnerable	3.76–4.69	27.63	23.2184874	5.78592	20,707.81	19.62343	0.6
Less vulnerable	1.39–3.75	31.93	26.8319328	2.25302	7193.893	6.817181	0.4
		119	100	Mean = 9.12	105,525.9		Mean = 1.125

100*100 sq m = 1 hectare (ha); Mg (megagrams) technically means tons

areas are imposed over granitic and gneissic surface, but pedimental regolith contributes such friable soil for erosion.

Actual soil loss

Results of actual soil loss in different vulnerable areas indicate accordant characters with spatial vulnerability of soil loss model. Surface lowering rate is maximum (2.5 mm/year) in the extremely vulnerable soil erosion areas and very low rate of surface lowering is noticed in less (0.4 mm/year) vulnerable areas (vide Table 2). These information obviously validate both spatial model and RUSLE based estimation of soil loss.

In fine, it can be said that such spatial vulnerability of soil loss model can provide decision support regarding where soil protection plan should be implemented in priority basis. Adoption of suitable measures in the erosion hotspot areas is essential to protect rampant nutrient rich top soil loss in such agriculturally dominated areas.

References

- Alin SR, O'Reily CM, Cohen AS, Dettman DL, Palacios-Fest MR, McKee BA (2002) Effects of land-use change on aquatic biodiversity: a view from the paleorecord at Lake Tanganyika, East Africa. *Geology* 30:1143–1146
- Amore E et al (2004) Scale effect in USLE and WEPP application for soil erosion computation from three Sicilian basins. *J Hydrol* 293:100–114
- Angima SD, Stott DE, O'Neill MK, Ong CK, Weesies GA (2003) Soil erosion prediction using RUSLE for central Kenya highland conditions. *Agric Ecosyst Environ* 97:295–308
- Araujo CC, Macedo AB (2002) Multicriteria geologic data analysis for mineral favorability mapping: application to a metal sulphide mineralized area, Ribeira valley metallogenic province Brazil. *Nat Resour Res* 11:29–43
- Asproth V, Holmberg SC, Håkansson A (1999) Decision support for spatial planning and management of human settlements. In: Lasker GE (Ed) *International institute for advanced studies in systems research and cybernetics. Advances in Support Systems Research*, vol 5. Windsor, pp 30–39
- Bagchi K, Mukerjee KN (1983) Diagnostic survey of West Bengal(s), Department of Geography, Calcutta University, Pantg Delta & Rarh Bengal; pp 17–19, 42–58
- Baigorria GA, Romero CC (2007) Assessment of erosion hotspots in a watershed: integrating the WEPP model and GIS in a case study in the Peruvian Andes. *Environ Model Softw* 22:1175–1183
- Banai R (1993) Fuzziness in geographic information systems: contributions from the analytic hierarchy process. *Int J Geogr Inform Syst* 7(4):315–329
- Bandopadhyay S (1987) Man initiated Gullies and slope formation in a lateritic terrain at Santiniketan, West Bengal. *Geogr Rev India* 49(4):22–23
- Barford CC, Wofsy SC, Goulden ML, Munger JW, Pyle EH, Urbanski SP et al (2001) Factors controlling long- and short-term sequestration of atmospheric CO₂ in a mid-latitude forest. *Science* 294:688–1691
- Barredo JJ, Benavidesz A, Hervhl J, van Westen CJ (2000) Comparing heuristic landslide hazard assessment techniques using GIS in the Tirajana basin, Gran Canaria Island, Spain. *Int J Appl Earth Obs Geoinform* 2(1):9–23
- Beedasy J, Whyatt D (1999) Diverting the tourists: a spatial decision support system for tourism planning on a developing island. *J Appl Earth Obs Geoinform* 3/4:163–174
- Boardman J, Shephard ML, Walker E, Foster ID (2009) Soil erosion and risk assessment for on- and off-farm impacts: a test case using the Midhurst area, West Sussex, UK. *J Environ Manag* 30:1–11
- Calijuri ML, Marques ET, Lorentz JF, Azevedo RF, Carvalho CAB (2004) Multi-criteria analysis for the identification of waste disposal areas. *Geotech Geol Eng* 22(2):299–312
- Carver SJ (1991) Integrating multi-criteria evaluation with geographical information systems. *Int J Geogr Inform Syst* 5(3):321–339
- Chakrabarty SC (1970) Some consideration on the evolution of physiography of Bengal. In: Chattopadhyay B (ed) *West Bengal, Geography Institute. Presidency College, Calcutta*, p 20
- Chaudhary A, Abhyankar VP (1979) Does precipitation pattern foretell Gujarat climate becoming arid. *Mausam* 30:85–90
- Dash SK, Jenamani RK, Kalsi SR, Kalsi SK (2007) Some evidence of climate change in twentieth-century India. *Clim Chang* 85(3–4):299–321
- Drobne S, Lisek A (2009) Multi-attribute decision analysis in GIS: weighted linear combination and ordered weighted averaging. *Informatica* 33(4):459
- Duxbury JM (1995) The significance of greenhouse gas emissions from soils tropical agroecosystems. In: Lal R, Kimble J, Levine E, Stewart BA (eds) *Soil management and greenhouse effect*. CRC Press, Boca Raton, pp 279–292
- Eastman JR (1997) *Idrisi for Windows, Version 20: tutorial exercises, graduate school of geography. Clark University, Worcester*
- Eastman JR (2006) *Idrisi andes: tutorial, clark labs. Clark University, Worcester*
- Eggermont H, Verschuren D (2003) Impact of soil erosion in disturbed tributary drainages on the benthic invertebrate fauna of Laka Tanganyika, East Africa. *Biol Conserv* 113:99–109
- Elwell HA, Stocking MA (1976) Vegetal cover to estimate soil erosion hazard in Rhodesia. *Geoderma* 15:61–70
- Flanagan DC, Nearing MA (1995) *USDA-water erosion prediction project: hillslope profile and watershed model documentation*. NSERL Report no. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette
- Foster GR, Toy TE, Renard KG (2003) Comparison of the USLE, RUSLE1.06c and RUSLE2 for application to highly disturbed lands. In: 2003 Proceedings of first interagency conference on research in the watersheds, Benson, pp 154–160. <http://www.tucson.ars.ag.gov/icrw/proceedings/foster.pdf>
- Gachene CK, Jarvis KNJ, Linner H, Mbuvi JP (1997) Soil erosion effects on soil properties in a highland area of Central Kenya. *Soil Sci Soc Am J* 61:559–564
- Ghosh K (2015) *Hydro-geomorphic appraisal of Bakreswar river basin, Ph.D. thesis submitted in Visva-Bharati University, pp 156–167*
- Ghosh K, Mukhopadhyay S, Pal S (2015) Surface runoff and soil erosion dynamics: a case study on Bakreshwar river basin, eastern India. *Int Res J Earth Sci* 3(7):11–22
- Harvey CA, Pimentel D (1996) Effects of soil and wood depletion on biodiversity. *Biodivers Conserv* 5:1121–1130
- Heywood I, Oliver J, Tomlinson S (1995) Building an exploratory multi-criteria modelling environment for spatial decision support. In: Fisher P (ed) *Innovations in GIS, vol 2*. Taylor & Francis, London, pp 127–136
- Islam MM, Sado K (2002) Development priority map for flood countermeasures by remote sensing data with geographic information system. *J Hydro Eng* 7(5):346–355

- Jankowski P (1995) Integrating geographical information systems and multiple criteria decision making methods. *Int J Geogr Inform Syst* 9(3):251–273
- Jagannathan P, Parthasarathy B (1973) Trends and periodicities of rainfall over India. *Mon Weather Rev* 101(4):371–375
- Jha VC (1997) Laterite and landscape development in tropical lands, a case study. In: Nag P, Kumara V, Singh J (ed) *Geography and Environment, Concept*, pp 112–144
- Jha VC, Kapat S (2003) Gully erosion and its implications on land use, a case study. *Land degradation and desertification*. Publ., Jaipur and New Delhi, pp 156–178
- Jha VC, Kapat S (2009) Rill and gully erosion risk of lateritic terrain in South-Western Birbhum District, West Bengal, India. *Soc Nat (Online)* 21(2):141–158
- Jiang H, Eastman JR (2000) Application of fuzzy measures in multicriteria evaluation in GIS. *Int J Geogr Inform Syst* 14:173–184
- Kar A, Bandopadhyay MK (1974) Mechanism in rills: an investigation in micro-geomorphology. *Geogr Rev India* 36(3):139–159
- Kelley DW, Nater EA (2000) Historical sediment flux from three watersheds into Lake Pepin, Minnesota, USA. *J Environ Qual* 29:561–568
- Kerr J (1997) The economics of soil degradation: from national policy to farmers' needs. In: Agus F, Kerr J, Penning de Vries FWT (eds) *Soil erosion at multiple scales: principles and methods for assessing causes and impacts*. CABI Publishing, Wallingford
- Kumar KK, Hoerling M, Rajagopalan B (2005) Advancing dynamical prediction of Indian monsoon rainfall. *Geophys Res Lett* 32(8)
- Lal R (1985) Soil erosion and sediment transport research in tropical Africa. *Hydrol Sci J* 30:239–256
- Lal R (1998) Soil erosion impact on agronomic productivity and environment quality. *Crit Rev Plant Sci* 17:319–464
- Lal R (2001) World cropland soils as source or sink for atmospheric carbon. *Adv Agron* 71:145–191
- Lal R (2003) Soil erosion and the global carbon budget. *Environ Int* 29:437–450
- Lanuza RL, Paningbatan EP (2010) Validation and sensitivity analysis of catchment runoff and erosion simulation technology (CREST): a GIS-assisted soil erosion model at watershed level. In: 2010 Proceedings of the international congress on environmental modeling and software modeling for environment's sake, Ottawa. <http://www.iemss.org/iemss2010/index.php?n=Main.Proceedings>
- Lin CY, Lin WT, Chou WC (2002) Soil erosion prediction and sediment yield estimation: the Taiwan experience. *Soil Tillage Res* 68:143–152
- Lufafa A, Tenywa MM, Isabirye M, Majaliwa MJG, Woomer PL (2002) Prediction of soil erosion in Lake Victoria basin catchment using GIS-based universal soil loss model. *Agric Syst* 73:1–12
- Maji A (2007) Assessment of degraded and wastelands of India. *J Indian Soc Soil Sci* 55:427–435
- Makropoulos C, Butler D (2005) Spatial ordered weighted averaging: incorporating spatially variable attitude towards risk in spatial multi-criteria decision-making. *Environ Model Softw* 21(1):69–84
- Malczewski J (2004) GIS-based land-use suitability analysis: a critical overview. *Prog Plan* 62(1):3–65
- Malczewski J, Rinner C (2005) Exploring multicriteria decision strategies in GIS with linguistic quantifiers: a case study of residential quality evaluation. *J Geogr Syst* 7(2):249–268
- Malczewski J, Chapman T, Flegel C, Walters D, Shrubsole D, Healy MA (2003) GIS-multicriteria evaluation with ordered weighted averaging (OWA): case study of developing watershed management strategies. *Environ Plan A* 35(10):1769–1784
- Mendes JFG, Motizuki WS (2001) Urban quality of life evaluation scenarios: the case of Sao Carlos in Brazil. *CTBUH Rev* 1(2):1–10
- Milevski I (2008) Estimation of soil erosion risk in the upper part of Bregalnica watershed-republic of Macedonia based on digital elevation model and satellite imagery. In: Proceedings from the 5th international conference on geographic information systems. Fatih University, Istanbul, pp 351–358
- Mondal D, Pal S (2015) A multi-parametric spatial modeling of vulnerability due to arsenic pollution in Murshidabad district of West Bengal, India. *Arab J Geosci*. doi:10.1007/s12517-015-1809-4
- Mukherjee A, Fryar AE, Howell PD (2007) Regional hydrostratigraphy and groundwater flow modeling in the arsenic-affected areas of the western Bengal basin, West Bengal, India. *Hydrogeol J* 15(7):1397–1418
- Ochumba PBO (1990) Massive fish kills within the Nyanza Gulf of Lake Victoria, Kenya. *Hydrobiologia* 208:93–99
- Oostwoud DJ, Bryan R (2001) Gully-head erosion processes and semiarid valley floor of Kenya: a case study into temporal variation and sediment budgeting. *Earth Surf Process Landf* 26:911–933
- Pandey A, Chowdary VM, Mal BC (2009) Sediment yield modeling of an agricultural watershed using MUSLE, remote sensing and GIS. *Paddy Water Environ*, 7(2):105–113
- Pimentel D (1993) *World soil erosion and conservation*. Cambridge University Press, Cambridge
- Pimentel D, Kounang N (1998) Ecology of soil erosion in ecosystems. *Ecosystems* 1:418–426
- Prasannakumar V, Vijith H, Abinod S, Geetha N (2012) Estimation of soil erosion risk within a small mountainous sub-watershed in Kerala, India, using Revised Universal Soil Loss Equation (RUSLE) and geo-information technology. *Geosci Front* 3(2):209–215
- Rashed T, Weeks J (2003) Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas. *Int J Geogr Inform Sci* 17(6):547–576
- Ray A, Shekhar S (2009) Ground water issues and development strategies in West Bengal. *Bhu-Jal News* 24(1):1–17
- Renard KG, Foster GR, Weesies GA, Porter JP (1991) RUSLE: revised universal soil loss equation. *J Soil Water Conserv* 46(1):30–33
- Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC (1997) Predicting rainfall erosion losses: a guide to conservation planning with the revised universal soil loss equation (RUSLE) US. Department of Agriculture, Agricultural Handbook 703, Washington, DC, p 404
- Rinner C, Malczewski J (2002) Web-enabled spatial decision analysis using ordered weighted averaging. *J Geogr Syst* 4(4):385–403
- Robert PS (2000) Engineer, soil management/OMAFRA; Don Hilborn-Engineer, Byproduct Management/OMAFRA
- Sanchez PA, Shepherd KD, Soule MJ, Place FM, Buresh RJ, Izac AN, Mokwunye AU, Kwesiga FR, Ndiritu CG, Woomer PL (1997) Soil fertility replenishment in Africa: an investment in natural resource capital. In: *Replenishing soil fertility in Africa*, soil science society of America Special Publication 51, Soil Science Society of America, Madison
- Santhi C, Arnold JG, Williams JR, Dugas WA, Srinivasan R, Hauck LM (2001) Validation of the SWAT model on a large river basin with point and nonpoint sources. *J Am Water Resour Assoc* 37(5):1169–1188
- Santhi C, Srinivasan R, Arnold JG, Williams JR (2006) A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. *Environ Model Softw* 21:1141–1157

- Sanyal J, Lu XX (2006) GIS-base flood hazard mapping at different administrative scales: a case study in Gangetic West Bengal, India. *Singap J Trop Geogr* 27:207–220
- Sehgal J, Abrol IP (1994) Soil degradation in India: status and impact. Oxford and IBH, New Delhi, p 80
- Sharda VN, Dogra P, Prakash C (2010) Assessment of production losses due to water erosion in rainfed areas of India. *J Soil Water Conserv* 65:79–91
- Sharda VN, Mandal D, Ojasvi PR (2013) Identification of soil erosion risk area for conservation planning in different states of India. *J Environ Biol* 34:219–226
- Sinha Ray KC, De US (2003) Climate change in India as evidenced from instrumental records. *Bulletin of the World Meteorological Organization* 52:53–59
- Tinker PB (1997) The environmental implications of intensified land use in developing countries. *Philos Trans R Soc Lond B* 352:1023–1033
- Toy TJ, Foster GR (1998) Use of the revised universal soil loss equation (RUSLE) version 1.06 on mined lands, construction sites, and reclaimed lands. US Department of Interior, Office of Surface Mining, Reclamation, and Regulation, USA
- Turpin N, Bontems P, Rotillon G et al (2005) AgriWaterBMP: systems approach to environmentally sound farming. *Environ Model Softw* 20(2005):187–196
- UNCED (1992) Agenda 21: programme of action for sustainable development, rio declaration on environment and development, statement of principles. Final text of agreement negotiated by governments at the United Nations Conference on Environment and Development (UNCED), 3–14 June 1992, Rio de Janeiro, Brazil, UNDP, New York
- UNEP (1997) World atlas of desertification, 2nd ed, Arnold London. In: Waugh D (ed) *Geography: an integrated approach*, New York
- UNFCCC (1992) United Nations framework convention on climate change. UNFCCC, Bonn
- UNFCCC (1997) Kyoto protocol to the United Nations framework convention on climate change. UNFCCC, Bonn
- UNFCD (1996) United Nations framework convention to combat desertification. Bonn
- US Department of Agriculture, Agricultural Research Service, National Sediment Laboratory (USDA-ARS-NSL) (2003) “RUSLE1.06c and RUSLE2,” USA. <http://www.sedlab.olemiss.edu/rusle>
- USDA-NRCS (2008) Revised universal soil loss equation Version 2, User’s Reference Guide, USDA Agricultural Research Service, Washington, DC
- Vohra BB (1985) Land and water: towards a policy for life-support systems (Vol. 2). INTACH, Indian National Trust for Art and Cultural Heritage
- Walling DE (2000) Linking land use, erosion and sediment yields in river basins. *Hydrobiologia* 410:223–240
- Walling DE, Webb BW (1983) Patterns of sediment yield. In: Gregory KJ (ed) *Background to paleohydrology*. Wiley, Chichester, pp 69–100
- Williams JR (1975) Sediment-yield prediction with Universal Equation using runoff energy factor. In: *Present and prospective technology for predicting sediment yield and sources*. US Department of Agriculture ARS-S40, pp 244–252
- Williams JR, Jones CA, Dyke PA (1984) A modeling approach to determine the relationship between erosion and soil productivity. *Trans Am Soc Agric Eng* 27:129–144
- Wischmeir WH, Smith D (1978) Predicting rainfall erosion losses: a guide to conservation planning. US Department of Agriculture, Agriculture Handbook No. 537
- Yager RR (1988) On ordered weighted averaging aggregation operators in multi-criteria decision making. *IEEE Trans Syst Man Cybernet* 18(1):183–190
- Zobisch MA, Richter C, Heiligteig B, Schlott R (1995) Nutrient losses from cropland in the central highlands of Kenya due to surface runoff and soil erosion. *Soil Tillage Res* 33:109–116