Mapping of Erosion Hazard in and around Kharagpur Hills, Bihar using hydrological indices

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Abstract

Soil is the most important gift of nature formed in hundreds/thousands of years covering the land surface but soil cover is depleting day by day due to geological and/or anthropological activities. Erosion is one of the most important geological processes in reducing the soil cover. Hence, there is a requirement to conserve the soil cover and the first thing which can be done in order to conserve the soil is the identification of vulnerable areas. Identification of vulnerable areas is of foremost importance which could be done by scientific methods. Hydrological Parameters are one of them which can be calculated using Geographic Information System. In this study, Digital Elevation Models have been processed in geographic Information System to calculate three important hydrological indices i.e., Sediment Transport Index, Topographic Wetness Index and Stream Power Index along with other parameters like Slope. Maps showing variability in Slope, Sediment Transport Index, Topographic Wetness Index and Stream Power Index have been prepared to understand the variability and the importance of each parameter in marking the vulnerable areas to erosion. With this, an Erosion Hazard Vulnerability Map of the study area (in and Around Kharagpur Hills, Munger-Jamui, Bihar) has been prepared using Weighted method of Geographic Information System. It has been found that Soil cover over the hills with Steep Slopes are more prone to erosion whereas Soil cover over the very gentle slopes or in the flat areas are least prone to erosion. Along with this it has also been found that river sediments deposited in the point bars along the banks of the river Ganges are also moderately to highly prone to erosion. The importance of spatial analyst tool of geographic information system has been utilized in delineating the vulnerable areas.

Keywords Soil, Erosion, Slope, Sediment Transport Index, Topographic Wetness Index, Stream Power Index

Introduction

In every scale from local to global, water, floods, and runoff contribute significantly to erosion and land degradation processes (Eswaran et al.2001; Ahmad et al. 2019). Erosion plays an important role in generating sediments and depleting soil cover over the land surface. Hydrological, Topographical and Geological features control the extent of erosion. In many parts of the world, agencies responsible for managing land and water are being required to identify the areas of land that are prone to erosion, sedimentation, salinization, nonpoint source pollution and water logging (Herndon, 1987; Moore et al. 1991). Water Power delivers topsoil and contributes strongly to the erosion and degradation of the land and then transports dirt and sediment to flat areas through natural processes, such as flow and gravity (Bannari et al. 2017). Flow accumulation is found in valleys and on slopes with steeper slopes, where large upslope drainage areas provide contributions to the flow, allowing for high erosion rates whereas areas of low slope are tending to have low runoff aggressiveness (Bannari et al. 2017). Erosion, also known as soil loss or landslides, is a natural denudation process or a component of the geomorphic evolution of terrain which yields different topographical features (Thorbury 1969; Vijth et al.2019). To develop effective management plans and mitigation strategies, it is important to determine whether the terrain is susceptible to erosion and classify it into different levels of susceptibility (Dai and Lee 2002; Ayalew et al. 2004; Bijukchhen et al. 2013; Erener et al. 2016; Pham et al. 2017; Vijith et al. 2019). It is possible to map these processes using relatively simple techniques by using the spatial distribution of topographic attributes as an indirect measure of their spatial variability. In order to predict these flow characteristics, topography has a profound impact on how water moves within landscapes. Topographic analyses of catchment areas are largely based on digital elevation models (Moore et al, 1991). There are number of hydrologically-based and topographically-derived parameters to mark the hazard vulnerable areas. (Moore and Nieber, 1989; Moore et al,1991).

Topography based attributes are of two types- Primary and Compound. Primary attributes are calculated using elevation and slope data whereas Compound attributes are calculated using primary attributes characterizing a particular process. Stream Power Index, Sediment Transport Index and Topographic Wetness Index are three most important parameters that have been utilized in analysing an area with respect to erosional processes.

Wetness indexes are used to illustrate how surfaces are saturating and how soil water content is distributed in landscapes (Moore et al.,1988,1993). Topographic Wetness Index was developed by Beven and Kirkby (1979). Using the TWI, it has been possible to study hydrological processes at the spatial scale (Beven et al., 1988; Famiglietti and Wood, 1991; Sivapalan and Wood, 1987; Sivapalan et al., 1990; Sorensen et al.,2006). When determining where water may flow or accumulate, the topography of a landscape is used (Moore et al.1991).

Stream Power plays an important role in the process of sediment transportation and deposition and also in modifying channel patterns. To understand all these geomorphic or hydrological processes, stream power index can be calculated. Stream Power Index is a measure of the erosive power of flowing water. It is calculated based upon slope and contributing area.

Sediment Transport Index is a nonlinear function of specific discharge and slope. Both catchments evolution and erosion theories play a role in determining how it is determined. (Moore et al.1992; Bannari et al. 2017). It calculates a spatially distributed sediment transport capacity and may be a better alternative to an empirical equation in evaluating erosion at landscape scales because it accounts explicitly for flow convergence and divergence (Moore et al. 1992; Desmet et al. 1996; Banari et al. 2017).

Study Area

The study area (Fig.1) can be divided geographically, geologically and administratively. It extends from 24°0′0″N to 26°0′0″N and 86°0′0″E to 87°0′0″E. Geographically, it covers the sub-basins of Gange river and Kiul river. Geologically, the areas in and around Kharagpur Hills is highly deformed and metamorphosed terrain characterised by phyllites, quartzites and Chhotanagpur Gneissic Complex (Mahadevan, 2002) representing some of the oldest rocks found in the state of Bihar. It is also characterized by the presence of younger alluvium near Munger town and older alluvium in the eastern part of study area. Administratively, it covers the Munger, Lakhisarai and some parts of Jamui and Khagaria districts of the Bihar state.

Methodology

Geographic Information System has been used to calculate various hydrological indices. Two number of Shuttle Radar Topography Mission (SRTM) Georeferenced Tagged Image File Format (GeoTIFF) of spatial resolution 30meters published on 23rd September, 2014 have been used. SRTM 1 Arc-second Global elevation which provides worldwide void filled data have been processed in geographic information system. A GIS was utilized to extract topographic profiles and attributes in the form of Slope, the stream power index (SPI), sediment transportation index (STI), and topographic wetness index (TWI) (Bannari et al.,2017). It has been processed in the following manner:

Slope Gradient: At a given point on a surface, Slope is the angle between horizontal plane and tangent plane as per Lehmann (1816). It is given as

Slope = arctan (Y2 + X2)1/2

Where Y represents horizontal Plane

X represents tangent plane

Sediment Transport Index: In the stream network of a given watershed, the sediment transport index can provide crucial information on sediment transport potential. The following steps have been followed to calculate STI:

a. Digital Elevation Model
b. Flow Direction
c. Flow Accumulation
d. Slope
e. Sediment Transport Index using Map Algebra.

Sediment Transport Index (STI) = $(As/22.13)^{0.6}$ x $(\text{Sin}\beta /0.0896)^{1.3}$

Where As means Flow Accumulation

Sinβ is Slope

Stream Power Index: At a given point on the topographic surface, the Stream power index can be used to determine potential flow erosion. It is the product of catchment area and slope. The following steps have been followed to calculate SPI:

a. Digital Elevation Model
b. Fill
c. Flow Direction
d. Flow Accumulation
e. Slope
f. Stream Power Index using Map Algebra

Stream Power Index (SPI) = In (CA * tanG)

Where CA means Catchment Area

G means Slope Gradient

Topographic Wetness Index (TWI): It is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction. It is also known as compound topographic index. It is used to analysis topographical control on hydrological processes. The following steps have been followed to calculate TWI:

a. Digital Elevation Model
b. Fill
c. Flow Direction
d. Flow Accumulation
e. Slope
f. Stream Power Index using Map Algebra

Topographic Wetness Index (TWI) = In(a/tanb)

Where a means local upslope through a certain point per unit contour length

tanb means local slope in radians

After calculating Slope, Sediment Transport Index (STI), Stream Power Index (SPI) and Topographic Wetness Index (TWI), we have reclassified each index/parameter into five classes and have assigned weights with respect to vulnerability to erosion while considering the geology of the study area.

Results and Discussions

Slope, Stream Power Index, Sediment Transport Index and Topographic Wetness Index have been extracted by processing SRTM Digital Terrain Elevation Data in geographic information system.

Slope:

Slope is one of the most influential factors in deciding the stability of a surface. Hence, it has been studied and calculated. The value of the slope gradient varies from 0 to 68.37 percent rise. This has been reclassified into five classes (Table 1), i.e., Class I (0 – 2.14%), Class II (2.15 – 5.09%), Class III (5.10 – 11.52%) Class IV (11.53 – 21.44%) and Class V (21.45 – 68.37%). Each class has been given weight as per its vulnerability to erosion. The highest weight of 5 value has been given to regions with the slope gradient between 21.45 and 68.37 whereas the lowest weight of value 1 has been given to regions with slope gradient between 0 and 2.14 respectively. The steeper slopes are more vulnerable to erosion in comparison to gentle slopes. Hence, a map (Fig.2) has been generated to understand the variation in slope gradient in the study area. It has also been found that Kharagpur hills along with its extended part in the central and southern portion of the study area is showing steep slope whereas areas in the Northern and Southern portion of the study area is showing gentle to very gentle slopes. It can be further corelated to the lithology of the area such that Kharagpur Hills which are made up of highly deformed rock bodies having steep slopes and remaining areas of Younger and Older Alluvium which are made up of river sediments having gentle to very gentle slopes. It can be inferenced from the above that Surface of the southern part of the area is sloping from South to North towards central part, i.e., towards river Ganga and Surface of the northern part of the area is sloping from North to South towards central part, i.e., towards river Ganga both forming middle Ganga plains.

Topographic Wetness Index or Compound Topography Index:

A Topographic Wetness Index or Compound Topography Index is a way to determine how a region's hydrological system is developing (Ahmad et al. 2019). It is very useful in delineating and identifying areas which can be saturated with water influenced by contributing factors like local slope gradient, etc. Hence, it has been studied and calculated. The value of the TWI varies from -8.99 to +14.45. This has been reclassified into five classes (Table 2), i.e., Class I (-8.99 to -4.30), Class II (-4.29 to -2.55), Class III (-2.54 to -0.25) Class IV (-0.24 to +2.95) and Class V (+2.96 to +14.45). Each class has been given weight as per its capability to water accumulation. The highest weight of 5 value has been given to regions with the TWI between -8.99 and -4.30 whereas the lowest weight of 1 value has been given to regions with TWI between +2.95 and +14.45 respectively. While using these values, a map (Fig.3) has been prepared showing variability in topographic wetness index in the region. It has been seen that the areas having steep slopes and are consisting of hard rock bodies showing negative or very low topographic wetness index. It means that they have lowest chances of accumulating water there but on the other hand, these areas will be more vulnerable to flash floods. These areas will also be forming large number of gullies influencing local flow dynamics. On the other hand, the areas having flat or gentle slopes and consisting of river alluvium are showing very high positive values of topographic wetness index. It means that they have highest chances of accumulating water there and are most vulnerable to the process of erosion and overflow. While observing the map, it can also be seen that areas on both banks of river ganga are most prone to overflow and flood particularly in the eastern and western part of the study area.

Stream Power Index:

Stream Power Index is one of the major compound attributes among hydrological parameters. It is influenced by slope gradient and flow accumulation. It is used to delineate the areas of deposition and erosion. Hence, it has been studied and calculated. The value of the Stream Power Index varies from -13.81 to +13.47. This has been reclassified into five classes (Table 3), i.e., Class I (-13.81 to -7.39), Class II (-7.38 to -2.68), Class III (-2.67 to -0.64) Class IV (-

0.63 to +2.56) and Class V (+2.57 to +13.47). Each class has been given weight as per its vulnerability to erosion. The highest weight of 5 value has been given to regions with the Stream Power Index between +2.57 and +13.47 whereas the lowest weight of value 1 has been given to regions with Stream Power Index between -13.81 and -7.39 respectively. While using these values, a map (Fig.4) has been prepared to show variability in SPI in the region. It can be seen that Kharagpur Hills and its extended part which are having steep slopes shows higher and positive values of SPI. It means that soil cover is vulnerable to erosion and soil thickness may also be thin in this area and would be having local channel system and depressions. On the other hand, the areas either flat or having gentle slopes shows very low and negative values of SPI. It means that they are vulnerable to floods and overflow as well as are best sites for deposition of river sediments. While observing the map, it is important to notice that there are some regions where numerous gullies are forming and hence influencing the movement of water and sediments.

Sediment Transport Index:

The Sediment Transport Index indicates how sediment accumulates and transports over space. In order to understand the above-mentioned parameters related to sediments, it has been calculated in geographic information system and studied. The value of the Sediment Transport Index varies from 0 to 2258.51. This has been reclassified into five classes (Table 4), i.e. Class I(0 to 53.14), Class II(53.15 to 230.28), Class III(230.29 to 549.12) Class IV(549.13 to 1062.83) and Class V(1062.84 to 2258.51). Each class has been given weight as per its vulnerability to soil erosion and degradation. The highest weight of 5 value has been given to regions with the Sediment Transport Index between 1062.84 and 2258.51 whereas the lowest weight of value 1 has been given to regions with Sediment Transport Index between 0 and 53.14 respectively. While using these values, a map (Fig.5) has been prepared showing variability in STI in the region. It has been found that areas like Kharagpur Hills which are made up of deformed hard rock bodies and also have steep slopes are showing very low or zero value of STI. It means that hard rock bodies are associated with low degree of sediment transportation leading to less erosion of rock bodies whereas areas like plains of middle ganga which are made up of river sediments alluvium and also have very gentle to gentle slopes are showing very High values of STI. This shows that sediments are more prone to be transported through various local channels. Another important aspect that can be mentioned that STI value is very high along the bank of river ganga and also local channels in the area indicating their capability to transport sediments and their erosion potential.

Erosion Hazard Vulnerability:

Erosion Hazard Vulnerability Map (Fig.6) has been prepared using the thematic maps of Slope, Topographic Wetness Index, Stream Power Index and Sediment Transport Index. This map has been generated using Map Algebra – Raster Calculator. Based on the final output map, one can clearly see where erosion is most vulnerable. The Erosion Hazard Vulnerability overlayed data has been classified into five classes (Table 5), i.e., Class I (Very Low), Class II(Low), Class III(Moderate) Class IV(High) and Class V (Very High). It can be seen that that Kharagpur Hills and its extended hilly areas is highly vulnerable as well as alluvium along the banks of river ganga and its tributaries are also moderately to highly vulnerable to erosion.

Conclusion

The GIS tool can be properly utilized to extract various hydrological parameters like Slope, Topographic Wetness Index, Stream Power Index and Sediment Transport Index from the Shuttle Radar Topography Mission (SRTM) Digital Terrain Elevation Data. River and Soil Erosion is one of the major issues of the Middle Ganga Plain and areas around Kharagpur Hills of Bihar. Using the above-mentioned indices, we can make erosion prone maps which can be further utilized for proper management of natural resources and also to prepare ourselves during floods.

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Figures and Tables

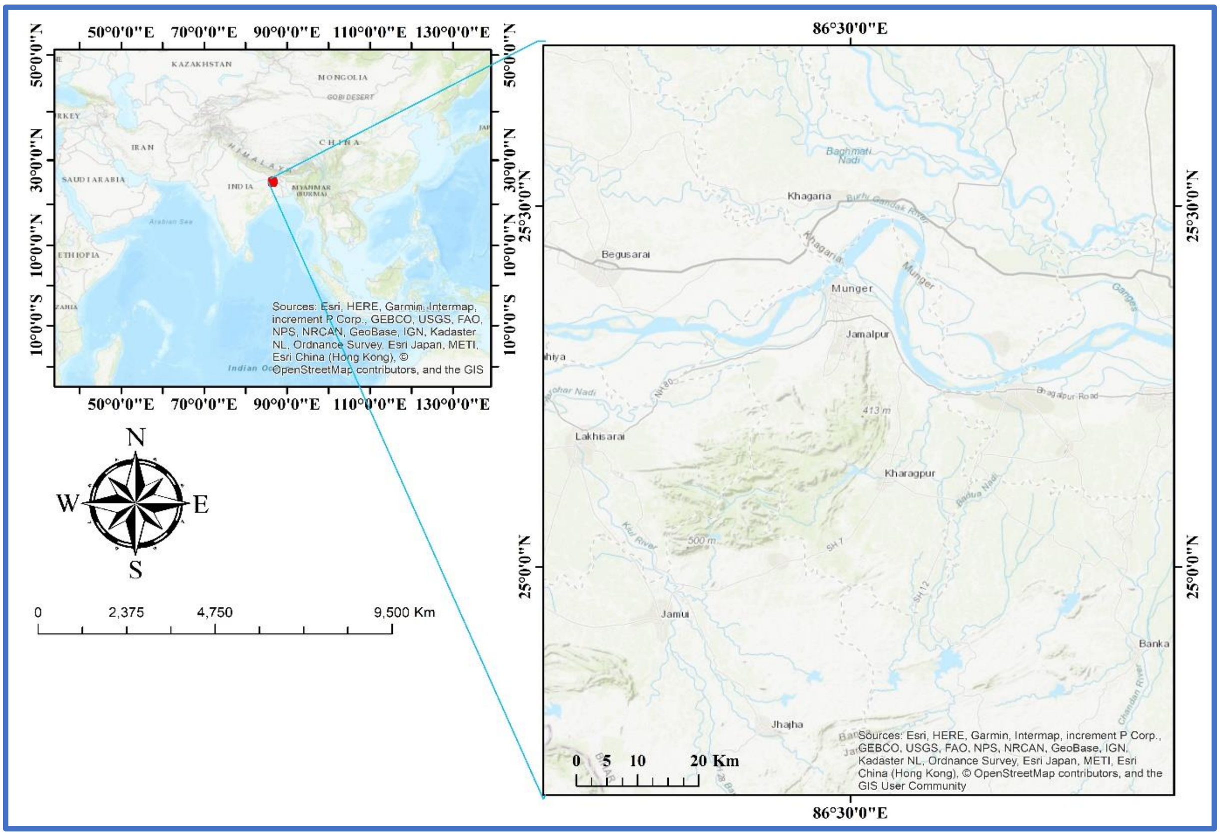

Figure1 Study Area Map

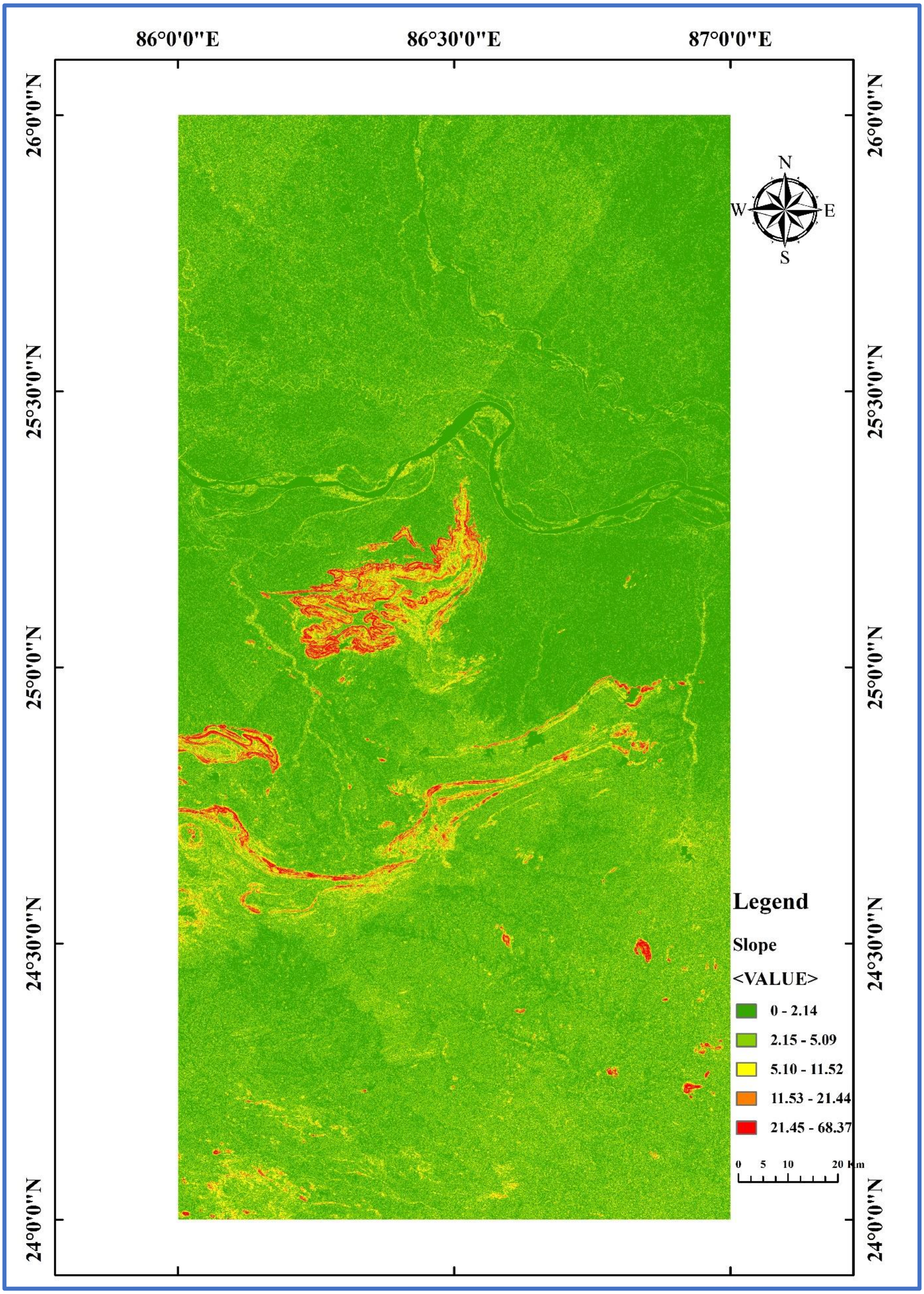

Figure 2 Map showing variation in slope gradient

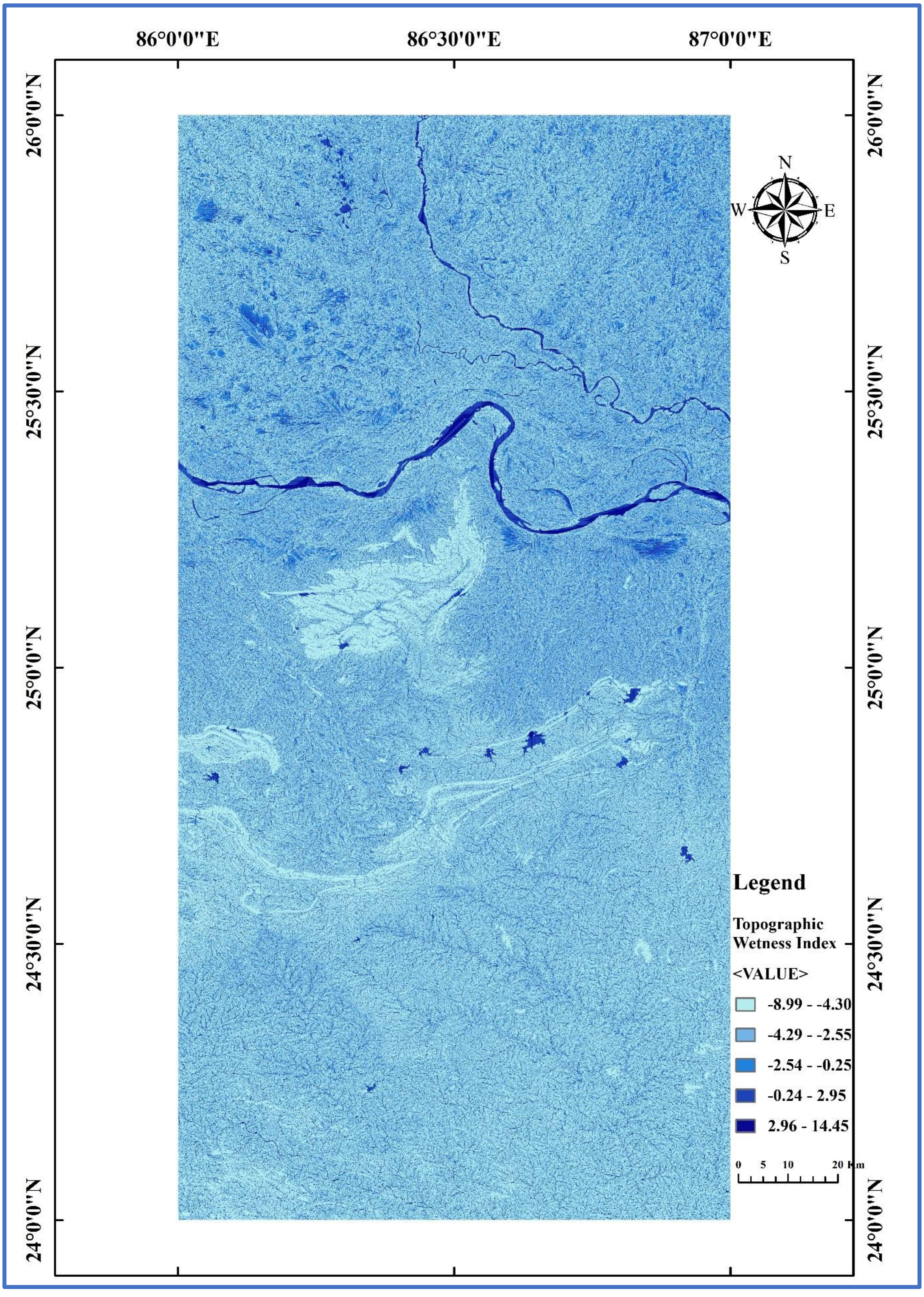

Figure 3 Map showing variation in Topographic Wetness Index

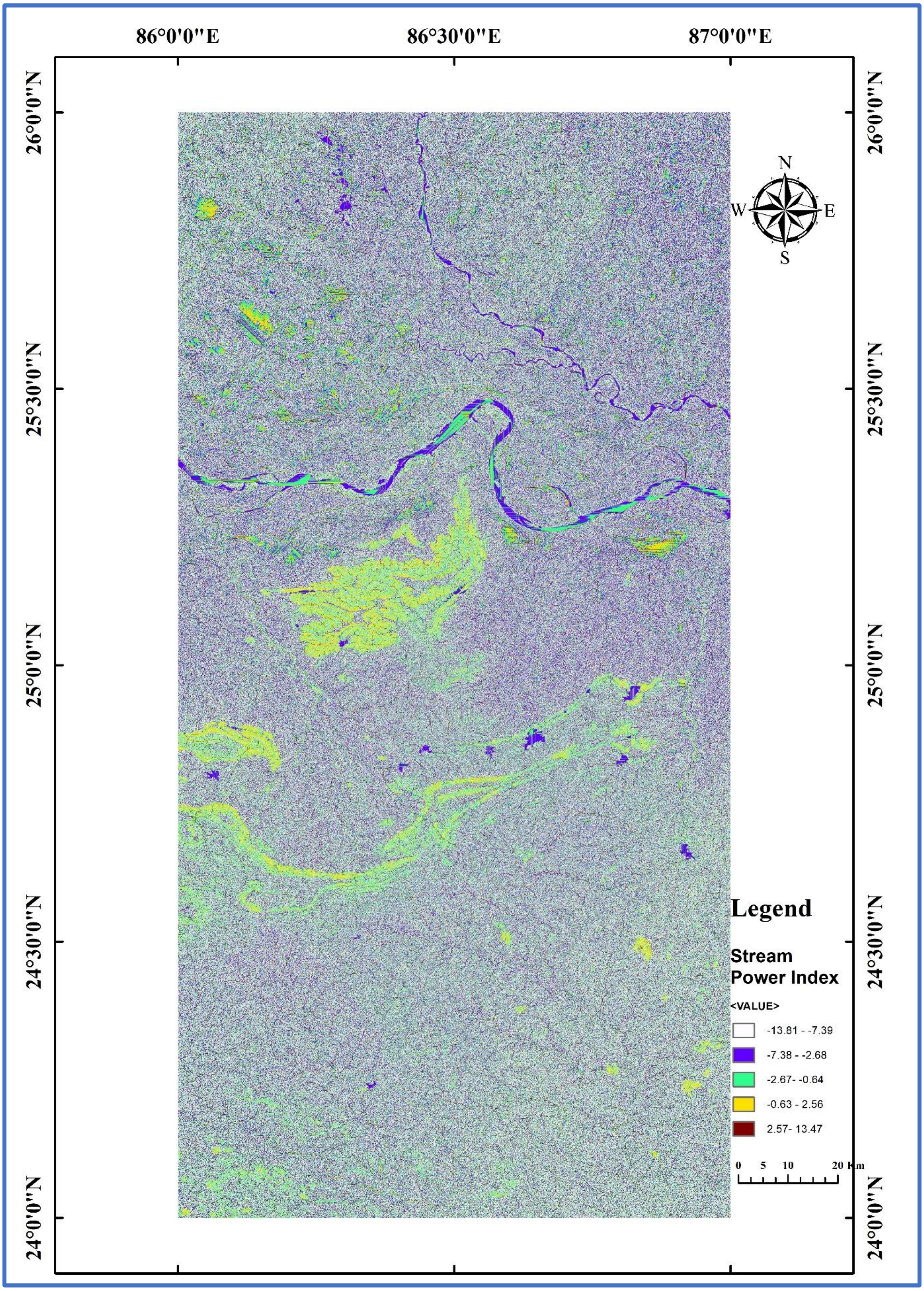

Figure 4 Map showing variation in Stream Power Index

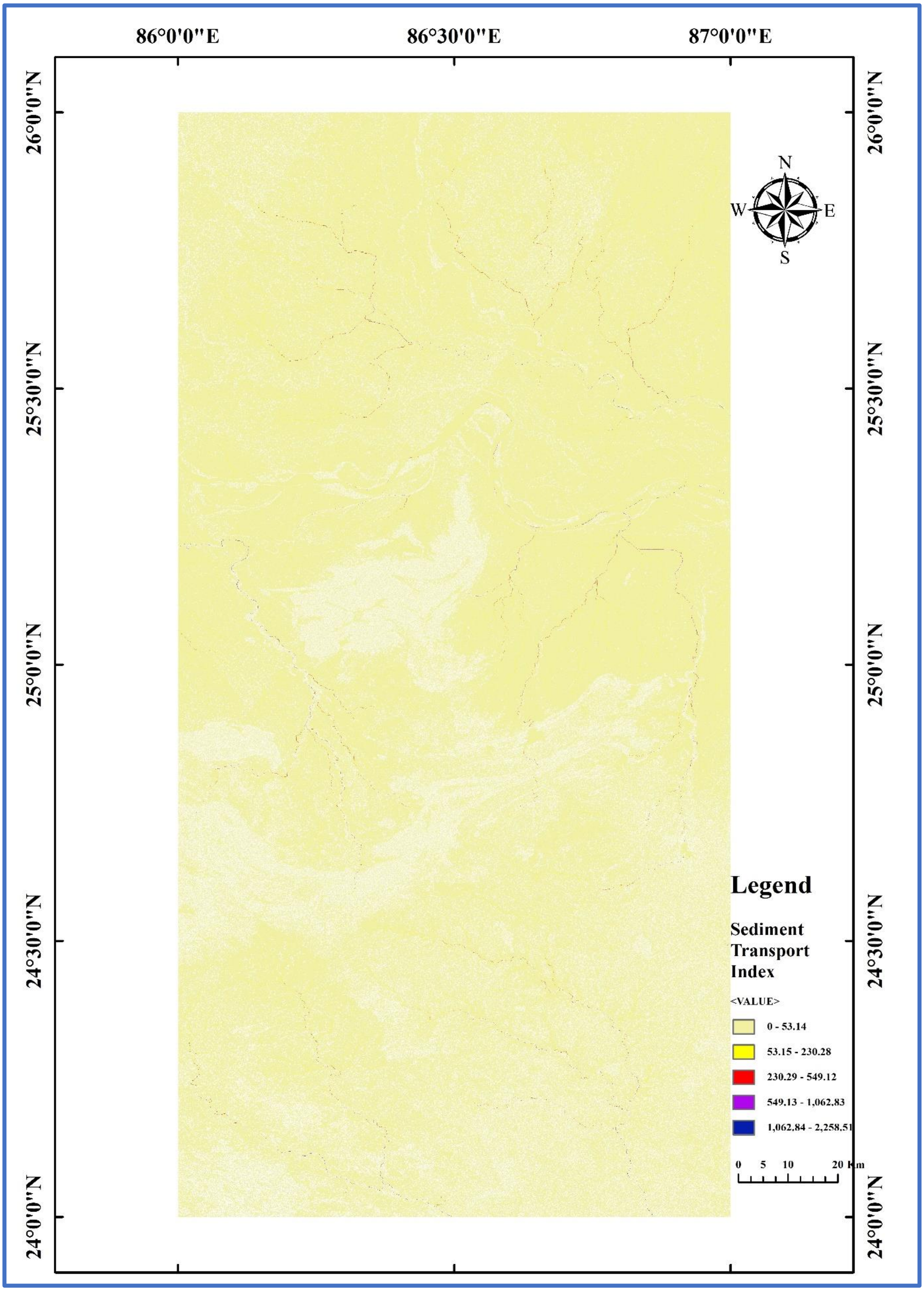

Figure 5 Map showing variation in Sediment Transport Index

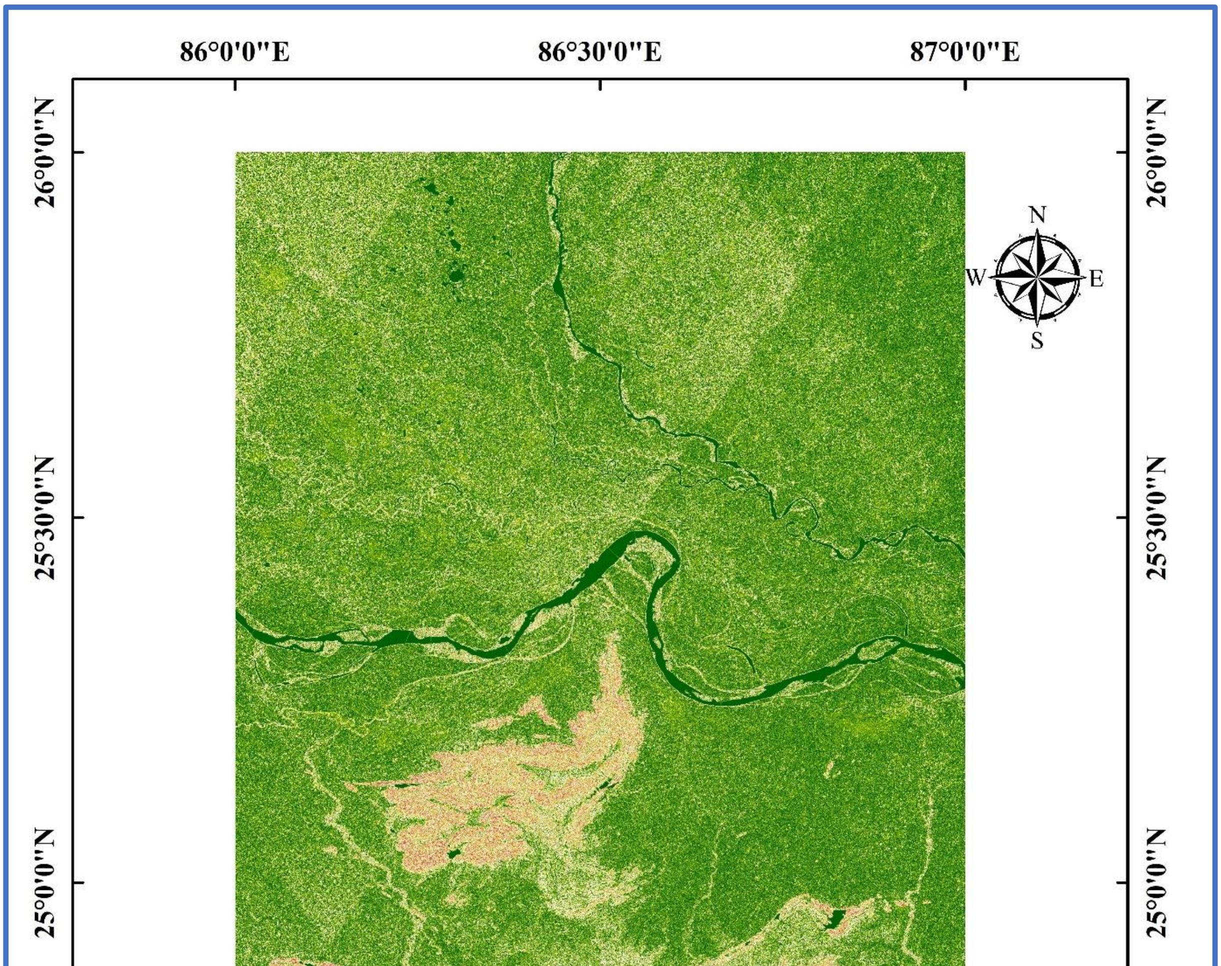

Figure 6 Erosion Hazard Vulnerability Map

Table 1: Slope			
SI. No.	**Values**	**Class**	**Potential Weight**
1.	0 to 2.14	I	1
2.	2.15 to 5.09	II	2
3.	5.10 to 11.52	III	3
4.	11.53 to 21.44	IV	4
5.	21.45 to 68.37	V	5

Table 2: Topographic Wetness Index			
SI. No.	**Values**	**Class**	**Potential Weight**
1.	-8.99 to -4.30	I	5
2.	-4.29 to -2.55	II	4
3.	-2.54 to -0.25	III	3
4.	-0.24 to +2.95	IV	2
5.	+2.96 to +14.45	V	1

Table 3: Stream Power Index			
SI. No.	**Values**	**Class**	**Potential Weight**
1.	-13.81 to -7.39	I	1
2.	-7.38 to -2.68	II	2
3.	-2.67 to -0.64	III	3
4.	-0.63 to +2.56	IV	4
5.	+2.57 to +13.47	V	5

Table 4: Sediment Transport Index			
SI. No.	**Values**	**Class**	**Potential Weight**
1.	0 to 53.14	I	1
2.	53.15 to 230.28	II	2
3.	230.29 to 549.12	III	3
4.	549.13 to 1062.83	IV	4
5.	1062.84 to 2258.51	V	5

Table 5: Erosion Hazard Vulnerability		
SI. No.	**Values**	**Class**
1.	3 to 6	I(Very Low)
2.	6 to 15	II(Low)
3.	15 to 30	III(Moderate)
4.	30 to 64	IV(High)
5.	64 to 125	V(Very high)