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Application of hydrological indices in developing erosional hazard vulnerability map in parts of the Gandak River Basin, Bihar

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Abstract

River erosion is one of the significant and unpredictable hazards in India. Soil that forms over hundreds of years depletes due to various geological phenomena and anthropogenic causes. Assessment of the vulnerable area is essential to take any remedial measures to control river erosion. Remote sensing and Geographical Information System techniques can be effectively utilized to assess the severity level of erosion as realistic as possible. Hydrological parameters can be calculated by using the Geographical Information System. We have processed the Digital Elevation Models in the Geographical Information System of the study area to calculate the important hydrological indices i.e., Topographic Wetness Index, Sediment Transport Index, Stream Power Index and slope gradients along with other relevant parameters. The erosion-susceptible areas are delineated based on variability found in the Sediment Transport Index, Stream Power Index, Topographic Wetness Index and Slope Gradient of the study area. An Erosion Hazard Vulnerability map of parts of the Gandak river basin in Bihar which is the study area has been prepared based on the Weighted method of Geographic Information System. The results of the hydrological parameters show a gentle slope in the study area which is prone to erosion. River bank erosion occurs due to very high river water flow, especially in the monsoon season, and river channel shifts due to heavy siltation. The spatial tools of the Geographic Information System have been used to demarcate the erosion susceptible areas. These maps can be used to prepare ourselves for flood hazards and to manage natural resources more effectively.

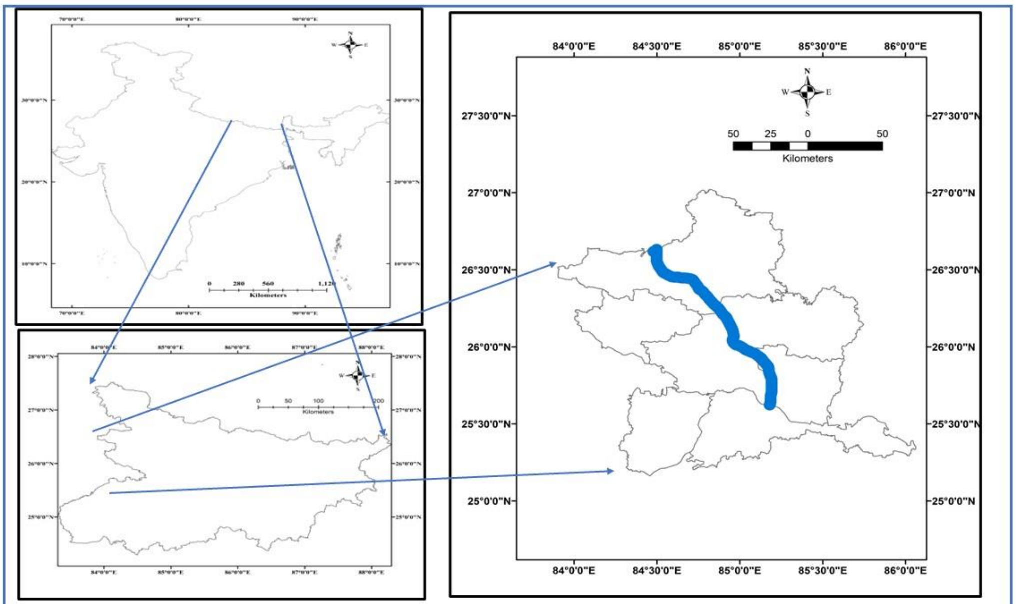
Keywords: Soil Erosion; Slope; Sediment Transport Index; Stream Power Index; Topographic Wetness Index

Introduction

Erosion and land degradation processes are heavily influenced by water, floods, and runoff at all levels, from the local to the global (Eswaran et al., 2001; Ahmad et al., 2019). A major component of erosion is the generation of sediments and the ensuing loss of soil cover over the land surface. There are geological, topographical and hydrological features that influence erosion to varying degrees. The process of erosion generates sediments and also depletes soil cover over the land surface (Sharma & Pandey, 2022). It is becoming increasingly important for agencies managing land and water to identify the area most vulnerable to erosion, sedimentation, salinization, nonpoint source pollution, and water logging everywhere in the world (Herndon, 1987; Moore et al., 1991). In addition to delivering topsoil, water power contributes to erosion and degradation of the land, and it carries dirt and sediment to flat areas by natural processes, such as flow and gravity (Bannari et al., 2017). In valleys and on steep slopes, where large drainage areas contribute to the flow, erosion rates can be high, while runoff aggressiveness is lower in low-slope areas (Bannari et al., 2017). In geology, erosion is a natural process of denudation or a component of terrain evolution that provides different topographical characteristics (Thornbury 1969; Vijth et al., 2019). Identifying and categorizing the terrain into different levels of erosion susceptibility is essential to develop effective management plans and mitigation strategies (Dai & Lee 2002; Ayalew et al., 2004; Bijukchhen et al., 2013; Erener et al., 2016; Pham et al., 2017; Vijith et al., 2019). To measure spatial variability, topographic attributes can be used as an indirect measure by mapping their spatial distribution. Topography has a profound impact on how water moves within landscapes, so it is vital in predicting how water will flow. Digital elevation models are widely used to analyze the topography of catchment areas (Moore et al., 1991). Hazard-vulnerable areas are marked by hydrologically based and topographically derived parameters (Moore & Nieber, 1989; Moore et al.,1991). Attributes based on topography are classified into two types: primary and compound. In the case of primary attributes, elevation and slope data are utilized, whereas, for compound attributes, the primary attributes characterizing the process are utilized. The three most important parameters that have been used to assess erosional processes in an area are the stream power index, sediment transport index, and topographic wetness index. The topographic wetness index shows how surfaces saturate and how soil water content is distributed in landscapes (Moore et al.,1988,1993). Beven and Kirkby (1979) developed the Topographic Wetness Index. TWI has been used to study hydrological processes at a spatial level (Sivapalan & Wood, 1987; Beven et al., 1988; Sivapalan et al., 1990; Famiglietti & Wood, 1991; Sorensen et al., 2006). It is important to study the topography of a landscape when determining the direction in which water may flow or accumulate (Moore et al.,1991). The role of stream power is crucial to sediment transportation, deposition, and channel pattern modification. A stream power index can be calculated to understand all the processes associated with these geomorphic or hydrological processes. Stream Power Index is a measure of stream erosive power. It is calculated by considering the slope and area contributing to the slope. An index measuring sediment transport which is also called as Sediment Transport Index is a nonlinear function of specific discharge as well as slope. The catchment evolution theory and erosion theory are both involved in determining this (Moore et al., 1992; Bannari et al., 2017). It can be used to evaluate erosion at landscape scales if flow convergence and divergence are explicitly included since it calculates a spatially distributed sediment transport capacity (Moore et al., 1992; Desmet et al., 1996; Bannari et al., 2017).

Study Area

The study area (fig.1) extends from 25º0'0" N to 27º0'0" N and 84º0'0" E to 86º0'0" E. Geologically, the study area is a part of the middle Ganga plain. The Gandak Basin is bordered by the Himalayas to the north, the river Ganga to the south, the Burhi Gandak Basin to the east, and the Ghagra Basin to the west. The alluvial plain was broadly divided into two categories: Older Alluvium (Bhangar) and Newer Alluvium (Khadar), each containing different sediment types (Pascoe,1973). Administratively, it covers the districts of Vaishali, Muzaffarpur, East Champaran, Saran, Siwan, and Gopalganj of Bihar along the course of the Gandak River in Bihar.



Map showing Study Area

Figure 1: Study Area Map

Methodology

Numerous hydrological indices have been computed using the Geographic Information System (GIS). In this study, we used a Georeferenced Tagged Image File Format (GeoTIFF) of spatial resolution 30 meters published by Shuttle Radar Topography Mission (SRTM) on 23rd September 2014. The Geographic Information System has been used to process SRTM 1arcsecond Global Elevation data, which provides void-filled data for the entire globe. In this study, GIS technology was used to extract topographic profiles and attributes such as Slope, Stream Power Index (SPI), Sediment Transportation Index (STI), and Topographic Wetness Index (TWI), (Bannari et al., 2017). The following steps have been taken to process it:

Slope gradient: Slope is the angle between a horizontal plane and the tangent plane at any given point on a surface as per Lehmann (1816) It is been calculated as follows:

Slope = arctan (Y2 + X2)1/2

where Y, represents the horizontal Plane, and X, represents the tangent plane.

Sediment Transport Index: The sediment transport index can provide valuable information about sediment transport potential in the stream network of a given watershed. STI is been calculated by the following steps:

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 (Sinβ /0.0896)1.3 Where "As" is Flow Accumulation and "Sinβ" is the Slope.

Stream Power Index: The Stream power index can be used to calculate the potential flow erosion at any given location on the topographic surface. It is determined by the catchment area and slope. Stream Power Index has been calculated by the following step:

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 * tan G)

where CA is the Catchment Area and G is Slope Gradient

Topographic Wetness Index (TWI): The slope and the upstream contributing area per unit width orthogonal to the flow direction determine it. Alternatively, it is also called as Compound Topographic Index. The method is used to analyze topographical control over the hydrological processes. To calculate the Topographic Wetness Index (TWI), the following steps have been followed:

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/tan b)

'a' represents the local slope through a certain point per unit contour length, and “tan b” signifies the local slope in radians.

After the calculation of Slope, Sediment Transport Index (STI), Stream Power Index (SPI) and Topographic Wetness Index (TWI), each index/parameter has been reclassified into five categories and weighted according to erosion vulnerability by the geology of the study area.

Results and Discussion

A Geographic Information System has been used to extract slope, stream power index, sediment transport index, and topographic wetness index from SRTM Digital Terrain Elevation Data.

Slope: The slope has been studied and calculated as it plays a very important role in determining the stability of the surface. The value of the slope gradient varies from 0 to 54.84 per cent rise. Five classes have been assigned to it (table 1), i.e., Class I (0 – 1.29%), Class II (1.29 – 2.58%), Class III (2.58 – 4.51%), Class IV (4.51 – 13.98%) and Class V (13.98 – 54.84%). A weight has been assigned to each class following how vulnerable it is to erosion. The regions with slope gradients between 13.98 and 54.84 have been given the highest weight of 5, and the regions with slope gradients between 0 and 1.29 have been given the lowest weight. When compared with gentle slopes, steeper slopes are more susceptible to erosion. To better understand the variation in slope gradient in the study area, a slope map has been generated (fig. 2). It can be inferred from the map that the slope of the study area varies from very gentle to gentle, this indicates that there is a possibility of erosion along the Gandak River bank in parts of the study area.

Table-1: Slope

Sr. No.	Value	Class	Potential Weight
1.	0.00 to 1.29	I	1
2	1.29-2.58	II	2
3.	2.58-4.51	III	3
4.	4.51-13.98	IV	4
5.	13.98-54.84	V	5

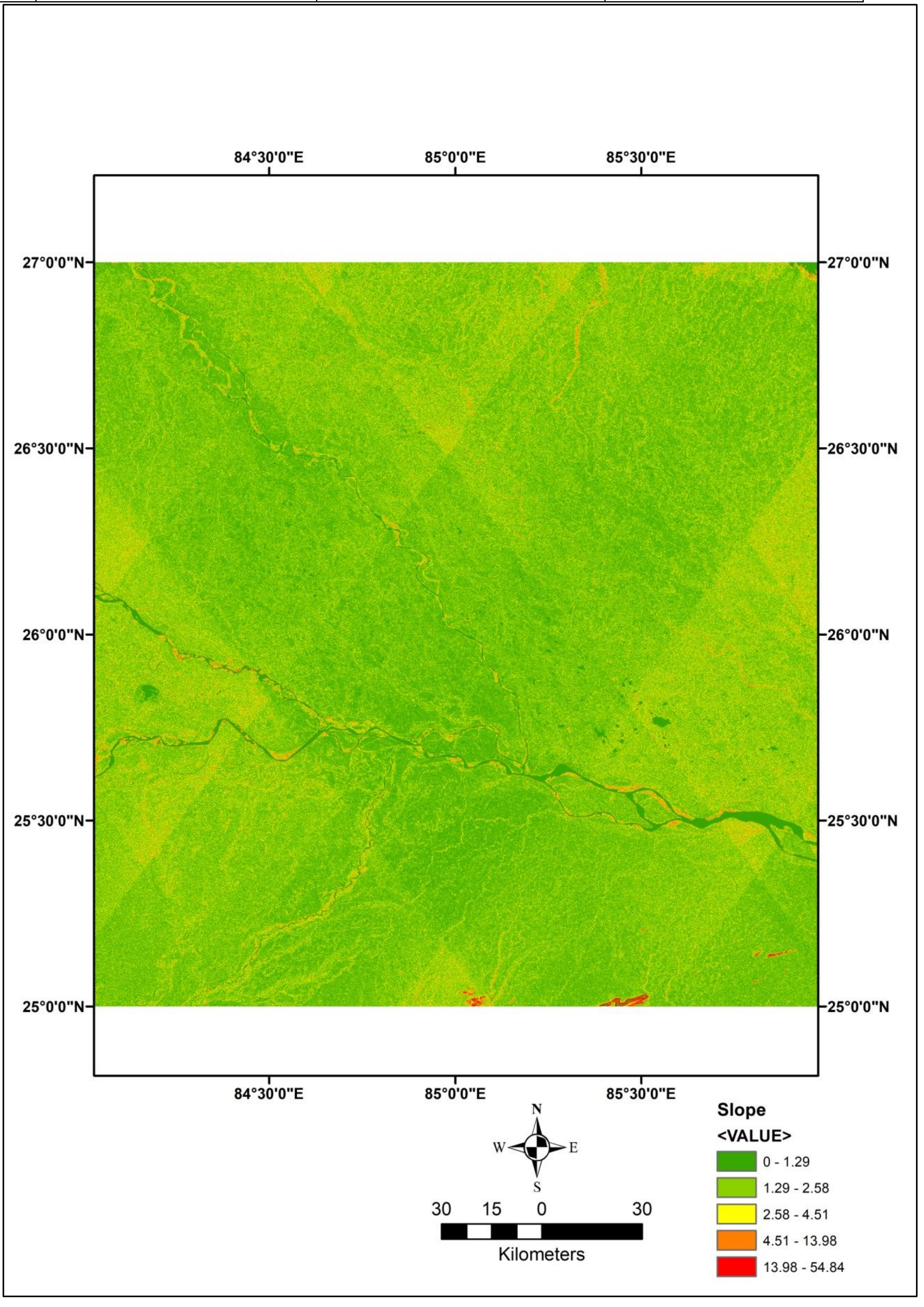


Figure 2: Map showing variation in slope gradient.

Topographic Wetness Index or Compound Topography Index: The development of a region's hydrological system is evaluated by the Topographic Wetness Index or the Compound Topography Index (Ahmad et al., 2019). It can easily identify and delineate areas that can become saturated with water as a result of local factors such as slope gradient. Therefore, it has been calculated and studied. The value of the TWI varies from -8.36 to 15.83. This has been classified into five classes (table 2), i.e., Class I (-8.36 to -3.80), Class II (-3.80 to -2.10), Class III (-2.10 to 0.17), Class IV (0.17 to 3.59) and Class V (3.59 to 15.83). A weight has been assigned to each class based on its ability to accumulate water. TWI values between -8.36 and -3.80 have been assigned the highest weight of 5 value, whereas TWI values between 3.59 and 15.83 have been given the lowest weight of 1. Based on these values, a map has been prepared (fig. 3) showing the variability of the topographic wetness index in the region. A very high positive value of the topographic wetness index can be observed in areas with gentle slopes and consisting of river alluvium. In other words, they are the most likely to accumulate water and are the most vulnerable to erosion and overflow.

Table 2: Topographic Wetness Index

Sr. No.	Value	Class	Potential Weight
1.	(-)8.36 to (-)3.80	I	5
2	(-)3.80 to (-)2.10	II	4
3.	(-)2.10 to 0.17	III	3
4.	0.17 to 3.59	IV	2
5.	3.59 to 15.83	V	1

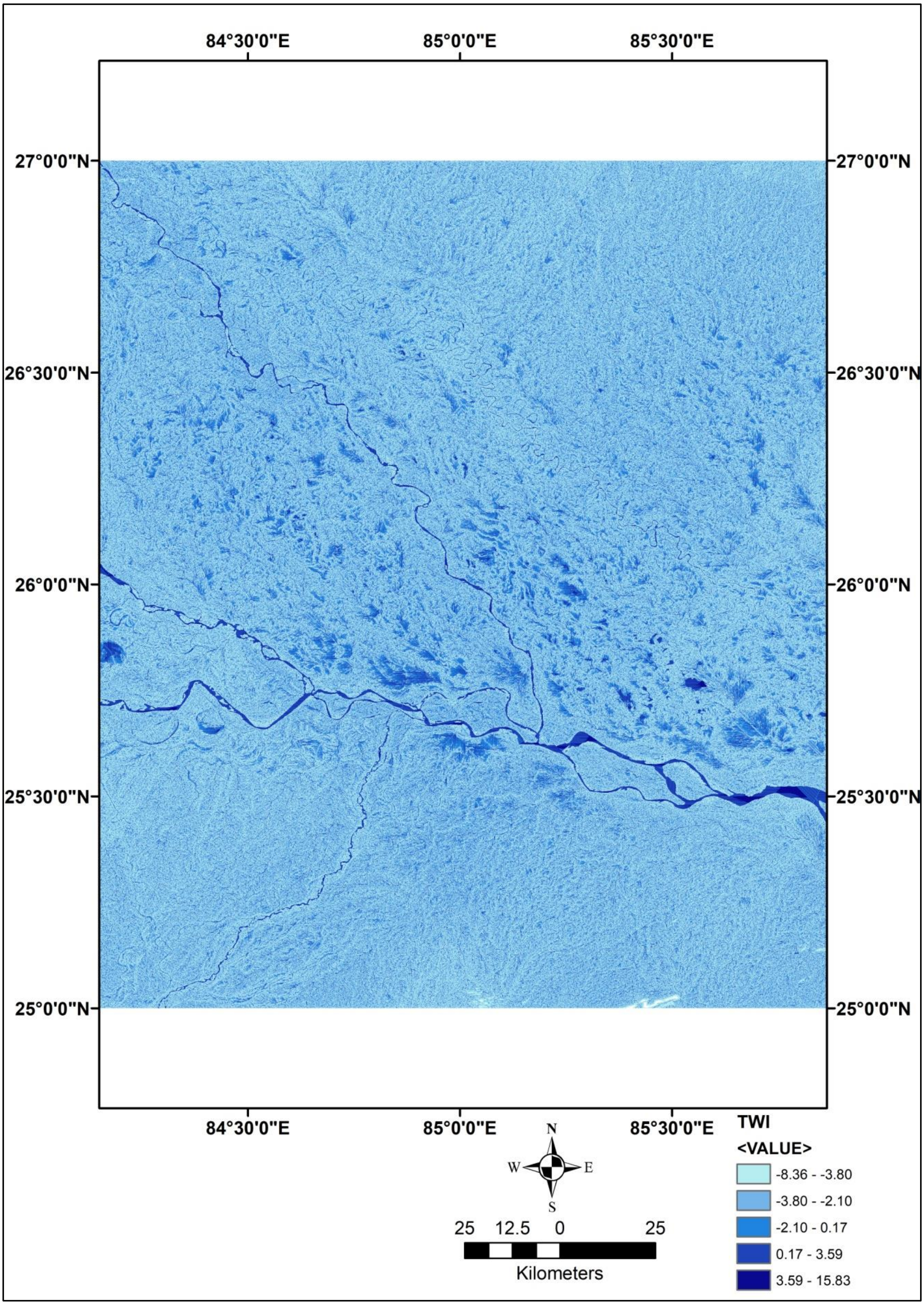


Figure 3: Map showing variation in Topographic Wetness Index (TWI).

Stream Power Index: One of the most important attributes of hydrological parameters is the Stream Power Index. It is influenced by the slope gradients and accumulations of flow. This tool is used to mark erosion and deposition areas. Therefore, it has been calculated and studied. The value of the Stream Power Index varies from -13.81 to 15.70. Five classes have been assigned to it (table 3), i.e., Class I (-13.81 to -08.14), Class II (-08.14 to -04.20), Class III (-04.20 to -01.88) Class IV (- 01.88 to 01.46) and Class V (01.46 to 15.70). A weight has been assigned to each class by how vulnerable it is to erosion. In this study, the highest weight has been assigned to regions with Stream Power Index between 01.46 and 15.70, whereas the lowest weight is assigned to regions with Stream Power Indexes between -13.81 and -08.14. Using these values, a map (fig. 4) was developed to illustrate the variability in SPI in the region. We can see the study areas of parts of the Gandak River basin have gentle slopes which show very low and negative values of SPI, which means these areas are flood-prone.

Table 3: Stream Power Index

Sr. No.	Value	Class	Potential Weight
1.	-13.81 to -8.14	I	1
2	-8.14 to -4.20	II	2
3.	-4.20 to -1.88	III	3
4.	-1.88 to 1.46	IV	4
5.	1.46 to 15.70	V	5

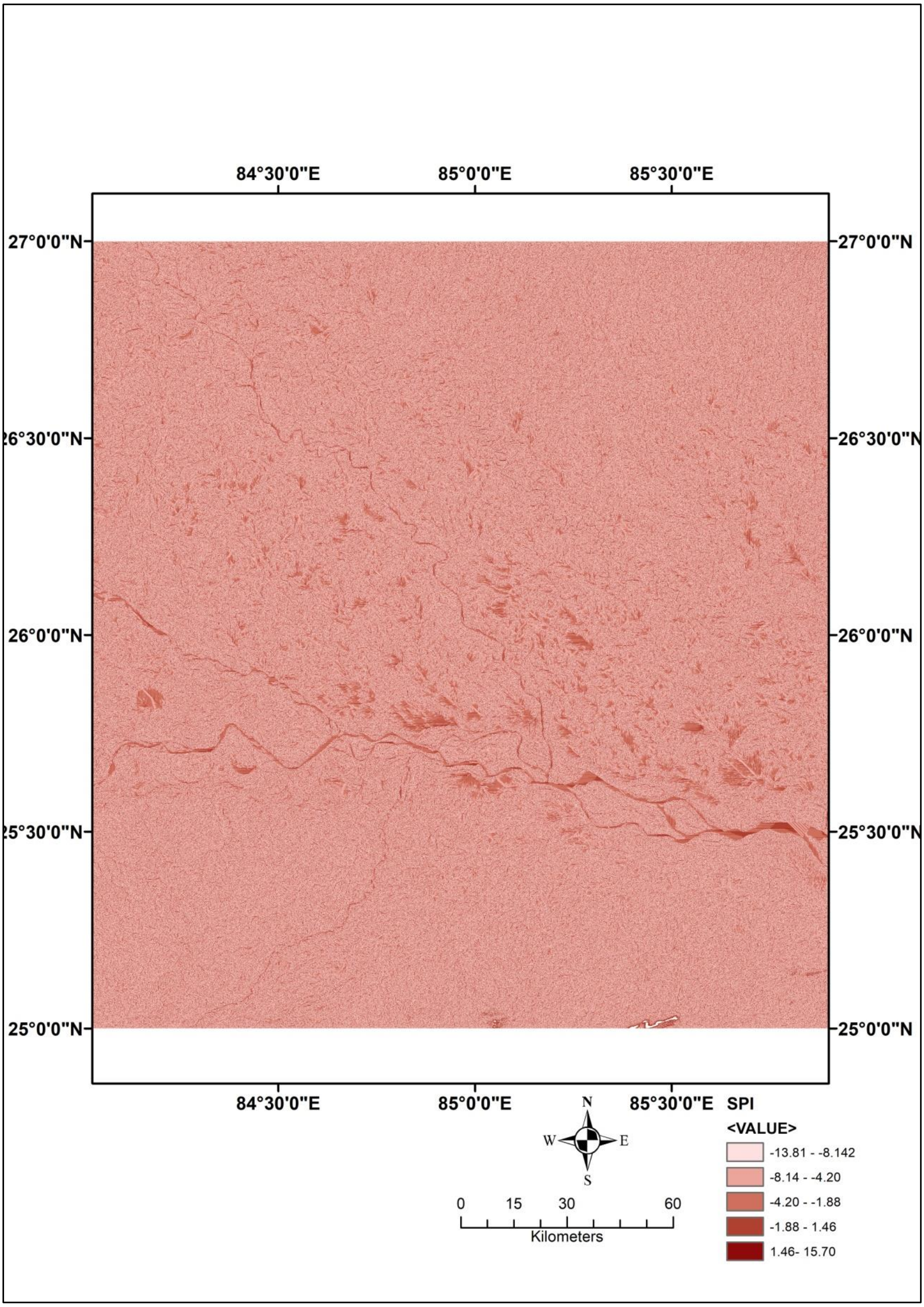


Figure 4: Map showing variation in Stream Power Index (SPI).

Sediment Transport Index: Using the Sediment Transport Index, we can calculate how sediment accumulates over time and transports from one place to another. We have used a geographic information system to calculate and analyse the Sediment Transport Index of the study area. The sediment Transport Index value ranges from 0 to 633.73. It has been reclassified into five classes (table 4), i.e. Class I (0 to 29.82), Class II (29.82 to 99.40), Class III (99.40 to 211.24), Class IV (211.24 to 402.60) and Class V (402.60 to 633.73). We have weighted each class per its vulnerability to soil erosion and degradation. A weight of 5 is assigned to regions with a

Sediment Transport Index ranging between 402.60 and 633.73, whereas a weight of 1 is assigned to regions with a Sediment Transport Index varying between 0 and 29.82. Using these values, a map (fig. 5) was prepared to show the variability in the Sediment Transport Index in the region. Overall, sediment depositional characteristics are predominant in the study area of the Gandak River basin of Bihar, particularly in flood-prone areas. Water flow in the river channel increases during the rainy season when there is heavy rainfall in the catchment area of the Gandak River, resulting in erosion along the banks of the river course.

Table 4: Sediment Transport Index

Sr. No.	Value	Class	Potential Weight
1.	0 to 29.82	I	1
2	29.82 to 99.40	II	2
3.	99.40 to 211.24	III	3
4.	211.24 to 402.60	IV	4
5.	402.60 to 633.73	V	5

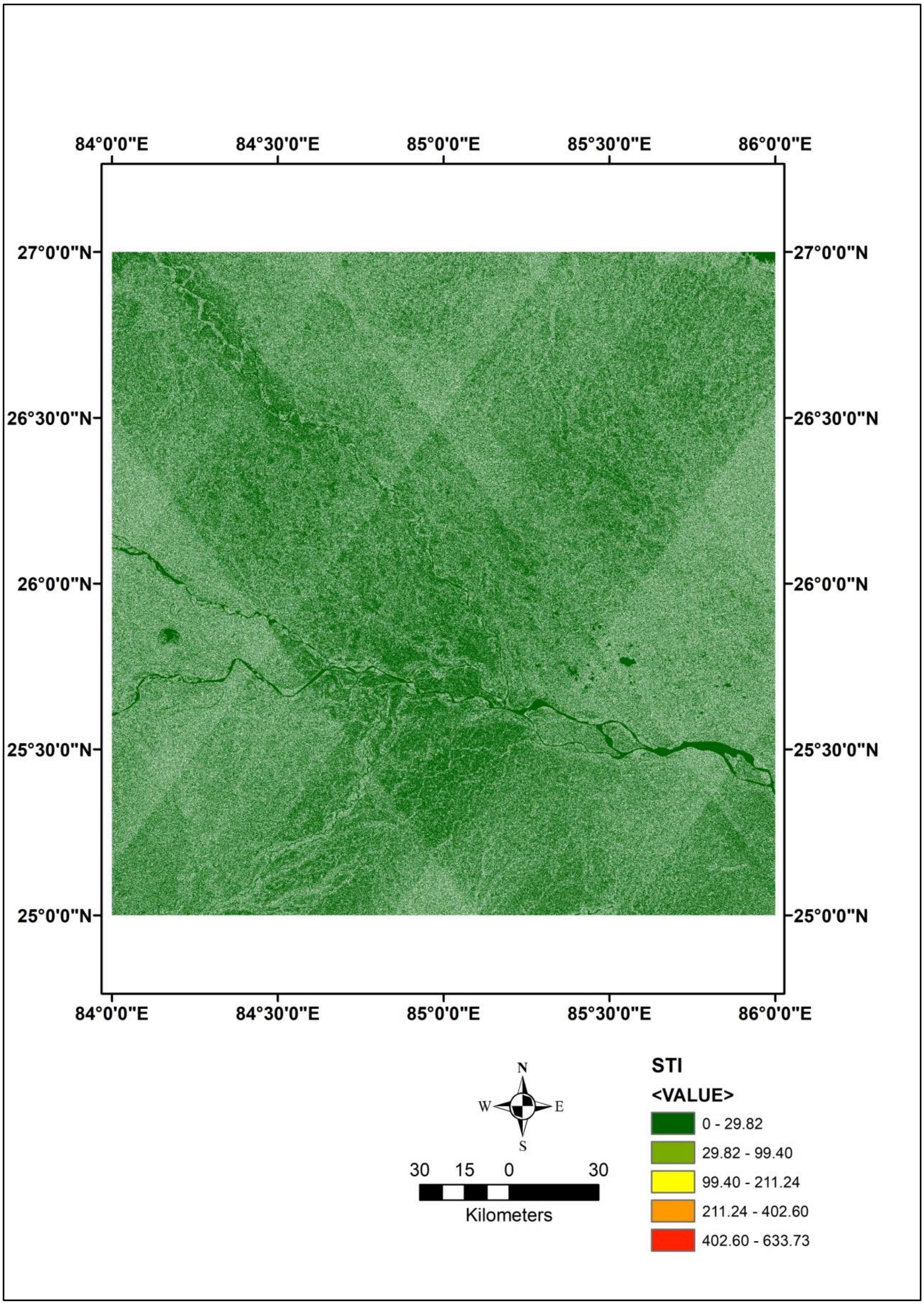


Figure 5: Map showing variation in Sediment Transport Index (STI).

Erosion Hazard Vulnerability: Based on the thematic maps of slope gradient, topographic wetness index, Stream power index, and sediment transport index, the Erosion Hazard Vulnerability Map (fig. 6) has been prepared. Map Algebra - Raster Calculator was used to generate this map. One can see erosion-vulnerable spots on the final output map. Based on the overlayed data, the Erosion Hazard Vulnerability map has been generated and classified into five classes (table 5); these are Class I (Very Low), Class II (Low), Class III (Moderate), Class IV (High) and Class V (Very High). Alluvium formations along the banks of the Gandak River are also moderate to highly vulnerable to erosion.

Table 5: Erosion Hazard Vulnerability Map

Sr. No.	Value	Class
1.	4 to 4.94	I (Very Low)
2	4.94 to 6.94	II (Low)
3.	6.94 to 8.95	III (Moderate)
4.	8.95 to 10.96	IV (High)
5.	10.96 to 20	V (Very High)

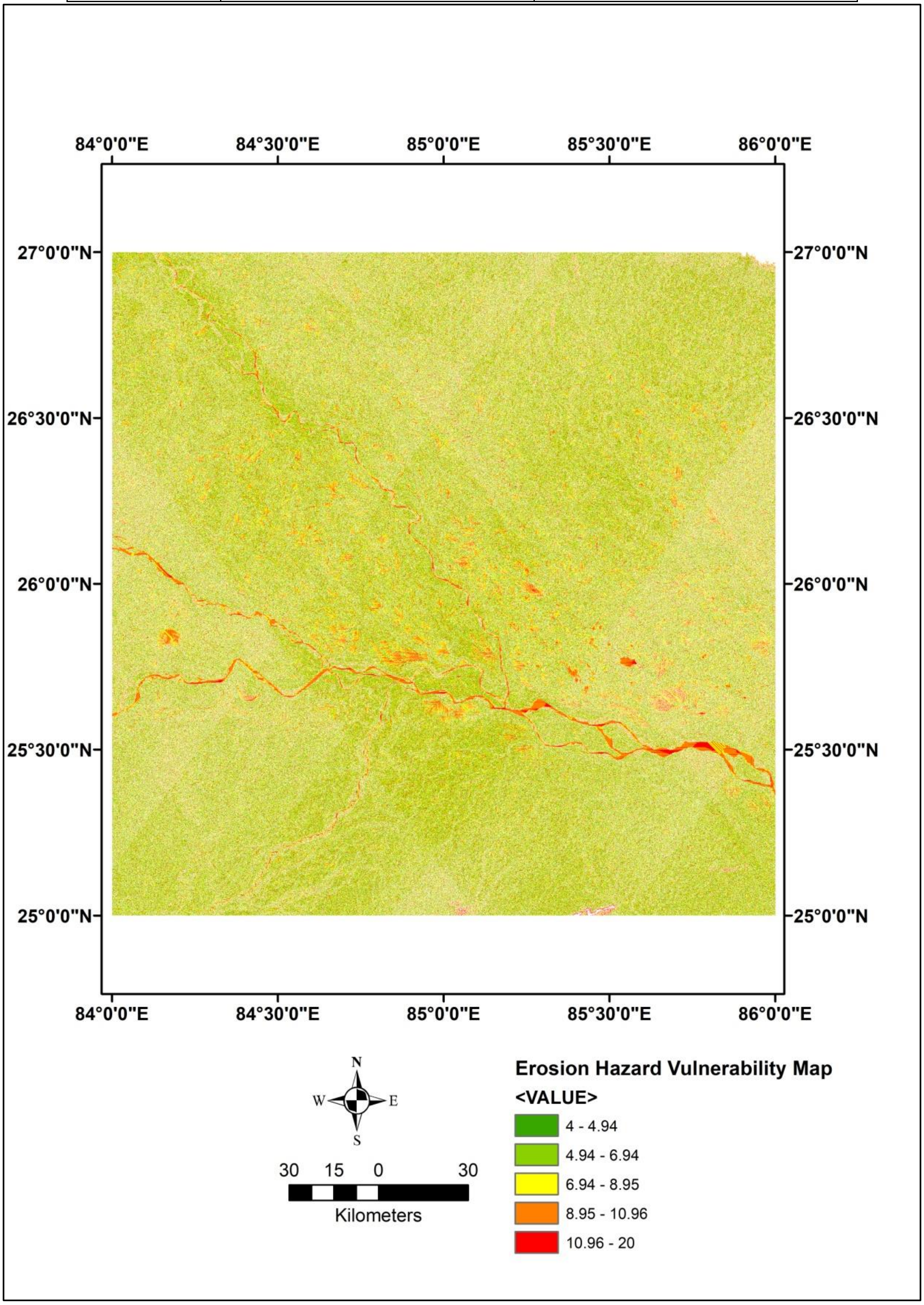


Figure 6: Erosion Hazard Vulnerability Map

Conclusion

Erosion is the most important hazard in the Gandak River Basin, Bihar. Erosion hazard vulnerable zones have been delineated using the GIS and Remote sensing methods. It has been found that areas along the banks of the rivers are more prone to erosion. In this study, it has been found that GIS tools are capable of extracting various hydrological parameters from Shuttle Radar Topography Mission (SRTM) Digital Terrain Elevation Data, such as slope, topographic wetness index, stream power index and sediment transport index. The slope gradient map, topographic wetness index map, stream power index map and sediment transportation index map have been generated and used to produce an erosion-hazard vulnerability map. These maps can be used to prepare ourselves for flood hazards and to manage natural resources.

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