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# Identification of Vulnerable Areas to Natural Hazards Along Rapti River System in U.P. (India) Using Satellite Remote Sensing Data and GIS

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## Abstract

This paper illustrates the case of Rapti river system in U.P. of India. The main purpose of this study is to identify the vulnerable areas to natural hazards by using multi-criteria model integrated with remote sensing and GIS is to provide more flexible and more accurate decisions to the decision makers. Based on this principle, the study aims to utilize space tools to extract physical data in a comprehensive approach as well as analyse and manipulate these datasets in GIS, thus determining the vulnerable areas to natural hazards. More specifically, the study aims to produce thematic maps for each type of existing natural hazards, among which geographic zones can be classified with respect to different risk levels. For this study, ten different criteria i.e. settlement, cultivated area, soil, geology, slope, erosional area, morphologically active river bankline reaches, embankments, spurs / studs, bridge, and barrages have been considered. The criteria for each of components were determined based on expert opinions and literature review. The result obtained from multi-criteria analysis has been classified in 5 categories i.e. very-highly sensitive, highly sensitive, highly-moderate sensitive, moderate sensitive, and not sensitive. Total 273 vulnerable areas to natural hazards have been identified, out of these vulnerable areas, total 98 vulnerable areas are very-highly sensitive, 69 vulnerable areas are highly sensitive, and 106 vulnerable areas are highly-moderate sensitive. Out of 98 very-highly sensitive vulnerable areas to natural hazards, we have visited 46 vulnerable areas to verify the vulnerability of the areas, and significant observations have been noted.

## Keywords

Vulnerable Areas, Natural Hazards, Remote Sensing, GIS, Rapti River

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## 1. Introduction

River floods represent the most frequent and expensive natural disaster affecting most of the countries around the world (Zwenzner et al., 2008) [1]. Natural hazards have become the foremost geo-environmental issue in many regions worldwide, since rarely a year goes by without any catastrophic event that harms both urban structure and human life (Guha-Sapir et al., 2011) [2]. Identification of vulnerable areas through remote sensing and GIS gives the precise location of sites where people, the natural environment or property are at risk due to a potentially catastrophic event that could result in death, injury, pollution or other destruction (Edwards et al., 2007) [3]. The identification of vulnerable people and places is key to enabling local communities to assess their vulnerability to natural disasters, improve their emergency management, and mitigate losses when a natural disaster occurs (Yoon, 2012) [4]. In the fields of geography and geo-hazard, a vulnerability index has been developed by combining

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vulnerability indicators to identify areas having a high vulnerability to natural disasters (Uitto, 1998) [5]. Multi-criteria models have been applied in several studies by decision makers is related geographically (Malczewski, 1999) [6], GIS may provide more and better information about decision making situations. GIS allows the decision maker to identify a list of data a pre-defined set of criteria with the overlay process (Heywood et al., 1993) [7].

The main objective of this study is to identify the vulnerable area to natural hazards in Rapti river system of Uttar Pradesh by using Multi-criteria model integrated with remote sensing and GIS data. To identification of vulnerable areas to natural hazards, we have been generated ten spatial criteria i.e. settlement, cultivated area, soil, geology, slope, erosional area, morphologically active river bankline reaches, embankments, spurs / studs, bridge, and barrages with 51 GIS data layers using ArcGIS 10.5 software and stored in geodatabase. Rank, and weightage scheme was used to scoring every criterion under consideration in the order of the decision maker's preference. Each criterion has a specific numeric value, which is represented the high to low vulnerability to natural hazards. Multi-criteria model has been developed to identify the vulnerable area to natural hazards. The result obtained from this study has been verified through field assessment survey at 46 vulnerable areas.

## 2. About the Study Area

Rapti river system extends from 26°18'00'' to 28°33'06'' North and 81°33'00'' to 83°45'06'' East covering an area of 15,153 $km^2$ are in India. Uttar Pradesh is the most densely populated state, because of the availability of water through the network of many rivers and tributaries. Majority of the population lives along the banks of rivers. The Rapti river and its 17 major tributaries (i.e. Ami river, Rohin river, Sera river, Burhi Rapti river, Chandan river, Gurra river, Ghonghi river, Kondara river, Ph Ghonghi river, Bahela river, Ban Ganga river, Payas river, Jamuaar nala[1], Mahwa nala[1], Pharend nala[1], Bathwa nala[1], and Teler nala[1]) have been selected for this study with 2 kilometres both side buffer. The location map of the study area is shown in the Figure 1. During monsoon season from June to September, Rapti river system transforms into a huge river, sometime endangering agriculture and people. Uttar Pradesh is the fourth Indian state to be affected by major flooding after Assam, Bihar and West Bengal in the same month (Daves, 2018) [8].

1 Nala means a stream in local parlance.

## 3. Data Used, Sources and Methodology

In this study, various basic thematic layers were created from different source including map, field study, satellite imageries and secondary data. Using ArcGIS 10.5 software tools, several maps were prepared including slope, soil, land use / land cover - settlement cultivated area, geology, erosional area, morphologically active river bankline reaches, river infrastructure - embankments, spurs / studs, bridge, and barrages. Data used, sources and methodology are shown in Table 1.

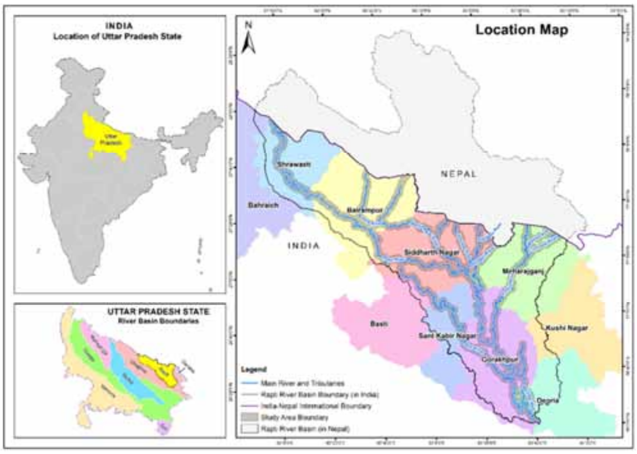


**Figure 1.** Location Map of Rapti River System.

## 4. Data Analysis and Mapping

### 4.1. Topographic Data

Topographic data is required for the demarcation of basin boundary, identification of the river network, stream ordering, and assessment of the basin characteristics such as slopes, reliefs, aspects, and others metamorphic parameters (Pareta et al., 2003) [9]. DEM is digital representations of the topography or landscape of an area (Pareta et al., 2014) [10]. The topography gives a panoramic view of the morphology of the area. Slope map has been created using Spatial Analyst Extension in ArcGIS 10.5, and Shuttle Radar Topography Mission (SRTM), DEM data with 30m spatial resolution [11]. Slope map of the study area is shown in Figure 2A and 2B.

### 4.2. Land Use Land Cover Mapping

The land use pattern of any locality reflects the complex physical processes that acting on the Earth's surface. These processes include the influence of climatic, geological, and topographic conditions on the distribution of soil, vegetation, and the occurrence of water. Moderate resolution satellite imagery i.e. Landsat-8 OLI and PAN sharpened satellite imagery with 15m spatial resolution from U.S. Geological

Survey (USGS), Earth Explorer [12] has been used for Land use and land cover with settlement and cultivated area data extraction. There are two methods to classify satellite image exists: digital classification (supervised / unsupervised) and manual classification (visual interpretation). The first method applies clustering algorithms using spectral, textural or contextual measures to perform classification with some (supervised) or no (unsupervised) human intervention. Visual interpretation needs human interpretation to identify and classify the image into objects. Land use and land cover mapping has been done by on-screen digitization. Land use land cover map 2019 of the study area is shown in Figure 2C.

**Table 1.** Data Used, Sources and Methodology.

| S. No. | Data layer / maps | Data sources and methodology |
|---|---|---|
| 1. | Survey of India Topographic Map at 1: 50,000 Scale | Survey of India Toposheets, 2005. http://www.soinakshe.uk.gov.in/ Toposheet No.: 63E / 10, 14; 63I / 02, 03, 07, 08, 11, 12, 16; 63J / 09, 13, 14; 63M / 08, 12; 63N / 01, 02, 03, 05, 06, 07, 09, 10, 11, 14, and 15 |
| 2. | Satellite Remote Sensing Data | Pre-Monsoon satellite remote sensing data (30m) from 1998 to 2018 have been downloaded from U.S. Geological Survey (USGS). Landsat-5 TM: 1998, 2004, 2006, 2007, 2008, 2009, 2010, 2010 Landsat-7 ETM$^+$: 2001, 2012 Landsat-8 OLI: 2013, 2014, 2015, 2016, 2017, 2018 Landsat-8 OLI and PAN sharpened satellite imagery with 15m spatial resolution. U.S. Geological Survey (USGS), Earth Explorer. http://earthexplorer.usgs.gov Acquisition Date: 16$^{th}$ April 2019. |
| 3. | Elevation Data | Shuttle Radar Topography Mission (SRTM), DEM data with 30m spatial resolution. NASA, & USGS EROS Data Centre. http://glcfapp.glcf.umd.edu:8080/esdi Acquisition Date: 02$^{nd}$ December 2007. |
| 4. | Land Use / Land Cover Map - 2019 | Land use and land cover map with settlement and cultivated area have been prepared by using Landsat-8 OLI and PAN sharpened satellite imagery with 15m spatial resolution and has been verify through limited field check. |
| 5. | Soil Map | District wise soil maps have been collected from National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) and updated through Landsat-8 OLI and PAN sharpened satellite imagery and has been verify through limited field check. |
| 6. | Geological Map | Geological quadrangle maps have been downloaded from Geological Survey of India (GSI) website and updated through Landsat-8 OLI and PAN sharpened satellite imagery, and Survey of India (SoI) Toposheets at 1: 50,000 scale with limited field check. http://www.portal.gsi.gov.in |
| 7. | Slope Map | Slope map has been created using Spatial Analyst Extension in ArcGIS 10.5, and SRTM DEM data with 30m spatial resolution. |
| 8. | Morphologically Active River Bankline Reaches | River bankline of Rapti river and its 17 major tributaries have been digitized in ArcGIS 10.5 software from 1998 to 2019. All banklines have been superimposed in one window to find the morphologically active river bankline reaches. |
| 9. | River Infrastructure | Riverine infrastructure data such as locations and physical attributes of bridges, embanakments, spurs and studs have been digitized on GoogleEarth© satellite imagery. Acquisition Date: 15$^{th}$ March 2019. |
| 10. | Barrage Details | The details of Rapti and Banganga barrages have been taken from CWC WRIS system. |

## 4.3. Soil Mapping

District wise soil maps of Rapti river system have been collected from the National Bureau of Soil Survey & Land Use Planning (NBSS&LUP), National Soil Survey. The soil maps have been geometrically registered to the base data to match Landsat-8 OLI satellite imageries. The geo-referenced soil maps have been used to assist in visual classification of satellite imagery for obtaining soil categories. The Geological Survey of India (GSI) maps, Survey of India (SoI) toposheets (1:50,000) [13], Landsat-8 OLI satellite imageries, and SRTM DEM data have been used for updating the soil categories (Pareta et al., 2012[a]) [14]. The final vector data layers have been stored in a geodatabase. The soil categories have been classified according to Indian Council of Agricultural Research (ICAR) soil group. Soil texture classes of Rapti River system are shown in Table 2 and map is shown in Figure 2D.

**Table 2.** Soil Textural Classes in Rapti River System.

| S. No. | ICAR Soil Group | Soil Textural Classes |
|---|---|---|
| 1. | Younger Alluvial Soils | Clay, Loamy Clay, Sandy Clay, Silt Clay |
| 2. | Younger Alluvial Soils | Loam, Silt Loam, Silt, Sandy Loam |
| 3. | Younger Alluvial Soils | Loamy Sand, Sand |
| 4. | Saline and Saline Alkali Soils | Clay, Loamy Clay, Sandy Clay, Silt Clay |
| 5. | Tarai Soils | Clay, Loamy Clay, Sandy Clay, Silt Clay |
| 6. | Tarai Soils | Loam, Silt Loam, Silt, Sandy Loam |
| 7. | Tarai Soils | Loamy Sand, Sand |
| 8. | Older Alluvial Soils | Clay, Loamy Clay, Sandy Clay, Silt Clay |
| 9. | Older Alluvial Soils | Loamy Sand, Sand |
| 10. | Older Alluvial Soils | Loam, Silt Loam, Silt, Sandy Loam |

## 4.4. Geological Mapping

River flow directions and river drainage systems pattern are not necessarily permanent features of the basin landscape. Geological changes can cause the river to flow in a different direction and become a tributary of a different drainage system. The geology of the basin plays an important role in the long-term morphological process. Published geological maps from Geological Survey of India (GSI) have been used for the preparation of a geological map of Rapti river system. This geological map has been updating through the satellite remote sensing data i.e. Landsat-8 OLI and PAN sharpened satellite imagery (15m) and SRTM DEM data (30m) by using ArcGIS-10.5 software along with limited field check (Pareta et al., 2012[c]) [15] Other ancillary data like Survey of India (SoI) topographical map at 1:50,000 scales has also used (Figure 2E).

Various geologists have contributed to diverse geological aspects of the study area. Notable among these are: Murthy and Mukhopadhyay (1967) [16]; Pandey and Bisaria (1986-87) [17]; Prasad et al., (1989) [18]; Jain and Sinha, (2003) [19]; and others etc. They have recorded the principal rock formations as described in Table 3.

**Table 3.** Litho-stratigraphic Succession of Rapti River System.

| Map Symbol | Lithology | Formation | Group | Geological Age | |
|---|---|---|---|---|---|
| $Q_2$fc | Active Flood Plain of Rapti: Grey coarse sand together with cobbles and pebbles of Quartzite, basic rocks and chert in Rapti | Channel Alluvium = Diara Formation | Newer Alluvium | Holocene | Quaternary |
| $Q_2$ft | Old Flood Plain: Grey, fine to medium grained micaceous sand, silt and clay | Terrace Alluvium | | | |
| $Q_1$fo | Older Alluvial Plain: Rudaceous facies comprising angular to sub rounded boulders, pebbles, cobbles, grits and clasts of quartzites; Poly cyclic sequence of grey, fine to coarse micaceous sand, silt and clay with kankar | Varanasi Older Alluvium = Gobardhan Formation | Older Alluvium | Middle to Upper Pleistocene | |
| $Q_1$fos | Isolated Sand Mounds: Poly cyclic sequence of grey, fine to coarse micaceous sand, silt and clay with kankar | | | | |
| $Q_1$fo ($F_1$) | Piedmont Plain | | | | |
| $Q_1$fo ($F_1$) P | Pediment | | | | |
| $Q_1$fo (Te) | Erosional Terrace | | | | |

Source: Geological Survey of India, First Edition. 1974 [20].

## 4.5. River Infrastructural Data

River infrastructures such as bridges, embankment, spurs, studs and barrages represent obstructions to channel and floodplain flows, which can be a source of substantial energy loss. Embankments and spurs / studs prevent river flow from spreading in the floodplain. The infrastructure is critical for the understanding of the morphological features of the river as they may be the primary cause for the changes in river course, fluvial conditions, and loop formations. Furthermore, the geomorphology of the river affects these infrastructures directly. Locations of these flood management assets can therefore be used as initial points for the identification of the vulnerable reaches. Riverine infrastructure data such as bridges, embankments, spurs and studs have been digitized on 2019 GoogleEarth satellite imagery. The river infrastructure map of the study area is shown in Figure 2F.

## 4.6. Morphologically Active River Bankline Reaches

Due to large variation of flows, the alluvial rivers such as Rapti river and its 17 tributaries have a large variation in their behaviour during the lean season and the flood season. In flood season, the deep channels swing laterally and erode the banks posing threat of serious damage to valuable property, urban and rural settlement, electric and communication lines, and cultivated area, etc. Multi-temporal satellite remote sensing data i.e. pre-monsoon Landsat satellite imageries of years 1998, 2001, 2004, 2006 to 2019 have been downloaded from U.S. Geological Survey (USGS), and the same have been digitized. Both banklines have been digitized for Rapti river system and its 17 major tributaries. These all banklines have been superimposed in one window to find the morphologically active river bankline reaches. We have identified approx. 105 morphologically active river bankline reaches in Rapti river system. The morphologically active river bankline reaches is shown in Figure 2G.

## 4.7. Demarcation of Erosional Areas

The erosion plays an important role in the changing environment of the river. It affects water flow, water quality, channel width / river depth and safe use of a river as a transportation corridor (Pareta et al., 2015) [21]. Generally, river bank erosion or deposition is a mechanism of sediment (bank material) transportation by a river that affects the river channel courses (Biswajit et al., 2013) [22]. The morphology and behavior of Rapti river undergo drastic changes in response to various flow regime. The erosion and flood are a common phenomenon in Rapti river, but it becomes a matter of serious concern when it takes the form of disaster. The study area also suffers from devastating flood. But the situation in the area is graver due to severe erosion along bankline with flood. During the monsoon season, enormous amount of water and sediments comes from the rivers coming from hills and the entire channel area becomes full of water. Due to this it affects the stability of the channels and the bankline.

River banklines digitized data from 2006 to 2019 have been used for this analysis. The two resultant shapefiles were superimposed in-order-to demarcate union wise erosional areas. The total area of erosion from all the unions were calculate by using ArcGIS 10.5 software. The erosional area from 2006 to 2007, 2007 to 2008, 2008 to 2009,…… 2018 to 2019 have been demarcated. The common erosional area from 2006 to 2019 has been extracted using GIS analysis (Figure 2H), which has been used for identification of vulnerable area to natural hazards.

# 5. Results and Discussions

## 5.1. Criteria for Identification of Vulnerable Areas to Natural Hazards

A variety of methods can be used to integrate the different criteria into a tool for identification of vulnerable areas to natural hazards. For this study, we have used the multi-criteria model integrated with remote sensing and GIS data. The vulnerable areas examination to natural hazard mapping study involve preparation of number of thematic databases such as land use / land cover - (i) settlement & (ii) cultivated area, (iii) soil, (iv) geology, (v) slope, (vi) erosional area, (vii) morphologically active river bankline reaches, river infrastructure - (viii) embankments, spurs / studs (ix) bridges, and (x) barrages of the area (Pareta et al., 2012[b]) [23]. The digitized maps are given as input into the ArcGIS 10.5 software tool. The vulnerable areas to natural hazard map have an important role in planning, development schemes, river basin managements. This map is useful for identification of unstable zones / vulnerable areas to natural hazards in the plain regions like Rapti river system in India.

## 5.2. Methodology for Identification of Vulnerable Areas to Natural Hazards

The methodology for locating the vulnerable areas to natural hazards is based on multi-criteria model integrated with remote sensing and GIS. For this, we have examined several individual criteria, assigning them relative levels of importance, and using a mathematical resultant model to identify the most vulnerable areas to natural hazards. By adopting this method, it is possible to systematically identify the criteria considered, clearly document the relative importance of one criterion over another, analyse the net outcome using a GIS, and then possibly revisit the mathematical relationships in this decision model. By revising the relative importance to identified criteria based upon the specific thematic databases under consideration, it is possible to generate the vulnerable areas map to natural hazards.

To achieve this, all the criteria are assigned a "rank" denoting their relative levels of importance within the vulnerability study. These ranks are assigned as numeric values ranging from 1 to 10, with 1 reflecting a low level of vulnerability and 10 reflecting a high level of vulnerability. For example, within the criteria of embankments, spurs / studs would have a different level of influence on the vulnerability, as compared with other river training structures. Further, the distance from each of these features would further modify the relative vulnerability based on the proximity to a specific river training structure. To properly include this geographic inconsistency across the vulnerability extents, a similar scale of 1 to 10 is used to assign individual "weights" based on the proximal relationship to each specific feature type within a specific criterion used in the decision model. Collectively, the weights, multiplied by the rank, provide a vulnerability score that cumulatively is used to identify the most vulnerable areas to natural hazards. The details of ranks and weights for criteria and their proximity analysis are presented in Table 4.

**Table 4.** Vulnerability Score for Identification of Vulnerable Areas to Natural Hazards.

| Criteria | Proximity Analysis | Rank ($R_i$) | Weights ($W_i$) | Score ($S_i$) | Remarks |
|---|---|---|---|---|---|
| *Active Channel Near to* Settlement ($S_{ET}$) | $S_{ET}$+0 m to100 m | 10 | 10 | 100 | Settlements and nearby area are highly prone to vulnerability due to loss of property, people, natural, economic, and social environment. So, for proximity analysis the high numeric numbers are assigned to settlements and nearby area. |
| | 100m to 200 m | | 9 | 90 | |
| | 200m to 300 m | | 7 | 70 | |
| | 300 m to 400 m | | 5 | 50 | |
| | 400 m to 500 m | | 3 | 30 | |
| *Active Channel Near to* Embankments, and Spurs / Studs ($E_{SS}$) | $E_{SS}$+0 m to100 m | 9 | 9 | 81 | An embankment is an artificial barrier / ridge that typically is used to hold back water, flood control and to prevent water from passing beyond desirable limits. Embankment is also protecting the settlement as well as highly valuable assets. Area nearby the embankment is highly prone, because if, embankment will breach, it will affect the settlement and assets. |
| | 100m to 200 m | | 8 | 72 | |
| | 200m to 300 m | | 6 | 54 | |
| | 300 m to 400 m | | 5 | 45 | |
| | 400 m to 500 m | | 2 | 18 | |
| Morphologically Active River Bankline Reaches ($M_{AR}$) | $M_{AR}$+0 m to100 m | 8 | 10 | 80 | Rapti river system are dynamic and continuously change their position, shape, and other characteristics with variations in discharge and time. So, morphologically active river bankline reaches are highly prone to vulnerability. |
| | 100m to 200 m | | 7 | 56 | |
| | 200m to 300 m | | 5 | 40 | |
| | 300 m to 400 m | | 3 | 24 | |
| | 400 m to 500 m | | 1 | 8 | |

| Criteria | Proximity Analysis | Rank ($R_i$) | Weights ($W_i$) | Score ($S_i$) | Remarks |
|---|---|---|---|---|---|
| Erosional Area ($E_{RA}$) | $E_{RA}$+0 m to100 m | 7 | 10 | 70 | Common erosional area over the years (2006 to 2019) along the both river bankline i.e. left river and right river bankline is also highly prone to vulnerability, because these river portions are not stable due to highly erodible bank material, variability of cohesive soil in bank material composition, and slope. |
| | 100m to 200 m | | 8 | 56 | |
| | 200m to 300 m | | 7 | 49 | |
| | 300 m to 400 m | | 3 | 21 | |
| | 400 m to 500 m | | 2 | 14 | |
| *Active Channel Near to Abutment* Bridges ($B_{RD}$) | $B_{RD}$+0 m to100 m | 6 | 8 | 48 | Bridges are usually used for transportation. The area nearby the bridge is highly prone to vulnerability. We have assigned higher numeric number near to the bridge, and lower number beyond the bridge. |
| | 100m to 200 m | | 7 | 42 | |
| | 200m to 300 m | | 5 | 30 | |
| | 300 m to 400 m | | 3 | 18 | |
| | 400 m to 500 m | | 1 | 6 | |
| *Active Channel Near to Affluxes Embankment* Barrages ($B_{RG}$) | $B_{RG}$+0 m to100 m | 5 | 7 | 35 | The barrage consists of a row of large gates that can be opened or closed to control the amount of water passing through the dam. Rapti barrage and Ban-Ganga barrage are situated in Rapti river system, which are highly prone to vulnerability. |
| | 100m to 200 m | | 6 | 30 | |
| | 200m to 300 m | | 4 | 20 | |
| | 300 m to 400 m | | 2 | 10 | |
| | 400 m to 500 m | | 1 | 5 | |
| *Active Channel Near to* Cultivated Area ($C_{UL}$) | $C_{UL}$+0 m to100 m | 4 | 8 | 32 | Cultivated area is also highly valuable resources. So, for proximity analysis the high numeric numbers are assigned to cultivated land and nearby area. |
| | 100m to 200 m | | 7 | 28 | |
| | 200m to 300 m | | 5 | 20 | |
| | 300 m to 400 m | | 3 | 12 | |
| | 400 m to 500 m | | 1 | 4 | |
| Slope ($S_{LP}$) | > 5° | 3 | 1 | 3 | Steeper slopes (<25°) are highly prone to vulnerability, but the slope below 10$^{o}$ has low vulnerability to the absence of debris over the slope surface. |
| | 5° - 10° | | 2 | 6 | |
| | 10° - 15° | | 5 | 15 | |
| | 15° - 20° | | 7 | 21 | |
| | 20° - 25° | | 9 | 27 | |
| | < 25° | | 10 | 30 | |
| Soil ($S_{OL}$) | Clay | 2 | 2 | 4 | Sandy soil is highly prone to vulnerability due to lose material, more porosity, and highly erosional properties, but clay soil has had the low vulnerability because of compact material. |
| | Silt Loam | | 6 | 12 | |
| | Sand | | 10 | 20 | |
| Geology ($G_{EO}$) | Active Flood Plain | 1 | 7 | 7 | Active flood plain, old flood plain, and older alluvial plain are highly prone to vulnerability due to lose material and has been assigned the high numeric numbers for proximity analysis. |
| | Old Flood Plain | | 6 | 6 | |
| | Older Alluvial Plain | | 5 | 5 | |
| | Erosional Terrace | | 4 | 4 | |
| | Piedmont Plain | | 3 | 3 | |
| | Isolated Sand Mounds | | 2 | 2 | |
| | Piedmont | | 1 | 1 | |

The multi-criteria model has been created and the ranks and weights are assigned to each category. The detail of the model is given below.

$$VA_{NH} = S_{ET} + E_{SS} + M_{AR} + E_{RA} + B_{RD} + B_{RG} + C_{UL} + S_{LP} + S_{OL} + G_{EO}$$

Where, $VA_{NH}$ = Sum of ratings of all causative criteria, $S_{ET}$ = Active channel near to settlement, $E_{SS}$ = Active channel near to embankments, and spurs / studs, $M_{AR}$ = Morphologically active river bankline reaches, $E_{RA}$ = Erosional area, $B_{RD}$ = Active channel near to abutment, bridges, $B_{RG}$ = Active channel near to affluxes embankment, barrages, $C_{UL}$ = Active channel near to cultivated area, $S_{LP}$ = Slope, $S_{OL}$ = Soil, $G_{EO}$ = Geology.

After collecting related data from the available sources described earlier, initial data maps were re-classed according to the score given in Table 5. Based on $VA_{NH}$ value, vulnerable areas map to natural hazards was classified in five categories and shown in Table 5, and Figure 3.

**Table 5.** Score wise Classification Scheme for Vulnerable Areas to Natural Hazards.

| S. No. | Vulnerability Classes | Total Score wise Classification Scheme |
|---|---|---|
| 1 | Very-highly sensitive | More than 300 |
| 2 | Highly sensitive | 200 to 300 |
| 3 | Highly-moderate sensitive | 150 to 200 |
| 4 | Moderate sensitive | 100 to 150 |
| 5 | Not sensitive | Less than 100 |

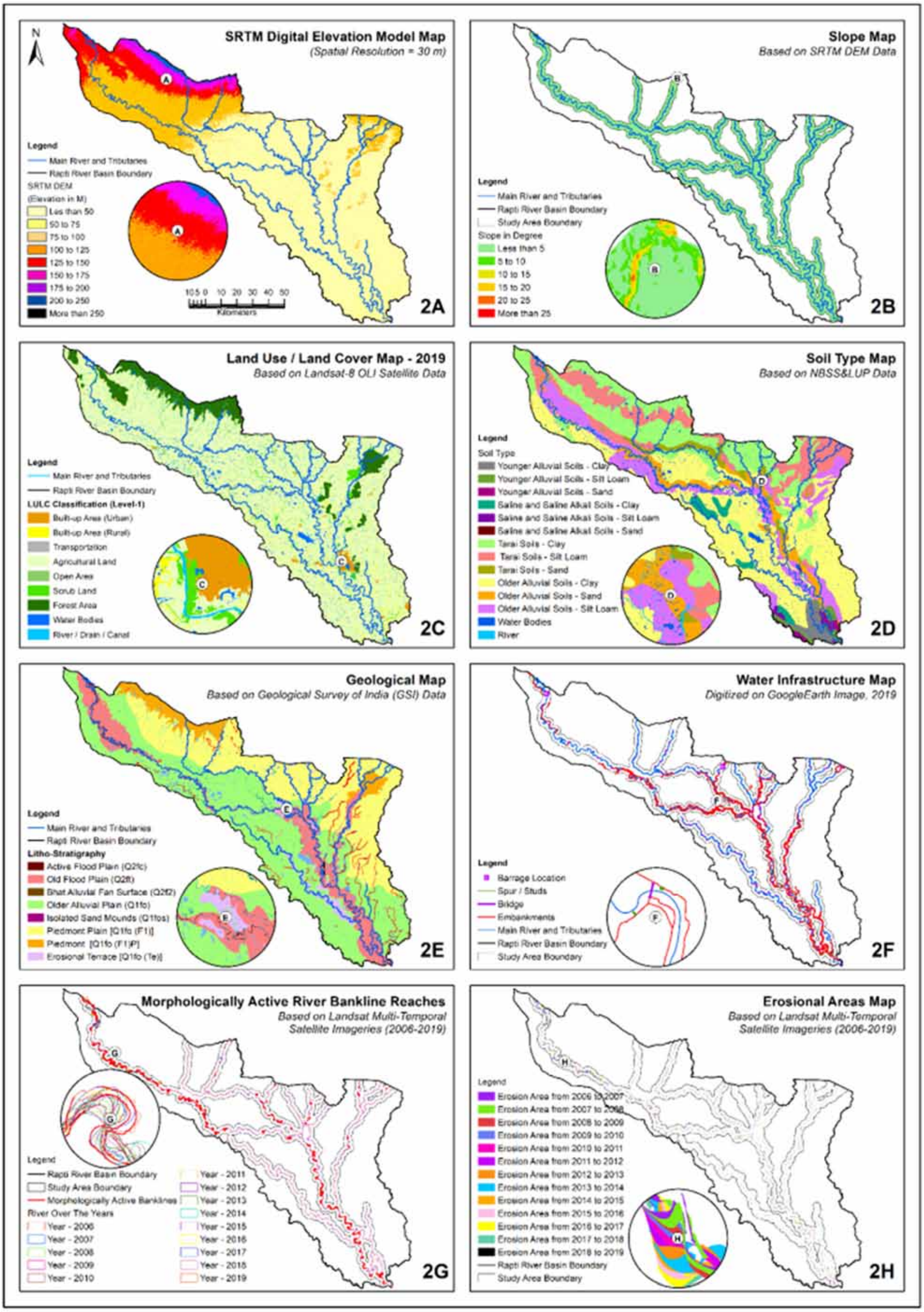


**Figure 2.** Various Thematic Maps of Rapti River System.

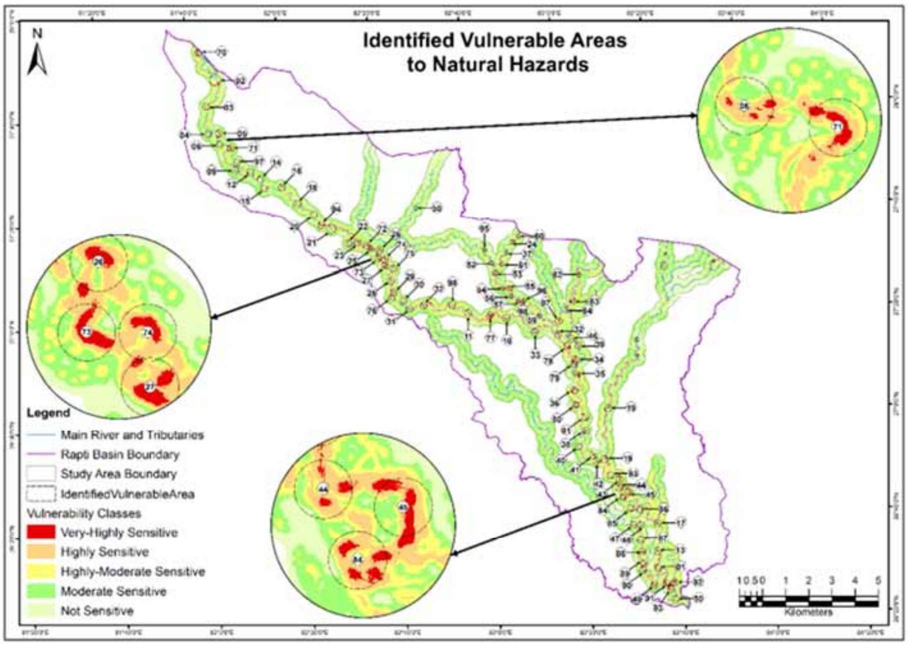


**Figure 3.** Identified Vulnerable Areas to Natural Hazards.

## 5.3. Field Assessment of Identified Vulnerable Areas

Based on this study, we have identified 273 number of vulnerable areas to natural hazards, out of these vulnerable areas, total 98 vulnerable areas are very-highly sensitive, 69 vulnerable areas are highly sensitive, and 106 vulnerable areas are highly-moderate sensitive, most of very-highly sensitive areas have been verified through the field visited. Out of 98 very-highly sensitive vulnerable areas to natural hazards, we have visited 46 vulnerable areas to verify the vulnerability of the areas. Significant observations of these areas are listed in Table 6.

**Table 6.** Field Assessment Observations of the Vulnerable Areas.

| S. No. | Photographs | Significant Observations of Vulnerable Areas |
|---|---|---|
| 1. |  | Laxmanpur Kothi (02): Located 1 to 1.5 km upstream of Rapti Barrage. An embankment is under construction from Rapti Barrage to the locality. It is suggested that the embankment is extended further north to stop erosion of left bank to the east. The eroding cliff has an undercut profile comprising of crumbly earth in the top 0.5m and silty loam below that is prone to erosion. |
| 2. |  | Majahgawan (05): Actively eroding left bank shifting towards embanked lane. There are some gaps in the set-back embankment, which need to be filled. High erosion rates identified from satellite imaging were confirmed by field observations and in discussions with villagers. Undercut profile and river bank slumping was observed due to sandy loam as the predominant bank material. |
| 3. |  | Andhra Purwa (12): There is heavy bank erosion at the meander bend, downstream of Ekona Bridge. Land cover is scrub land and shrubs within 100m of the bank line; land use is agriculture. No structures present and no evidence of recent management on eroding left bank. Construction of an embankment on the left bank is required. |
| 4. |  | Gosainpur (18): Considerable erosion was observed on the right bank upstream of Kondhri Ghat Bridge and a stud structure is required together with an embankment to be prepared downstream of the bridge. Deposition of sandy sediment was observed on both banks, where the eroding bank is the right bank. Scattered rural settlement is found beyond 100m of the location. |
| 5. |  | Pipra Ghat (25): A major bridge is under construction immediately downstream of the location. The river is eroding on the right bank and towards the south east abutment and approach road. The site is becoming more vulnerable and regular monitoring is required. Considerable deposition was observed on the left bank. Set-back embankments were seen at both banks and a rural village was located on the left embankment. |
| 6. |  | Hadirgarh Village (26): Sensitive zone with erosion of the left bank extending up to the embankment and it is possible that the river will breach embankments during the high flood level in the monsoon period, which will pose risks to Ghoplapur and Naiasukhawa Villages. Eroding cliff is primarily composed of silty loam, which is prone to erosion. An oxbow lake was observed north of the site. |

| S. No. | Photographs | Significant Observations of Vulnerable Areas |
|---|---|---|
| 7. |  | Shawagunj (27): The eroding cliff is undercut, 4m in height and primarily composed of clay. Slumping of the river bank is observed and no structures are present to protect the bankline. River training works i.e. stud, spur, cutters are required to protect the embankment. A major bridge is located downstream that may be affected by river bank shifting in the upstream reach. |
| 8. |  | Baitnar (28): Higher erosion rates are occurring upstream of the embankment on the left bank towards the abadi area (village side). Slumping of recent deposits and unvegetated mid-channel bar was observed on the site. The one metre high left river bank has a vertical profile with toe composed of silty clay. |
| 9. |  | Bamdaye (29): Erosion on the left river bank is significant at the meander bend. The profile of the erosional cliff is vertical with toe, 4.5m in height comprising clay loam. A moderate sized village is located behind the embankment to the north of the location. It is suggested that the embankment is modified in height and extended further to the south, in addition to flood management structures to protect the bankline. |
| 10. |  | Veerpur Kohal (30): River erosion is very high towards the embankment side. Extensive erosion during the last monsoon is observed from satellite imaging, field observation and confirmed by villagers. Erosional cliff (left bank) is very susceptible to erosion - 5-6 metre height, undercut, slumping and predominant material is loamy sand. River training works are required to protect the bankline. |
| 11. |  | Pikaura Village (31): The most significant and vulnerable observation is the village located immediately on the left riverbank top, just upstream of the Shrirshiya Ghat Bridge. According to villagers, the water levels during the monsoon reach 0.8m from riverbank top and every year, flood water (approx. 1m) breaches into the village. A reinforcement of the riverbank is required to protect the nearby village and north-east abutment. |
| 12. |  | Mali Mainha (32): The river has shifted substantially towards the south embankment and erosion is more prominent between spur structures. The edge of the eroding cliff is now 50-100m from the set-back embankment, however the water level during high discharge overtops the right bank and reaches the embankment. According to a local villager, during high flood level, water has breached embankment and flowed into the village. |
| 13. |  | Bangarha Bugurg (33): Water levels during the monsoon period are up to the set- back embankment (30m from the right banktop) and it is possible to breach the embankment. Evidence of recent management was observed in the form of porcupines (damaged) and stud / spur structures (damaged). However, stud / spur structures need to be repaired. |
| 14. |  | Kahlauri (34): The distance between the river banktop and the set-back embankment is only 50m. Behind the embankment there is a village 450m away. Other observations include an unvegetated mid-channel bar, point bar and sparse forest on the right bank, boulder and earthen embankment in good condition and extensive agricultural land. |
| 15. |  | Koni Village (35): Sensitive zone along the embankment with high flood level, according to villagers, reaching 1.5-2m below embankment top. The embankment has recently been fortified with boulder pitching. A main road and small settlements are located behind the embankment. Other evidence of recent management includes bamboo crates with cement bags filled with bricks, rip-rap and cutters. |
| 16. |  | Vishunpur Kachar (36): The embankment is in good condition with boulder pitching, however regular monitoring is required. River training works observed include spur and stud structures (damaged and in need of repair), boulder pitching, bamboo crates, brick cutters and rip-rap. Regular monitoring of these flood management structures is required to assess future action plan. |
| 17. |  | Matiyara (37): The river is shifting to the west, towards set-back Sahajnva Dumariya embankment; right bank comprises predominantly of medium loam. Eroding cliff is 6m in height, has an undercut profile and natural (no structures within 100m). The set-back embankment (and rural village / main road along it) is 600m from eroding cliff. Major impact is loss of agricultural land. |
| 18. |  | Neerpur (38): A rural village, an overhead tank and a mobile tower are located within 200m of the embankment. Water level reaching embankment during monsoon, 1-2m below embankment top. The earthen embankment is in good condition with boulder pitching, however it is suggested that regular assessment is carried out. |
| 19. |  | Kuduri (39): A river bank failure (slumping) was observed and erosion is high on the right bank (sandy substrate). An embankment arm is almost washed-out. River training works i.e. stud, spur, cutters are required to protect the embankment. The distance between the river bank line and the embankment is only 75m. Major impact is foreseen on agriculture and the embankment in the near-future if no interventions are implemented. |
| 20. |  | Tikariya (40): River to the west and eroding the right bank towards the embankment. Composite erosional cliff comprising predominantly of sandy loam is located 100m from the embankment and 800m from a rural village/electricity pylon. Land within 100m of the channel is agriculture and scrubland and shrubs. |

| S. No. | Photographs | Significant Observations of Vulnerable Areas |
|---|---|---|
| 21. |  | Utrasot (41): Agricultural land and scattered rural settlement are located immediately behind the embankment. A road is under construction on the top of the embankment. Ten spur structures with boulder pitching are in good condition at the location. Erosion occurs between spur structures. Other river training works i.e. bamboo crates are required to protect the embankment. |
| 22. |  | Barhua (42): The right bank is eroding - sandstone boulder pitching on the slope of the embankment and rip-rap at the toe. The spur structures at this location have been shortened to stud structures to avoid impeding of the river. The water level during the monsoon reaches 2m below the embankment during high flood. A rural village located immediately adjacent to the embankment, as well as highway, electric sub-station. |
| 23. |  | Duhiya (43): River erosion occurs on the left bank towards the embankment on the East (5-10m between the active channel the embankment during non-monsoon). Rural settlements are located on the top of and behind the embankment. The embankment side facing the river is in poor condition. The eroding cliff on the left bank is primarily loamy sand. Major impacts on road, electricity pylon, govt. school and temple. |
| 24. |  | Badhara (44): The river has eroded the right bank up to the supports of the electricity pylon which is a vulnerable zone. The undercut profile (3-4m) of the right bank indicates high rates of erosion. Land is mostly agriculture and scrubland and shrubs with scattered rural settlements and trees. An un vegetated point bar is located on the left bank and litter was observed in the channel and on the banks. |
| 25. |  | Hathiya Praras (45): There are two sets of embankments at this location. Villagers have suggested that the height of embankment closest to the river should be increased. During the monsoon period, water has overtopped the embankment and flowed into the rural village. At this location, the embankment can be extended, and river training works for example stud, spur and cutters are required to protect the bankline. |
| 26. |  | Kushma (46): River is directly adjacent to the embankment along narrow active channel. Here, boulder pitching, and Rip-rap is observed but the stud structures are very damaged, beyond repair. At least one Spur structure is almost washed-out. Left bank is actively eroding further downstream. River training works i.e. stud, spur, cutters are required to protect the embankment and riverbank erosion. |
| 27. |  | Sohgaura (47): There is an oxbow lake to the north of the site and the Singhora Bridge, 500m downstream of site. During monsoon, water level is 2m below the top of the embankment. A rural village is located within 350m of the embankment. There are damaged stud structures further down right bank that need to be repaired. The composite eroding cliff is predominantly loamy sand. |
| 28. |  | Dumraila (48): The left river bank is eroding at a high rate and shifting from WSW to ENE towards the set-back embankment at Chhitarahi Thuni. The river bank is slumping to the north of the location, where the erosional cliff is taller, and the embankment is further away. River training works for example stud, spur and cutters are required to protect the embankment. A rural village is located 750m from the eroding cliff. |
| 29. |  | Majhawaliya (49): Upstream and downstream of this locality, right bank erosion is high, and the river is directly hitting the embankment. Here, similar river training works should be implemented to protect the embankment. Other observations are a 5.5m wide asphalt road in poor condition on the top of the embankment, an adjacent rural village with a school and much litter in the area. |
| 30. |  | Jagdeshpur (50): The river is shifting on the right bank from roughly north-east to south-west and south. There are no flood management structures or embankments. River training works for example bamboo crates, stud, cutters, and porcupines are urgently required to protect the nearby village. "Jagdeshpur" village is in the danger zone and may be washed-out in the next monsoon period. |
| 31. |  | Bahwarya (51): The village is very close to the vulnerable zone. Deposition occurs on the left bank and erosion towards the village in the West. There are no flood management structures or embankment. An embankment is required to protect the village. The distance between the bank line and the village is approximately 30 to 40m. |
| 32. |  | Badhouya (52): The river is hitting the embankment directly downstream of the locality adjacent to the rural village. Erosion is more predominant between the two spur structures. The river bank profile of the eroding cliff is under-cut with toe and slumping of bed material is common and comprises sandy clay loam. |
| 33. |  | Sonaulee Nankar (53): At this locality, a local drain has been cut into the right bank, where flood water during the monsoon season flows towards village. Downstream of this village, erosion is more predominant on the right bank. There are many spur / stud structures, geobags and porcupines at the location, but these are not enough to protect the bankline and the embankment, as shown by visible damage. |
| 34. |  | Udhana Tal (54): The river is directly eroding the stud / spur structures and towards the embankment i.e. riverbank shifting to the SSE. The damaged stud / spur structures need to be repaired. River training works for example bamboo crates, porcupines, and cutters are required to protect the embankment. The eroding cliff has a steep profile - 4m height, comprising loamy sand and rip-rap at toe. |

| S. No. | Photographs | Significant Observations of Vulnerable Areas |
|---|---|---|
| 35. |  | Mahuaari (55): Water levels during monsoon period are up to the embankment and the right bank is considered 'embanked'. The river is eroding on the right bank and depositing on the left bank. There are stud structures protected by geobags filled with earthen material, porcupines and spur structure at the location. Small rural settlement is situated adjacent to the embankment. |
| 36. |  | Narkathi (56): The condition of the embankment (3.5 m height) is poor and in need of repair. The river is directly hitting the embankment during monsoon. Other areas downstream and upstream are more prone to erosion and in the future, the embankment can be breached. More river training works for example stud, spur, and cutters are required to protect the embankment. |
| 37. |  | Badkee Dadeeya (57): Erosion is significant between spur structures and water level during monsoon is at embankment. A rural village is located on top of and immediately behind the embankment. The embankment height is approximately 4m. The actively eroding left bank is 5m in height (from active channel to bank top) and the soil type is classified as sandy loam. Rip-rap is observed at the toe of bank. |
| 38. |  | Kakrahi (58): Erosion is significant between spur structures on the right bank. The spur structures are damaged to very damaged at this location and need repair as soon as possible. A very sensitive and vulnerable zone - eroding cliff between spur structures is only 1 m from the embankment and has an under-cut river bank profile. This site is critical with significant erosion and damage to the flood management structures. |
| 39. |  | Puraina (59): Water level during high flood discharge overtops eroding cliff on the right bank and reaches the embankment (2m below embankment top), as told by villagers. There are no other flood management structures at the site. The under-cut eroding cliff is 10-15m in height and comprises loamy sand that is susceptible to high erosion rates. River training works for example stud, spur, and cutters are required to protect the embankment. |
| 40. |  | Bagulahawa (60): A major bridge is under construction and immediately upstream of locality a canal system is under development. A barrage is located around 2.5 km downstream of the location (along straight line). River training works for example cutters, boulder pitching, porcupines, and bamboo crates are required to protect the embankment. |
| 41. |  | Badhula (61): A rural village is located on the top of the embankment. The embankment has sandstone boulder pitching and is approximately 4.5m in height and 2m in width (local transport). Rip-rap was recorded at the edge of the eroding left bank. The left embankment has been breached and a village flooded during the monsoon season. The gap in the embankment is suggested to be filled before the next monsoon. |
| 42. |  | Tharwa (62): Sensitive zone - actively eroding cliff shifting towards the embankment and the village (60m NW) on the left bank. The set-back embankment is located within 100m of the eroding cliff, covering mango orchard. The eroding cliff is approximately 10m in height and has a vertical to steep profile comprising silty clay loam. |
| 43. |  | Maphi Mahauya (63): Very close to the busy asphalt road along the embankment within 20-25m. Damaged spur structures (3-4 width) on the left bank require repair. Steep and vegetated erosional cliff (height - 4 m) between the spur structures is prone to erosion, comprising silty clay loam. |
| 44. |  | Kataha Tola (64): During high flood level, water overtops the left river bank and erodes the embankment. The river is eroding the right bank immediately upstream of the location and is shifting roughly NE to SW. There are damaged brick and boulder cutters in the area in need of repair. The composite eroding cliff comprises silty clay loam. Regular monitoring of this critical vulnerable site is advised. |
| 45. |  | Jalalgarh (68): The right bank is actively eroding and shifting from East to West towards the embankment. The composite eroding cliff comprises sandy clay and no flood structure or recent management was observed. The set-back embankment is located 50-200m from the river banktop and a rural village is located 1 km from the embankment. River training works for example stud, spur and cutters are required to protect the embankment. |
| 46. |  | Jhavar Kot (69): At the meander bend, the right bank is 'embanked' and approximately 15m from the active channel during non-monsoon. High flood levels during monsoon reach 2m below the embankment, as told by villagers. Near the top edge of the embankment, there are slightly damaged cement bags filled with earthen material. A rural settlement is situated to the WNW of the location immediately behind the embankment. |

## 6. Conclusion

The main objective of this study was to define a general method for identification of vulnerable areas to natural hazards based on methods developed throughout the last three decades. The most suitable method for application in a specific case is highly dependent on the main objectives and needs of the study (e.g. flexible, widely applicable, efficient, and accurate) and on the quality, availability, and reliability of the data. The success of identification of vulnerable areas to natural hazards depends heavily on criteria used. We have used ten criteria namely, settlement cultivated area, soil, geology, slope, erosional area, morphologically active river bankline reaches, embankments, spurs / studs bridge, and barrages, which are very useful criterions.

Many vulnerable areas in Rapti river system that we visited need urgent attention for flood and erosion control as those areas are not equipped with proper embankments and other river training structures. Erosion is intensive in those sites and lives of human and livestock as well as land and properties are at risk. Some of the important embankments were constructed long back and these have a huge risk to the people and their properties in case of a breach. Embankments, spurs, studs, concrete porcupines, cutters, bamboo crates, polybags filled by river bank material, etc. are used at various vulnerable sites, but at many of the sites visited, these are eroded away or damaged by the flood water. Additional protection is required to protect the actively eroding river bank line and embankments.

Providing absolute protection to all flood prone areas against all magnitude of floods is neither practically possible nor economically viable. Such an attempt would involve very high cost. Hence a realistic approach in flood management is to provide a reasonable degree of protection against flood damages at economic cost through a combination of structural and non-structural measures. Therefore, administrative of this area can use these datasets of classification for specific vulnerable areas to natural hazards and should draw programmes for regular monitoring the critical vulnerable reaches.

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