

An indicator based approach for assessing the vulnerability of riparian ecosystem under the influence of urbanization in the Indian Himalayan city, Dehradun

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ABSTRACT

Riparian ecosystems are critical biological habitat that needs to be preserved. These systems face multiple stresses of altered water regime, increased human interference and biological invasion, climate change, land developments and other site-specific issues that may include eutrophication and urbanisation. In due course of urbanisation, riparian vegetation is replaced by both impervious and less permeable surfaces causing more frequent floods, greater total surface runoff, and decreased time to produce runoff. This may result in flooding of the city when a substantial rain is received. In this study, we evaluated the vulnerability of riparian zones in Dehradun city of India due to urbanisation using a series of indicators extracted from remote sensing data. The changes in the landscape pattern of the riparian zones were examined by analyzing and manipulating Landsat-8 and Sentinel-2 datasets using Google Earth Engine, ArcGIS 10.1 and ERDAS IMAGINE 2014 software. Factors influencing the changes within the riparian area were identified using higher resolution image, existing base maps and reconnaissance surveys to qualify them as one of the indicators. Anthropogenic activities such as new residential buildings, infrastructure (such as roads), farming activities and commercial activities (industrial set up) were some of the factors contributing to the vulnerability of riparian zones. The final indicators in the form of riparian zone slope, extent of the riparian area, vegetation cover, human disturbance were mapped as raster layers and were integrated in a GIS environment to obtain final vulnerability map. This was intersected with settlement density map to categorize the vulnerability levels for three settlement density classes of low, medium and high. The findings reveal a significant land cover change within the riparian zones over a period of twenty years (2000 to 2019) with various levels of human encroachment. It was observed that 26.15% of the riparian area falls under low, 47.68% under medium, 12.98% under high, and 13.19% under very high vulnerability classes. Furthermore, the coverage percentage of high vulnerability class was largest in the low and high settlement density areas of riparian zones accounting for 36.96% and 51.48%, respectively. The majority of the area (74.36%) falls under medium vulnerability class under medium settlement density class. The study provides an opportunity to map riparian zone vulnerability considering predominant indicators of vulnerability that could be mapped using remotely sensed data and application of GIS tools.

1. Introduction

Riparian ecosystems are three-dimensional space of direct interaction between terrestrial and aquatic ecosystems (Gregory et al., 1991). They are narrow strips of land located along banks of rivers, streams, and water networks (Fu et al., 2017). They form a unique ecosystem that acts as a transition zone between the land and water bodies with varying levels of interactions. The strength of interaction varies across space and time (Naiman and Decamps, 1997) and largely depends upon

the contrast of features and activities happening in adjacent patches of ecological units (Baxter et al., 2005; Cey et al., 1999; Elmore and Beschta, 1987; Gregory et al., 1991; Vidon et al., 2010). The riparian ecosystem acts as a semipermeable membrane that regulates the flow of material and energy between the two environment (Naiman and Decamps, 1997). They offer series of ecosystem services and functions such as reservoirs of biodiversity, flood mitigation, wetland products, bank stabilization and protection, recreation and tourism, and water purification (Bennett and Simon, 2004; Fu et al., 2017; Ghermandi

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et al., 2009; Hruby, 2009; Naiman et al., 1993; Pettit and Naiman, 2007).

The riparian area being a transition zone accommodates high biodiversity (Bayley, 1995; Castello et al., 2013; Junk, 1993), provides habitat for critical rare and threatened species (Gregory et al., 1991; Naiman and Decamps, 1997; Planty-Tabacchi et al., 1996) and are prone to various levels of threats such as biological invasion (Planty-Tabacchi et al., 1996), eutrophication (Cey et al., 1999; Fischer and Fischenich, 2000; Vidon et al., 2010) and encroachment by humans (Jackson et al., 2009; McWilliam et al., 2012; Sunil et al., 2010; Wohl, 2011). Riparian zones are often altered by human interferences primarily due to new construction of buildings, infrastructure (such as roads), farming activities and other commercial activities such as industrial set up (Burton and Samuelson, 2008; Fernández et al., 2014; Fu et al., 2017; Thilagavathi et al., 2011). "The degree of vulnerability of a riparian zone, varies with site and situation depending on the kind of threat it is exposed to. Therefore, different regions may have different factors that threaten these systems to make them vulnerable. For example, the riparian zones receiving continuous fertilisers from the adjoining agriculture lands would be more vulnerable to eutrophication than the area having no such influence (Cey et al., 1999; Fischer and Fischenich, 2000; Vidon et al., 2010). Therefore, identification of the factors that could be considered as indicators of vulnerability for riparian zones would also be site specific. In particular, the riparian ecosystems of urban areas are under the influence of continuous encroachment and other factors that need to be investigated.

Urbanization is a process of population concentration or urban growth by natural ways or through immigration (Finkenbine et al., 2000; Sati, 2013; Thilagavathi et al., 2011). Urbanization is a social process, whereby cities grow and societies become urban (Sati, 2013). Urbanization results in both drastic and increasingly widespread habitat alteration (Marzluff and Ewing, 2001; McKinney, 2006). During the urbanization process, riparian vegetation is replaced by both impervious and less permeable surfaces (Beyerlein, 1996; Finkenbine et al., 2000). Impervious surfaces cause large and more frequent floods, greater total surface runoff, and takes less time to produce runoff (Morisawa and LaFlure, 1979; Neller, 1988; Williamson et al., 1993). This leads to urban flooding when heavy rain is witnessed in the city. Hence, the vulnerability of riparian zones may also be linked to the vulnerability of the urban system. Therefore, the assessment of influence of urbanisation on various levels of vulnerability of urban riparian zones is important.

The vulnerability can be referred to as the state of propensity to impairment from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt (Adger, 2006). The key parameters of vulnerability are the stress to which a system is exposed, its sensitivity, and its adaptive capacity (Adger, 2006; Berkes et al., 2008; Carpenter et al., 2001; Folke, 2006; McCarthy, 2001). In the context of riparian zones, the level of vulnerability would vary upon the kind of stress and its magnitude together with the resilience or the adaptive capacity of the system to bear that stress. The use of term vulnerability is context-specific (Füssel, 2007; Giupponi and Biscaro, 2015; Gupta et al., 2020; Hinkel, 2011; Kumar et al., 2018b; Pandey et al., 2018; Pokhriyal et al., 2020; Smit and Wandel, 2006) and can be used to define different levels of threats to which a system is exposed or is likely to witness the harm in near future. Vulnerability assessment is more in vogue for the assessment of climate change impacts on natural, social or socio-ecological systems (Gupta et al., 2020; Kalra and Kumar, 2019; Kumar et al., 2020, 2019b, 2018a). However, we refer here to vulnerability assessment in the context of prevailing drivers of changes that would alter the natural condition of the riparian zones to a state that is undesirable from ecological and social point of view.

How vulnerable are these riparian zones to urbanization pressure is one of the key question for the planners and policy makers? To address this question, here we evaluate the vulnerability of the existing riparian

zones across the city of Dehradun in the Himalayan region of India using a series of indicators extracted from remote sensing data. We hypothesised that once field based understanding is available the remotely sensed images can be used for mapping prominent indicators of vulnerability in urban riparian zones. With this assumption, the specific objectives of this paper are to: (1) delineate and classify the riparian zones using remotely sensed images in order to understand the landscape change pattern within the riparian zone; (2) identify factors that would qualify as one of the indicators for mapping riparian zone vulnerability; (3) develop vulnerability indices for the evaluation of the riparian zones, and; (4) evaluate the vulnerability of the riparian zones under different classes of settlement density.

2. Methodology

2.1. Study area

The study was conducted in Dehradun, a mountainous landscape of the Indian Himalayan region that has witnessed rapid urbanisation in the past decade. Dehradun is the capital city of Uttarakhand state in India having its extent between latitudes 29° 58' – 31° 2' N and longitudes 77° 34' – 78° 18' E (Fig. 1). It is located at a distance of 250 km north of India's capital New Delhi having a predominantly mountainous landscape with rich forests and water streams. It covers an area of 3088 sq. km. with a population of 1.7 million as per 2011 census (Khan, 2013). Dehradun enjoys its strategic location with undulating topography (Jain, 2007). The average elevation of the city is 450 m above sea level. The climate of the region is humid subtropical. It experiences temperature that ranges from below freezing point in winter to as high as 36 °C in summer. Summer temperatures can reach up to 44 °C for a few days and a hot wind blows over North India. Winter temperatures are usually between 1 and 20 °C and fog is quite common in winters like in the plains. Dehradun also experiences large precipitation during June to September (as a result of monsoon) and little rainfall during December to February due to western climate disturbance (Pankaj and Kumar, 2009). It receives an average annual rainfall of 2073.3 mm. The urbanization process in Dehradun is not systematic and well planned, mainly due to the unplanned construction of houses and other infrastructure amenities (Sati, 2013). Usually, people construct houses without scientifically examining the location and fragility of the landscape. This activity poses a significant impact on the riparian zones within the city and urban sprawl, thereby making them vulnerable. Dehradun has a large network of water streams (Fig. 1). However, they are under continuous influence of human encroachments contributing to the vulnerability of the accompanying riparian zones.

2.2. Data sources and analytical tools used

Primary data collected through field surveys as well as remotely sensed satellite images were used in this study. The predominant factors that could be used as one of the indicators were decided after field observations. Multispectral satellite (Landsat – 7, 8 and Sentinel-2) datasets were extracted using Google Earth Engine (GEE). The GEE provides planetary-scale geospatial analysis through large scale cloud computing to extract various archived geospatial layers to perform scientific analysis (Gorelick et al., 2017). Shuttle Radar Topography Mission (SRTM) data was sourced from United State Geological Survey (USGS) Earth Explorer website (<https://earthexplorer.usgs.gov/>). The manipulation, processing and handling of remotely sensed data involved the use of GEE (<https://code.earthengine.google.com/>), ArcGIS (<https://www.esri.com/en-us/arcgis/about-arcgis/overview>) and ERDAS EMAGINE (<https://www.hexagongeospatial.com/products/power-portfolio/erdas-imagene>) software as shown in Fig. 2.

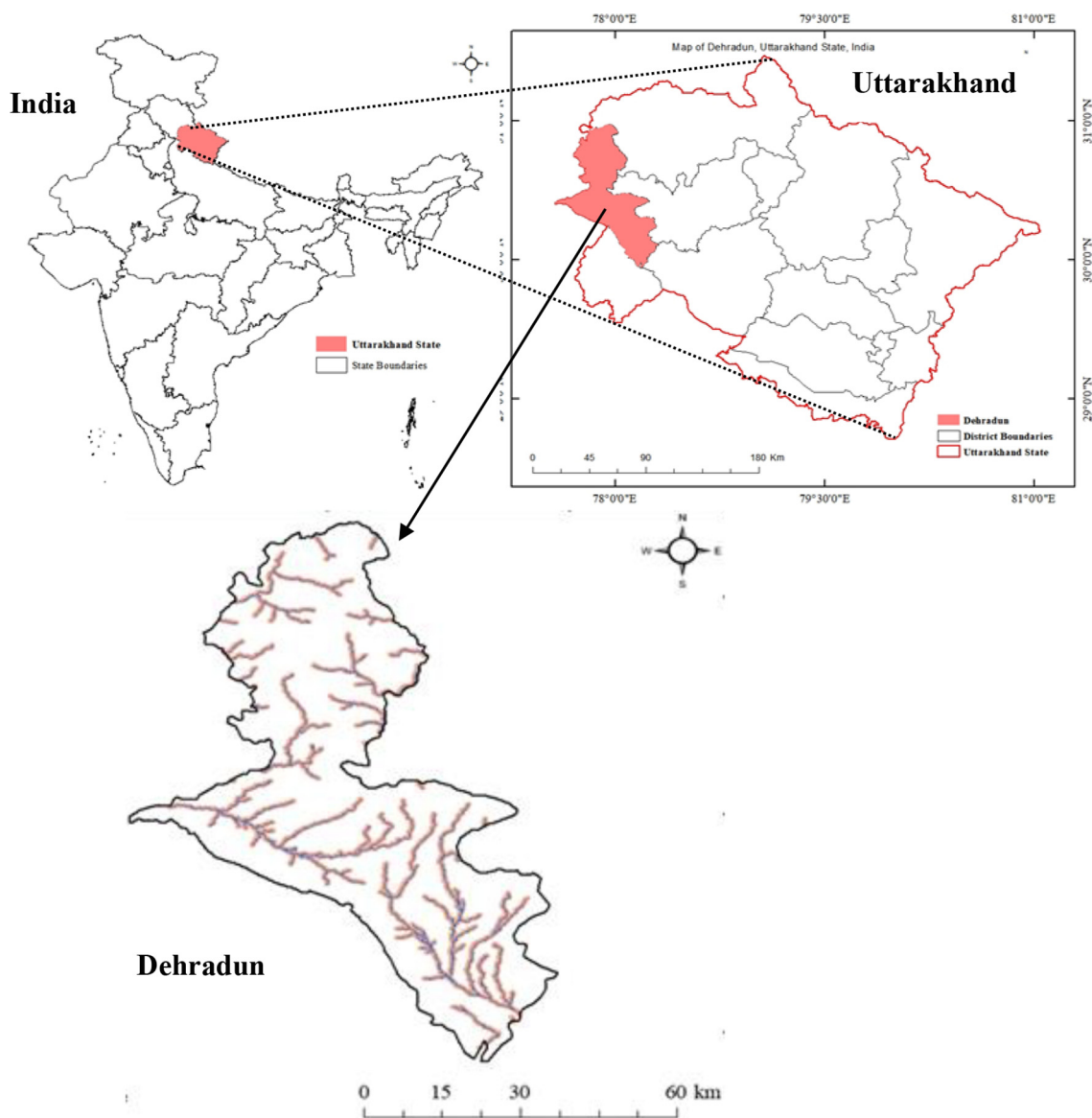


Fig. 1. Location map of the study area, Dehradun (showing network of streams forming riparian zones) in Uttarakhand state of India.

2.3. Delineation and classification of the riparian zones using remotely sensed images

The GEE was used for the interpretation and derivation of water pixels present in the Landsat-8 and Sentinel-2 datasets. Methodology, as suggested by Donchyts et al., (2016), was adopted for the detection of surface water in the images in an automated manner using an adaptive thresholding procedure. This technique applies two key algorithms of “Otsu thresholding” and the “Canny edge detector”. Initially, the Normalized Difference Water Index (NDWI) was used to detect water pixels followed by Canny edge detector. A bimodal distribution of water and land pixels was obtained by applying Otsu’s method that separates water from land. Further description can be referred to in the work done by Huang et al., 2018 and Thissen, 2019. For having a confirmatory test to achieve better accuracy through the reiteration of the entire process, the derived water pixels were overlaid on Google Earth images to mark the river area. The spatial analyst tool of ArcGIS was used to create a buffer zone of 500 m for the demarcation of the riparian zone along both sides of the delineated river streams obtained through the above steps.

The fixing of buffer width is subject-specific and consideration of

500 m was done following the recommendations of Aslan and Trauth (2014) and Jontos (2004). Also, it was observed that most of the stretch of the river course making riparian zone in the study region extend to either urban, agriculture or the forest cover, where, any stretch of land after 500 m measured distance from the centre line of the river is covered by urban, agriculture or the forest cover and there was no sign of riparian zone beyond this measured length. Hence, we fixed a length of 500 m buffer for marking riparian zone. The script for obtaining cloud-free image composite of Landsat (7 and 8) datasets for the period 2000 and 2019 was implemented in GEE. The images were saved in Google drive and later downloaded from the drive for its manipulation and handling using ERDAS and ArcGIS software.

The images of Landsat 7 were used to develop land cover map of the year 2000 in ERDAS software using supervised classification with Maximum Likelihood Classifier, similarly, the land cover map of 2019 was developed using Landsat 8 image. Dominant categories of land cover, viz., waterbody, built-up area, agriculture and forest vegetation was mapped for the riparian zone (Table 1). A change matrix to see categorical changes of one land cover type for the year 2000 to another cover type in the year 2019 was done using ERDAS. This provided an estimate of proportionate land cover change from one category to

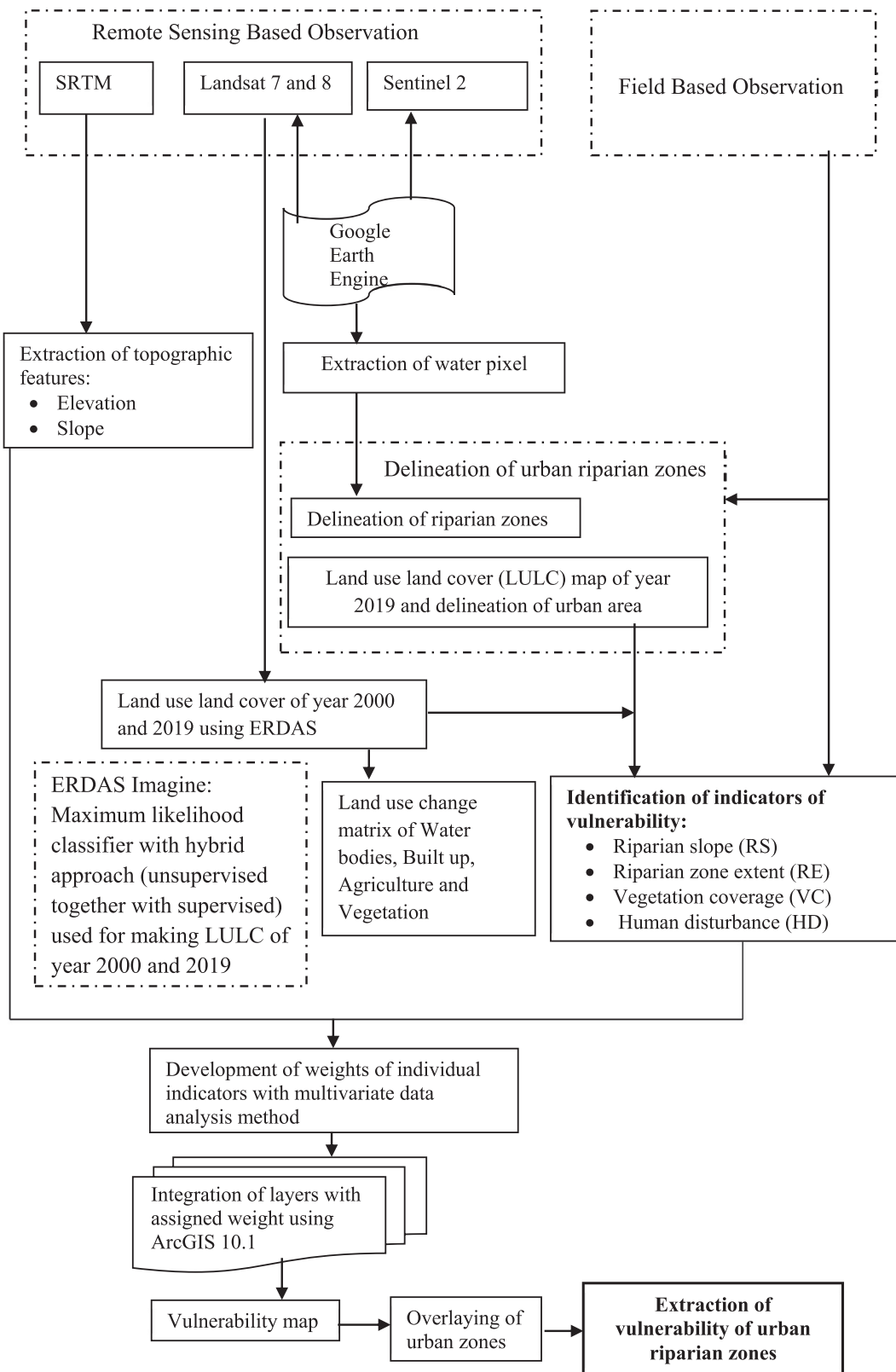


Fig. 2. Schematic representation of steps involved in the study.

another over 20 years.

2.4. Identification of indicators of vulnerability and development of indicator layers

The assessment of vulnerability is guided by the factors that influence the riparian zones significantly. The most predominant factors that

Table 1
Classification scheme and description of classes.

Land Cover Classes	Description
Water body	Rivers, lakes and wetlands
Built-up	Industrial and commercial area, residential area, land covered by any building
Agriculture	Paddy field, fallow agriculture land, crop land including grasses
Vegetation	Forest area other than agriculture lands with deciduous or evergreen trees, broad leaf and conifer trees, mixed trees, barren forest land

Table 2
Evaluating indicators for the riparian zones vulnerability and their weights.

Indicators	Sub-indicators	Description of indicators	Source of data
Bank topography	<i>Riparian slope (RS)</i>	The percent change in the elevation over a certain distance. More the slope more is vulnerability and vice versa.	SRTM DEM
	<i>Riparian zone extent (RE)</i>	Euclidean distance from river centre line where more the proximity to rivers shore line more unstable is the terrain and indicates more vulnerability.	Sentinel images
Riparian vegetation	<i>Vegetation coverage (VC)</i>	VC denote percent canopy cover density where high density would have less vulnerability and vice versa.	Indian state of forest report
Human interferences	<i>Human disturbance (HD)</i>	Relative density of settlement and farmland pixels. More the density more is vulnerability.	Landsat images

would contribute to the vulnerability of the riparian zones were identified through field surveys. The vulnerability of riparian zones may be guided by several factors (presence of specific industry, soil type, forest cover density, dominance of forestry species having high rate of evapotranspiration, presence of plant as well as animal invasive species, any unique human practices like bathing, washing, idol immersion, etc.), however, for the present study only the most predominant factors were recognised to consider as indicators of vulnerability. The identified indicators were mapped as spatial layers of raster file for their integration to obtain vulnerability value. The pixel values of each of the indicator layers were normalised (using Eqs. (1) and (2)) (Little, 2013; Moeller, 2015) to have same range in all of the indicators layers. The kind of relationship the indicator layers have with the vulnerability decided the equation to be used. Eq. (1) was used for the inverse relationship between the indicator and the vulnerability, for example, the relationship between forest density classes (low to high density of forest vegetation) and the riparian zone vulnerability is that the area with low density vegetation would be more vulnerable and vice versa; whereas, Eq. (2) was used for having direct proportional relationship, for example, higher the slope of riparian zones, more the vulnerability and vice versa.

$$\text{Range standardise}(X) = \frac{X_{max} - \text{layer}}{\text{Diff}} \tag{1}$$

$$\text{Range standardise}(Y) = \frac{\text{layer} - Y_{min}}{\text{Diff}} \tag{2}$$

where, X_{max} is the maximum value of pixels in an indicator layer; Y_{min} is the minimum value of pixels in the indicator layer; $Diff$ is the difference between the maximum and minimum pixel values of selected indicator layer.

2.5. Making of vulnerability indices by integrating indicator layers

The weight allocation to each indicator layers were done by assessing the variability of pixel values within the indicator layers, where greater variability would lead to lesser weight and vice versa as also suggested by Iyengar and Sudarshan (1982). The weights for each indicator layers were obtained using Eqs. (3) and (4).

$$w_i = \frac{k}{\sqrt{\text{Var}(y_i)}} \tag{3}$$

$$\text{and } k = \left[\sum_{i=1}^4 \frac{1}{\sqrt{\text{Var } y_i}} \right]^{-1} \tag{4}$$

where, w_i indicates weight assigned to i^{th} indicator layer, k is normalised constant, Var is variance of pixel values in i^{th} indicator layer.

The integration of all the indicator layers was done using Eq. (5).

$$VI = \sum_{i=1}^k w_i I_i \tag{5}$$

where, VI represents Vulnerability Index, k represents number of indicator layers, w_i is the weight of i^{th} indicator layer, I_i represent pixel values of i^{th} indicator layer.

The final values of pixels representing vulnerability level were categorised into four classes of vulnerability, viz., low, medium, high and very high. The grouping of the pixel values into four classes were done on the basis of dividing the entire pixel values into four classes in a way so that there is maximum variability between groups while within each group there be minimum variability. Accordingly, the cut off values to frame the groups were decided. Class breaks were identified so that the best group have similar values and in a way to maximize the differences between classes. This was achieved by using Jenks algorithm available in ArcGIS software.

The four indicator layers of riparian slope (RS), riparian zone extent (RE), vegetation cover density (VC) and human disturbance (HD) (Table 2) were considered for the present study as per the field observation and logical thinking which indicates the major prevailing causes of changing vulnerability in the study area. Riparian slope (RS) was obtained after processing of SRTM (30 m resolution) data, riparian zone extent (RE) was obtained as the Euclidean distance measured from the river centre line using ArcGIS spatial analyst tool, vegetation cover density (VC) was obtained from Forest Survey of India (FSI, 2011) as raster image file, settlement density raster to make human disturbance (HD) layer was derived using Sentinel image of European Space Agency.

2.6. Mapping vulnerability percentage cover within different levels of urbanization

To assess the influence of urbanisation on the vulnerability, three different levels of urbanisation (low, medium and high) were recognised on the basis of settlement pixel density coverage. The percentage distribution of vulnerability within each classes of urbanisation was obtained by intersecting the spatial layers of vulnerability and urbanisation classes in ArcGIS after converting both layers into vector file following the method suggested by Cui et al., (2016).

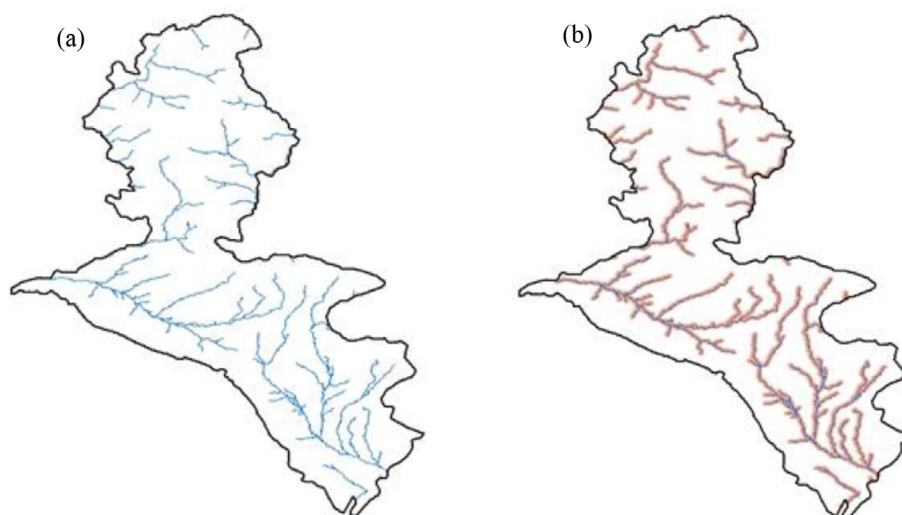


Fig. 3. Riparian zones of Dehradun, India: (a) river streams; and (b) 500 m buffer zone identified as riparian zone.

3. Results and discussion

3.1. Delineation of the riparian zones

The river streams and its corresponding riparian zones of Dehradun, delineated as the 500 m buffer along both sides of the river stream is presented in Fig. 3. Four dominant categories of land cover identified in the riparian zone of study area are water body, built-up area, agriculture lands and vegetation with dominant trees. The land cover mapped for the corresponding years of 2000 and 2019 is presented in Fig. 4. A significant change in the alteration of one land cover category into other was witnessed during the comparison years. The water body, built up and agriculture classes increased from 3.68% to 11.10%, 15.51% to 19.36% and 16.80% to 18.70% respectively, while vegetation class decreased from 64.01% to 50.84%. The distribution of land cover within riparian zones of Dehradun during years 2000 and 2019 is depicted in Table 3.

3.2. Identification of factors influencing the riparian zones

3.2.1. Anthropogenic factors

The dominant anthropogenic activities prevailing within the riparian zones of Dehradun is presented in Table 4. The major activities included construction of residential buildings, development of infrastructure such as roads, agriculture activities and commercial activities.

3.2.2. Topography

The elevation and slope of Dehradun riparian zones are presented in Fig. 5. The elevation and slope of the riparian zone ranges 285 m–2453 m and 0°–71° respectively (Fig. 5).

3.3. Development of vulnerability indices and its mapping

The final vulnerability was obtained by assigning weights derived for each of the indicator layers and adding them using Eq. (6). However, one should be cautious of using the formulae directly for calculating the vulnerability of a riparian zone, as the weight contribution of each of the indicator layers would vary for different sites and regions.

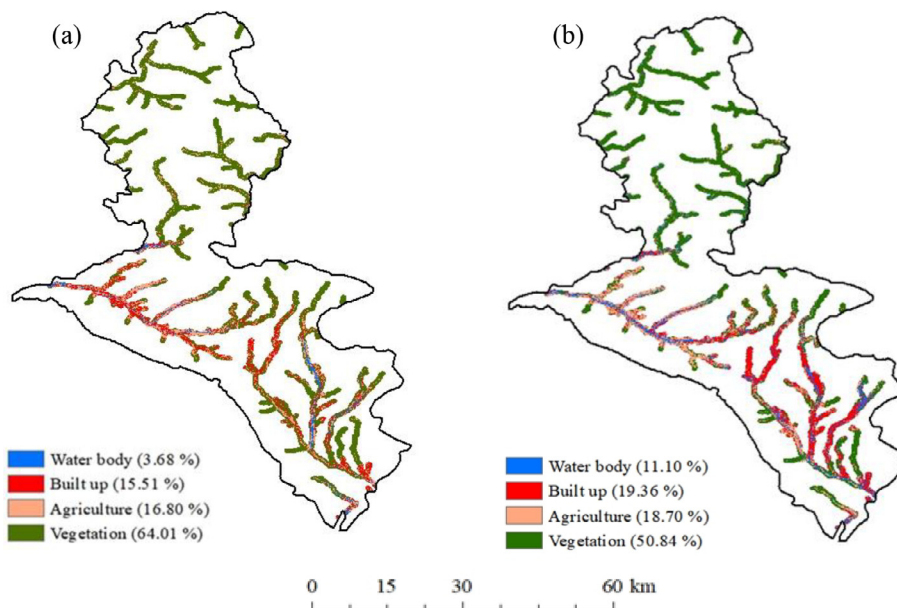


Fig. 4. The land cover map of riparian zones of Dehradun, India: (a) year 2000; (b) year 2019.

Table 3
Land cover distribution of Dehradun riparian zone during year 2000 and 2019.

land cover class	2000		2019		Percentage change (2000 to 2019)
	Area (km ²)	Percentage (%)	Area (km ²)	Percentage (%)	
Water body	23.17	3.68	69.71	11.10	+200.86
Built Up	97.52	15.51	121.57	19.36	+24.66
Agriculture	105.63	16.80	117.44	18.70	+11.18
Vegetation	402.56	64.01	319.28	50.84	-20.69
Total	628.88	100	628	100	

Table 4
The prevailing human activities within the riparian zones.

S/N	Anthropogenic activities
1	Construction of residential buildings
2	Construction of roads
3	Agriculture activities/ farming
4	Commercial activities including industries

Even the individual layers may not be the same as indicated here. It would also be much dependent upon the specific site conditions and prevailing situations at a given place. However, the methodology demonstrated here can be used to map site specific riparian zone vulnerability.

$$VI = RSX0.5 + REX0.05 + VCX0.33 + HDX0.12 \tag{6}$$

Here VI stands for vulnerability index, RS is riparian slope, RE is riparian zone extent, VC is vegetation cover, and HD is human disturbance. The final integrated value of pixels representing VI within riparian zones was used to map the spatial extent of riparian zone vulnerability as shown in Fig. 6. It was observed that the 26.15% of the riparian zone have low vulnerability, 47.68% have medium vulnerability, 12.98% have high vulnerability, while 13.19% have very high vulnerability.

3.4. Mapping vulnerability under different levels of urbanization

The distributions of vulnerability within different categories of settlements identified as low, medium and high urbanisation levels are presented in Figs. 7–9. Whereas, the total area and percentage cover of

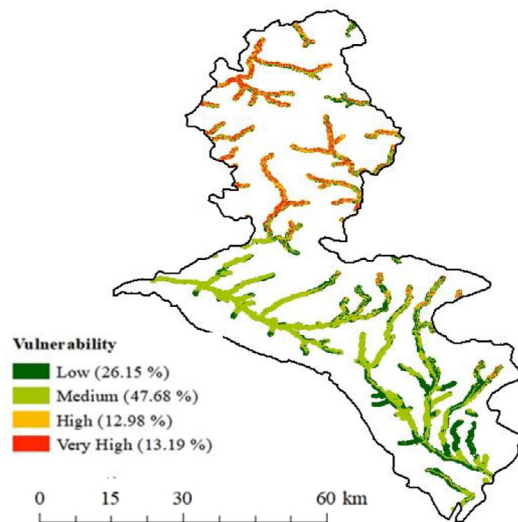


Fig. 6. The vulnerability map of urban riparian zones of Dehradun, India.

four different vulnerability levels (low, medium, high and very high) for each of the urbanisation classes in the urban riparian zones of Dehradun is presented in Table 5.

3.5. Discussion

The assessment of riparian zones of Dehradun, India was done to understand the dynamics of land cover changes over a period of

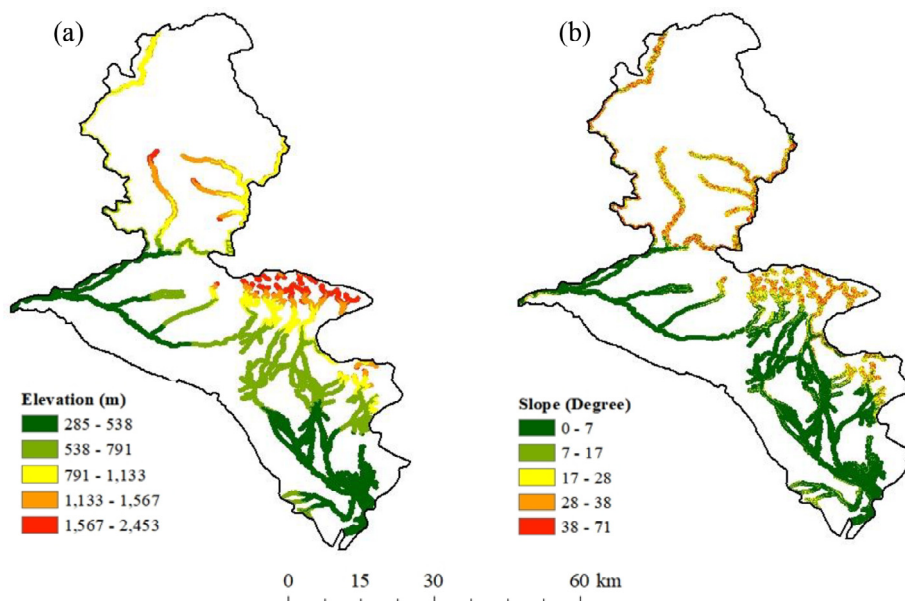


Fig. 5. The topography of the riparian zones in Dehradun, India: (a) elevation ranges (m) within the riparian zones; (b) slope variation (degree) in the riparian zones.

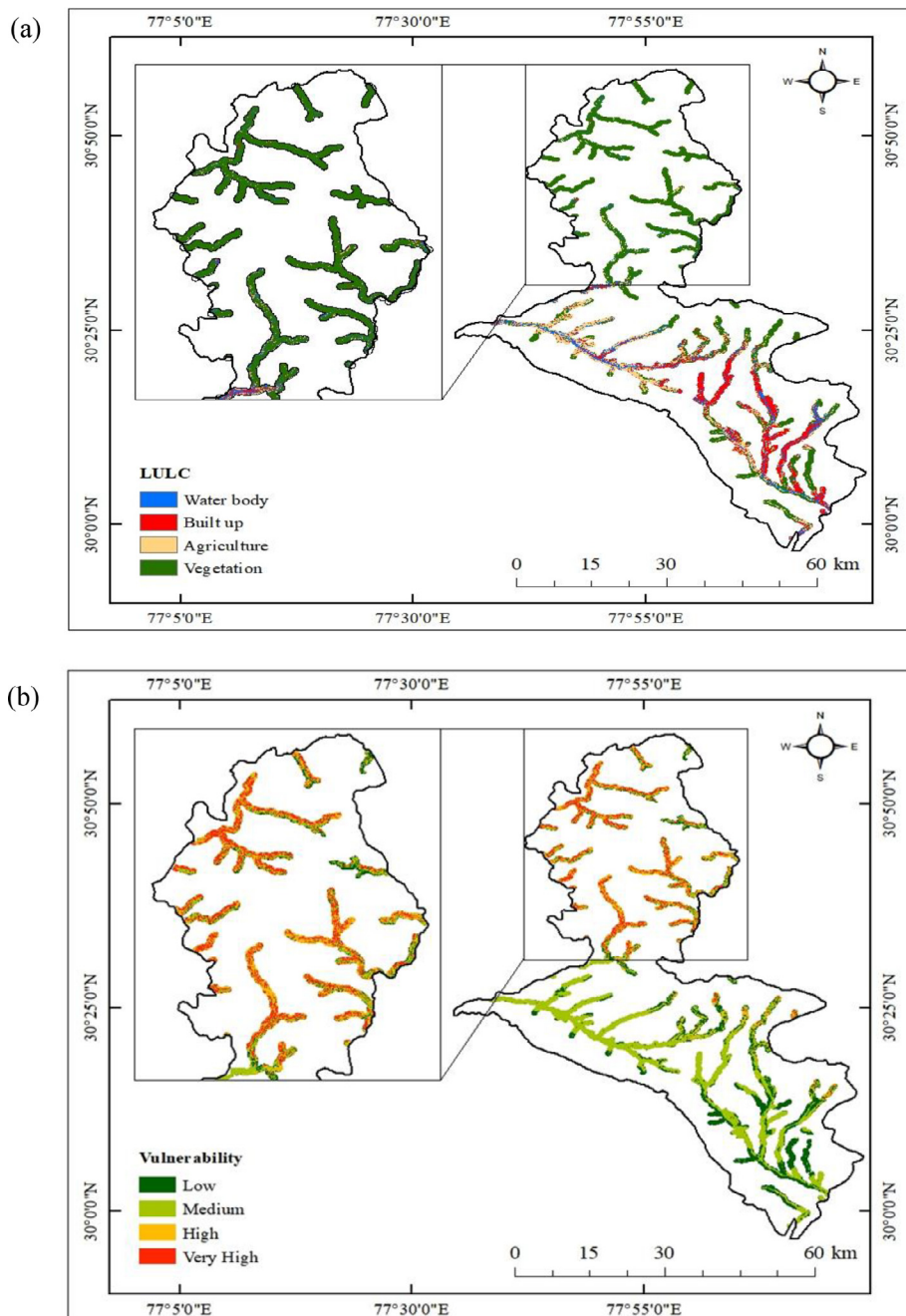


Fig. 7. Map showing different levels of vulnerability in the riparian zones of Dehradun, India with low urbanisation: (a) panel showing regions with low urbanisation in the zoomed portion, (b) vulnerability levels in the low urbanisation region highlighted in zoomed view.

20 years (2000–2019) and it was observed that riparian zones have witnessed significant changes in these 20 years in terms of changing land cover. The water body, built up and agriculture cover has increased, whereas vegetation cover has decreased significantly (Table 3). This indicates that riparian regions of the city have undergone alteration with temporal evolution of varying stability to influence changing land cover. This might have different impacts on the riparian zone extent and quality over the assessment period. Several studies reported that changes in land-use types and its spatial arrangement within a riparian zone have a significant impact to influence its overall condition (Fernandes et al., 2011; Fernández et al., 2014; Fu et al., 2017; Konarska et al., 2002; Kreuter et al., 2001; Lu and He, 2014; Miserendino et al., 2011). According to Fernández et al., (2014), presence of vegetation is positively related to riparian quality while

settlements or urban development and agricultural activities reduce riparian quality. The presence of land classes other than vegetation within riparian zones typically represent physical and functional discontinuities and also reduces riparian vegetation regeneration capacity (Fernández et al., 2014). Besides, Amis et al., (2007) and Wasson et al., (2010) reported that greater the vegetation coverage within riparian zones, the higher the quality. However, the vulnerability of riparian zones under projected changes of land use cover would vary (Singh et al., 2020) and it would be interesting to assess vulnerability under future scenarios. The study implemented Remote sensing and GIS tool which has also been used successfully earlier for mapping riparian zones of the study region (Savita et al., 2018). The application of remote sensing and GIS tools have provided opportunity to study various other landscape based phenomena and are important for scientific

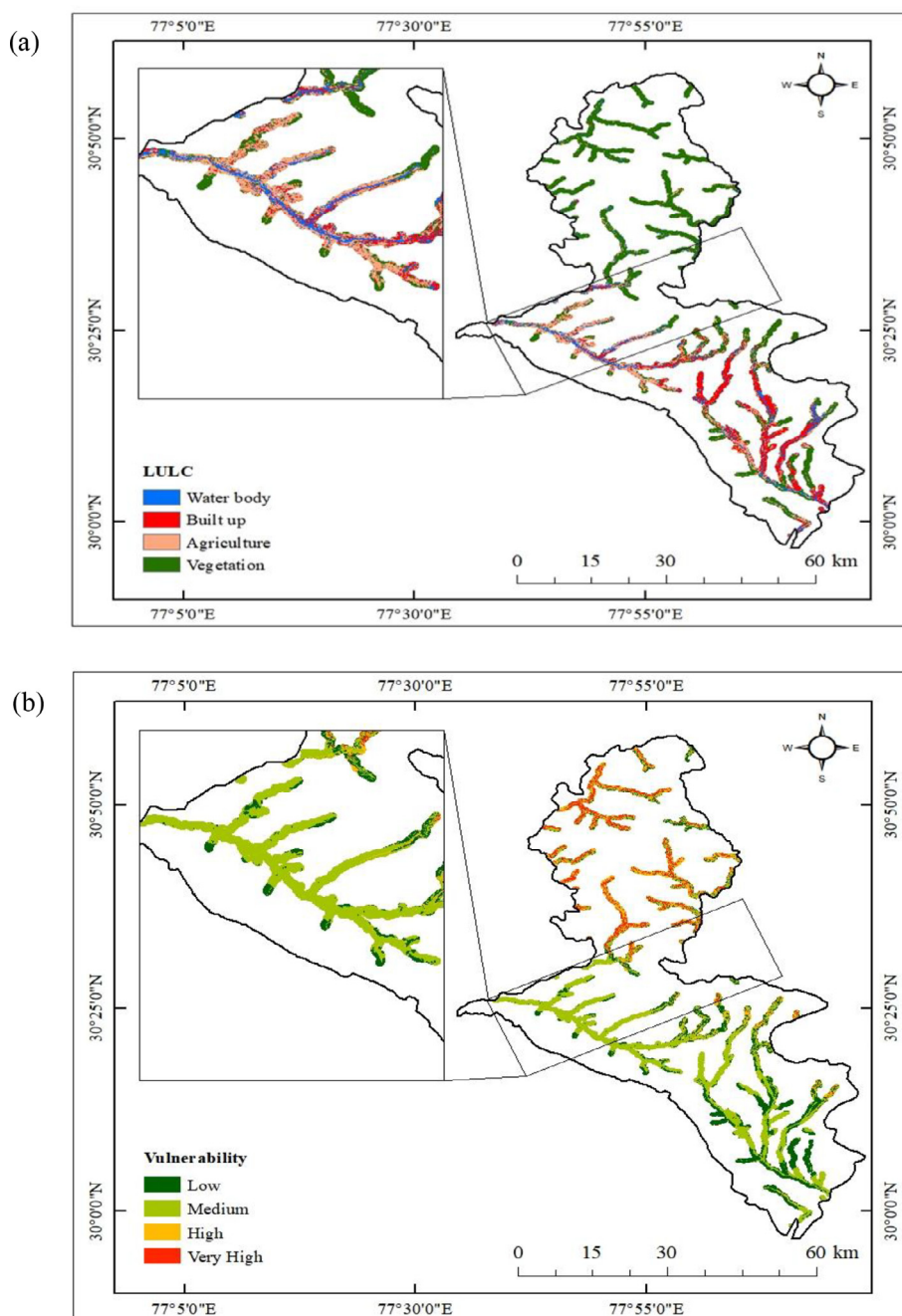


Fig. 8. Map showing different levels of vulnerability in the riparian zones of Dehradun, India with medium urbanisation: (a) panel showing regions with medium urbanisation in the zoomed portion, (b) vulnerability levels in the medium urbanisation region highlighted in zoomed view.

investigation and planning (Kumar et al., 2019a, 2019b; Lo et al., 1997; Shalaby and Tateishi, 2007; Weng, 2001).

The anthropogenic activities identified within the riparian zones (Table 4) suggest that these activities were responsible for the changes within the riparian zones. Several studies related landscape changes within riparian zones to human disturbance (Baker et al., 2007; Malanson and Cramer, 1999). The presence of human induced activities within the riparian zones confirms the report of Fu et al., (2017) that human activities and natural factors drive continuous change within riparian zones. The identified human activities within these zones corroborated the report of Fernandes et al., (2011) that riparian habitats are threatened due to human activities.

The elevation of Dehradun riparian zone ranges from 285 to 2,453 m amsl. According to Fernández et al., (2014), riparian condition

of a more gentle relief is usually worse than mountainous terrain. Also, the slope of Dehradun riparian zone ranges from 0° to 71°. This implies that Dehradun riparian zone is characterized by both broad and open terrain and narrow and entrenched terrain. According to Oakley et al., (1985) riparian area with 17°–39° slope can be referred to as a broad and open terrain, with well-developed floodplains, deep and fine soil texture, and relatively open to wind disturbance, while riparian area with 40° and above slope is a narrow and entrenched area, with poorly developed floodplains, shallow and coarse soil texture, that is relatively sheltered from wind disturbance. In addition, slope indicates the type, frequency, and magnitude of erosion/deposition processes that occur in a riparian zone. Riparian zones with slope $\leq 39^\circ$ indicate deposition process while slope $\geq 40^\circ$ indicates active erosion and transport process (Oakley et al., 1985). Vidon and Hill (2004) also reported that the slope

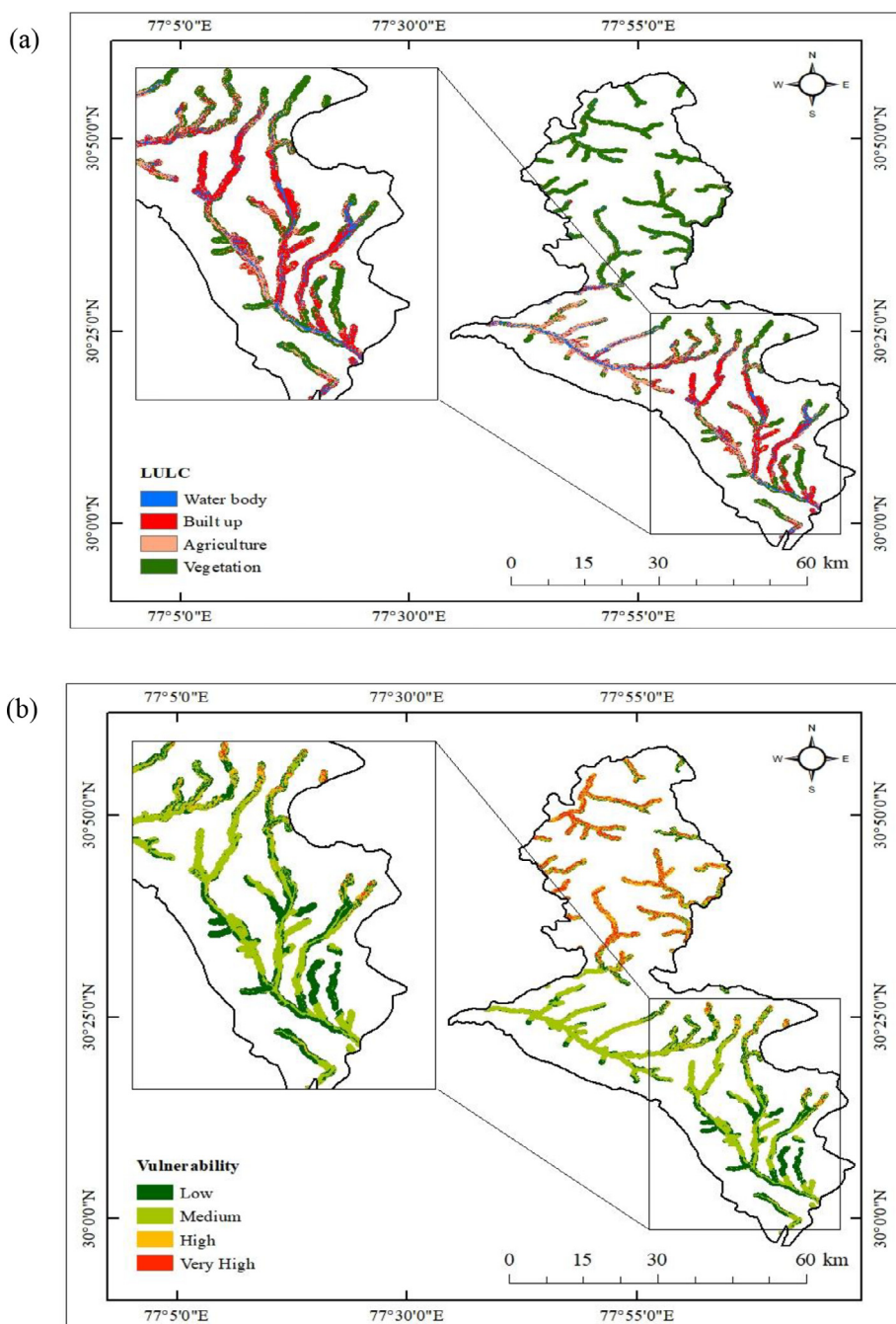


Fig. 9. Map showing different levels of vulnerability in the riparian zones of Dehradun, India with high urbanisation: (a) panel showing regions with high urbanisation in the zoomed portion, (b) vulnerability levels in the high urbanisation region highlighted in zoomed view.

Table 5

Distribution of vulnerability classes under low, medium and high urbanisation in the riparian zones of Dehradun, India.

S/N	Vulnerability levels	Low urbanisation		Medium urbanisation		High urbanisation	
		Area (km ²)	Percentage (%)	Area (km ²)	Percentage (%)	Area (km ²)	Percentage (%)
1	Low	39.04	12.01	28.52	15.19	190.84	41.14
2	Medium	69.54	21.38	139.66	74.36	238.80	51.48
3	High	96.44	29.65	11.12	5.92	26.06	5.62
4	Very High	120.20	36.96	8.52	4.54	8.14	1.75
Total		325.22	100	187.82	100	463.84	100

gradient, especially at the riparian zone-upland margin, influences the hydraulic gradient and the volume and velocity of water entering the riparian zone. When the riparian zone is flat, the stream water level acts as a fixed point around which the water table fluctuates, whereas when the slope directly borders the river, the effect of stream water level on water table dynamics in the riparian zone is negligible (Burt et al., 2002).

Most of the riparian zones of Dehradun urban area are categorised as medium vulnerability (47.68%), followed by low (26.15%), very high (13.19%) and high vulnerability level (12.98%). While considering the role of different levels of urbanisation contributing to various vulnerability classes, it was surprising to observe that riparian zones of Dehradun are well managed and most of the areas with high urbanisation show low levels of vulnerability. The indicators considered for mapping the vulnerability included forest vegetation cover density and the slope apart from the levels of human interferences denoted by settlement density classes. The low vulnerability in the urban riparian zones suggests for better condition of vegetation cover and the slope stability compared to the regions that are not within the reach of urbanisation. Vulnerability must not be assessed considering the indicators used in this study as the indicators of vulnerability would be site specific and it may or may not match with the selected indicators of the present study for other riparian zones.

4. Conclusion

This research focused to evaluate the vulnerability of riparian zones within urban sprawls of Dehradun in India considering the indicators that might have the largest influence on the riparian zones to make them vulnerable. The temporal evolution of land use changes in riparian zones makes the vulnerability a dynamic process, and for assessment, the vulnerability may vary. It was observed that the vulnerability of riparian zones is site and situation specific which may vary over a period of time. The different levels of urbanisation may have different vulnerability depending upon the site characteristics such as slope, percentage cover of agriculture activities, vegetation cover, commercial activities, built-up area, etc. The major human interferences in riparian zones are usually in the form of farming, residential and commercial buildings, development of infrastructures like roads, and other activities that may vary from one region to other. The largest area of the riparian zones of Dehradun was found within medium vulnerability level, while the least area is within high vulnerability level. Furthermore, the largest area of low, medium and high settlements of Dehradun riparian zones are within very high, medium and medium vulnerability level, respectively. The study demonstrates the successful application of remote sensing and GIS tools for the acquisition of relevant information in the form of indicators that can be used for mapping the vulnerability of riparian zones. The vulnerability assessment of the urban area is important because of the rapid urbanisation and changing courses of riparian areas with various levels of urbanisation. This study would be useful for the policymakers and planners, especially those who are involved in urban development and city planning.

CRedit authorship contribution statement

Oluwayemisi Samuel Olokeogun: Data processing, Software handling, Analysis and drafting of MS. **Manoj Kumar:** Conceptualization, Methodology, Investigation, Software handling and editing of MS.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

influence the work reported in this paper.

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Appendix A. Supplementary data

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