



# Morphometric analysis using fuzzy analytical hierarchy process (FAHP) and geographic information systems (GIS) for the prioritization of watersheds

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## Abstract

River basins are prone to degradation due to soil erosion induced by anthropogenic activities and natural calamities. In this study, an integrated approach using morphometric analysis, geo-informatics, and fuzzy analytical hierarchy process was employed to prioritize the watersheds. Hydrological parameter “erosion” is a major deciding factor to assess and prioritize the watersheds using the fuzzy analytical hierarchy process (FAHP) method in the Peddavagu watershed of the Krishna river basin. The major characteristics of watershed parameters such as basin length ( $L_b$ ), drainage density ( $D_d$ ), form factor, stream frequency ( $F_s$ ), elongation ratio ( $R_e$ ), circularity ratio ( $R_c$ ), drainage texture ( $T$ ), bifurcation ratio ( $R_b$ ), and compactness constant ( $C_c$ ) are arranged in matrix form for FAHP analysis. The FAHP analysis was carried out using Triangular Fuzzy Network; for further analysis, the values were classified as follows: 1.25 as moderate susceptibility, 1.5 as high susceptibility, and 1.75 as very high susceptibility. The results of FAHP analysis showed that five watersheds have a very high susceptibility to erosion (30.32%), 16 watersheds as high susceptibility (53.28%), and the remaining 10 watersheds were categorized as moderate susceptibility (16.4%). It implies that soil and water conservation measures have to be implemented on priority in “very high susceptibility category watersheds,” followed by the “high susceptibility” and “moderate susceptibility” categories. Furthermore, the universal soil loss equation (USLE) equation was used to compare the outcomes of the FAHP method. The results have been compliant with FAHP analysis, and the very high susceptibility, high susceptibility, and moderate susceptibility categories were having sediment yields of 54.96 t/ha/year (4D2D1-26), 30.00 t/ha/year (4D2D3-31), and 15.07 t/ha/year (4D2D2-17). The Spearman rank correlation coefficient has been used to validate the USLE and Fuzzy simulations. The results have shown a strong positive correlation for the study area. As the integrated morphometric analysis using FAHP for prioritizing watersheds has shown reliable outcomes, this method has the potential for adoption in other case studies elsewhere.

**Keywords** GIS · FAHP · Prioritization · Watersheds · Morphometric analysis

## Introduction

The arid and semiarid regions recurrently experience a shortage of freshwater resources due to the ever-growing

population and rainfall aberrations induced by El-Nino or climate change (Singh et al. 2014; Banerjee et al. 2017). Moreover, the river basins are susceptible to soil erosion due to anthropogenic activities, climate change-induced droughts, land degradation, etc. (Islam et al. 2019). So, the collective management and development of land and water resources in an integrated and comprehensive way are imperative to achieve water and food security (Kumar and Mukherjee 2005). The extensive land and water development primarily include assessing small watersheds, which play a crucial role in implementing soil and water conservation measures (Biswas et al. 1999; Chandrashekar et al. 2015). Watershed is a natural hydrological unit that constitutes an area that collects precipitation that drains through the mainstream and its tributaries from upstream to downstream to a common outlet

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called “Pour point” (Prabhakaran and Raj 2018). The stream network (drainage or morphometric) analysis of a watershed helps identify and assess the degradation and loss of biodiversity due to floods, soil erosion, and runoff discharges (Soni 2017; Prabhakaran and Raj 2018).

Morphometric analysis of the streams, shapes, and dimensions of watersheds using empirical equations provides an understanding of the properties and behavior (runoff and sediment yield) of the sub-watersheds or watersheds of a river basin (Biswas et al. 2014) typically. The quantitative analysis and assessment of morphometric parameters provide insights related to the characteristics of rocks, rock formation, and hydrology (Singh et al. 2014; Rai et al. 2017). The hydrological behavior depends upon the shape, size, land use, soil, slope, and rainfall intensity of a watershed. Moreover, these parameters can also influence the formation of new streams, or sometimes they change the course of the older streams of a watershed. These streams can be recognized, identified, and processed using the temporal datasets of satellite imagery or aerial photography and topographical maps. Several researchers have shown confidence in the use of morphometric studies, remote sensing, and GIS analytical tools as they have demonstrated a significant role in planning and designing of various hydraulic structures in the development of watersheds within a river basin (Vincy et al. 2012; Sreedevi et al. 2013; Vittala et al. 2004).

The size and boundary of a watershed depend on the stream size, and it might constitute an area of some hectares to square kilometers. The Watershed Atlas of India published by the All-India Soil Survey and Land Use Planning Survey (AIS & LUS), Government of India (GOI) contains registered watersheds of all the river basins. As per the watershed atlas classification, India’s river basins have been categorized into six water resource regions. These regions are further sub-categorized into river basins, and attribute codes are assigned for each river basin up to the sub-watershed level as follows: 4E3C5. In 4E3C5, 4 indicates the region, E indicates river basin name (e.g., Ganga basin), 3 indicates catchment, C indicates sub-catchment, and 5 indicates a watershed number. Several Indian researchers have referred to the Watershed Atlas of India to delineate the river basins up to the watershed level (Parupalli et al. 2018; Chopra et al. 2005; Singh 2006; Nag 1998; Thakkar and Dhiman 2007). Researchers and planners can quickly implement the assessment of large areas covering a river basin from the satellite imagery, topographic maps, and GIS tools as they can assist in extracting, storing, and analyzing the morphometry of the drainage network (Rai et al. 2017). The topographical maps and GIS tools are useful to extract stream network, slope, and aspects to analyze the morphometry. But with the availability of new methods and advanced algorithms, streams are automatically derived from Digital Elevation Models (DEM). In addition to this, watersheds are also delineated from satellite-based DEMs using

tools such as SWAT, HEC GEOHMS, etc. (Das et al. 2016; Reddy and Reddy 2015; Niyazi et al. 2019). Several researchers have used the SWAT model to delineate watersheds to analyze the morphometric parameters and prioritize the watersheds (Niyazi et al. 2019; Parupalli et al. 2018; Thomas and Prasannakumar 2015; Panhalkar et al. 2012; Aher et al. 2014). Some researchers have used land use categories, change analysis (Biswas and Biswas 2015; Iqbal and Sajjad 2014; Javed et al. 2009) and weighted overlay analysis (Javed et al. 2009) for morphometric analysis. The spatial and temporal land use changes were assigned ranks based on the percentage change of specific land use. The ranks of land use categories and morphometric analysis are added together to assess the compound rank, and the lesser value has high priority, and higher value has lower priority. These studies have shown that ranks assigned for land use changes and morphometric parameters are useful to prioritize critical watersheds based on the land use change.

Some researchers developed expert systems using artificial neural network (ANN), fuzzy analytical hierarchy process (FAHP) (Aher et al. 2013; Rahaman et al. 2015), Kohonen neural network (KNN) (Sivasena Reddy and Janga Reddy 2013; Raju and Kumar 2011), multi-criteria analysis, and Monte Carlo simulation to prioritize watersheds. These expert systems standardize, automate, and increase the robustness of the investigation. Thus, GIS and artificial intelligent (AI) systems have shown reliability in the automatic prioritization and categorization of watersheds. The FAHP method allows researchers to evaluate the identified criteria based on expert’s inputs to determine ranks or priorities or statistical analysis that analyze the watershed conditions (Jaiswal et al. 2015). Such analysis helps researchers achieve the best when implementing integrated watershed management practices (De Steiguer et al. 2003; Jaiswal et al. 2014). The FAHP method was employed in the Paraguaw river basin located in Brazil to assess water management plans (Srdjevic and Medeiros 2008). In another study, the FAHP with different erosion hazard parameters (EHPs) has been used as a pronouncement for the identification of naturally stressed sub-watershed in the Nagwan watershed of the Hazaribagh district in Jharkhand, India (Mishra et al. 2018). The FAHP was used along with remote sensing and geospatial data to delineate and evaluate potential groundwater zones in central India of the Korbha district (Singha et al. 2019) and Panipat region (Kaur et al. 2020) of the Yamuna sub-basin. In another study, fuzzy analytical hierarchical process (AHP) was used for morphometric analysis to prioritize sub-watersheds based on soil erosion in the Jainti River basin, Jharkhand, Eastern India (Hembram and Saha 2020). The FAHP method and morphometric parameters are used to evaluate soil erosion risk in micro- to sub-watershed levels in several basins across India (Nag et al. 2020; Nitheshnirmal et al. 2019; Sadhasivam et al. 2020).

In West Iran regions, researchers have combined GIS and AHP to determine the weight criteria and sub-weight criteria for improving decision-making to improve the sustainability and reduce land degradation in Zagros forests (Babaie-Kafaky et al. 2009). In another case study, the Sediment Yield Index modeling outputs obtained from GIS and FAHP were used (Chowdary et al. 2013) in prioritizing the micro-watersheds. The FAHP method was used to solve the fuzziness in prioritizing sub-watersheds in the Benisagar reservoir catchment in Madhya Pradesh, India (Jaiswal et al. 2015). In the Birjand aquifer, AHP and Fuzzy AHP methods were applied to determine suitable water harvesting areas to support the decision-makers (Khashei-Siuki and Sharifan 2020). Generally, the watersheds are prioritized using the sediment yield or soil loss assessment conducted using the universal soil loss equation (USLE), which was widely used several years (Das et al. 2020; Hembram and Saha 2020; Mishra et al. 2018; Jaiswal et al. 2015). It has been observed that FAHP has gained popularity over the years in water resources as well. Simultaneously, the technique is posed with a couple of criticisms on the decision-making process, arbitrary ranking, the underlying theory of statistics, and mapping (Deng 1999; Hill and Zammet

2000; Jaiswal et al. 2014; Ahmed et al. 2018). However, the outputs of this method were successfully used for decision-making in various fields like transportation, flood protection, marketing, purchasing of items, and banking, etc., including watershed management (Jaiswal et al. 2014). Our research has shown that the hydrological model-generated watersheds are generally not integrated with the local- or country-delineated watershed register codes. The register codes are crucial for planning, decision-making, prioritizing, and implementing the management plans. The watersheds generated from the model might create some undesired confusion during planning and decision-making. To overcome this issue, hydrological modelers need to integrate the country of origin’s watershed register codes with model-delineated watersheds.

Moreover, only very few studies have attempted to use the FAHP method or compound parameter method in water resources without integrating register codes in the hydrological model. The study aims to develop an integrated approach focusing on hydrological model, watershed register codes, and FAHP analysis. This study objective was to apply the above-developed methodology for prioritizing watersheds in the Peddavagu river basin.

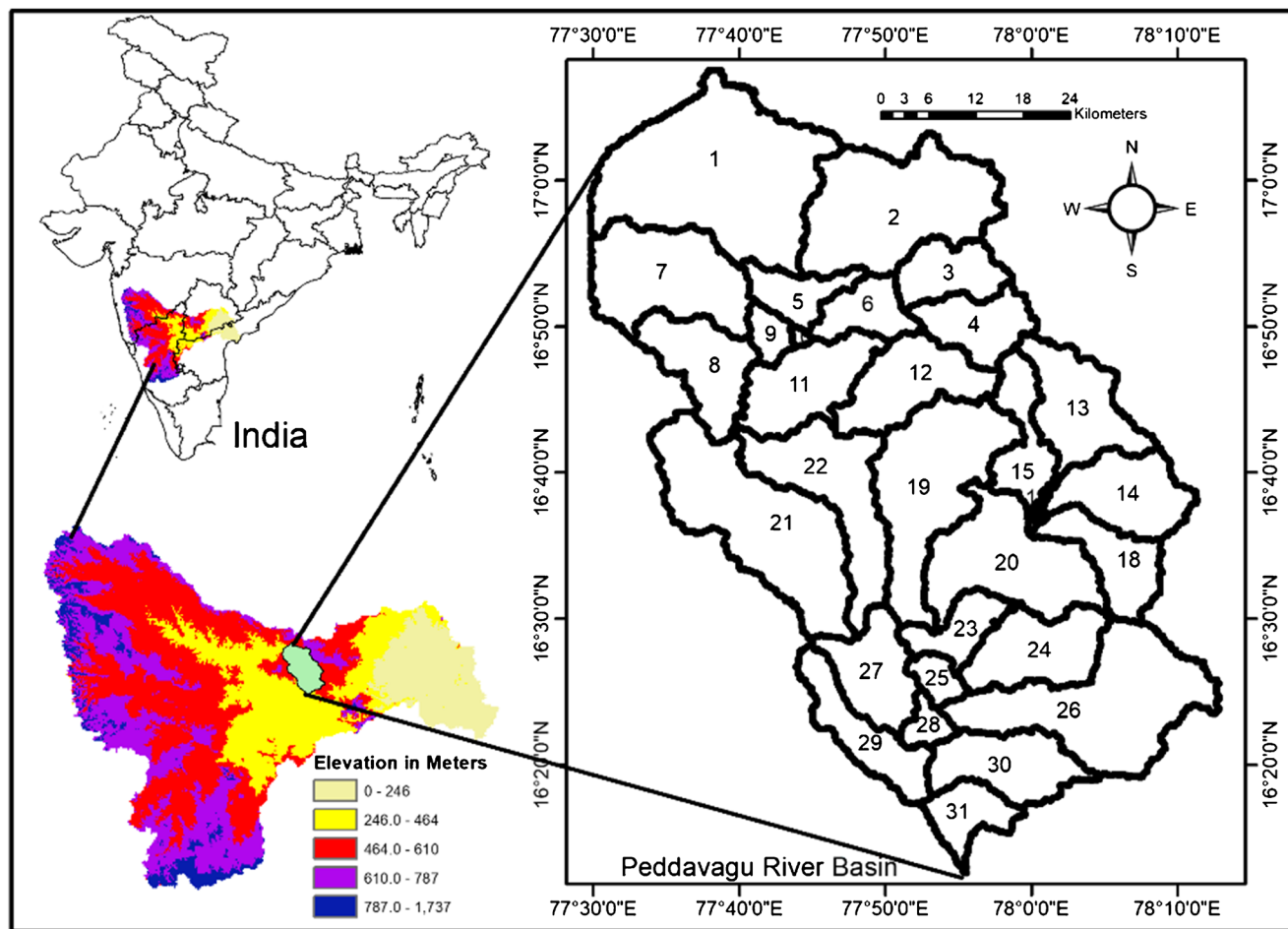


Fig. 1 Location map of the Peddavagu River Basin

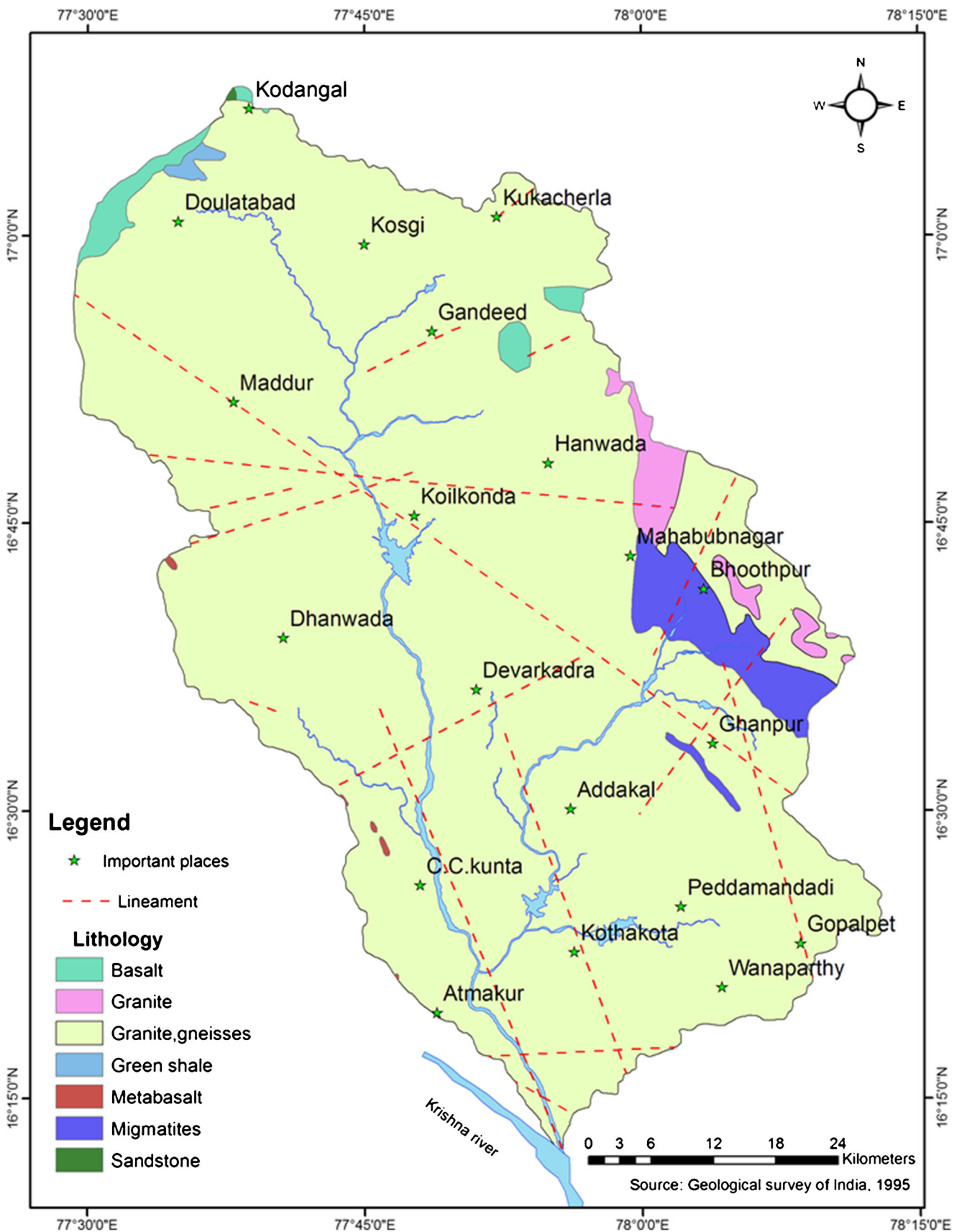


Fig. 2 Geology map of the study area

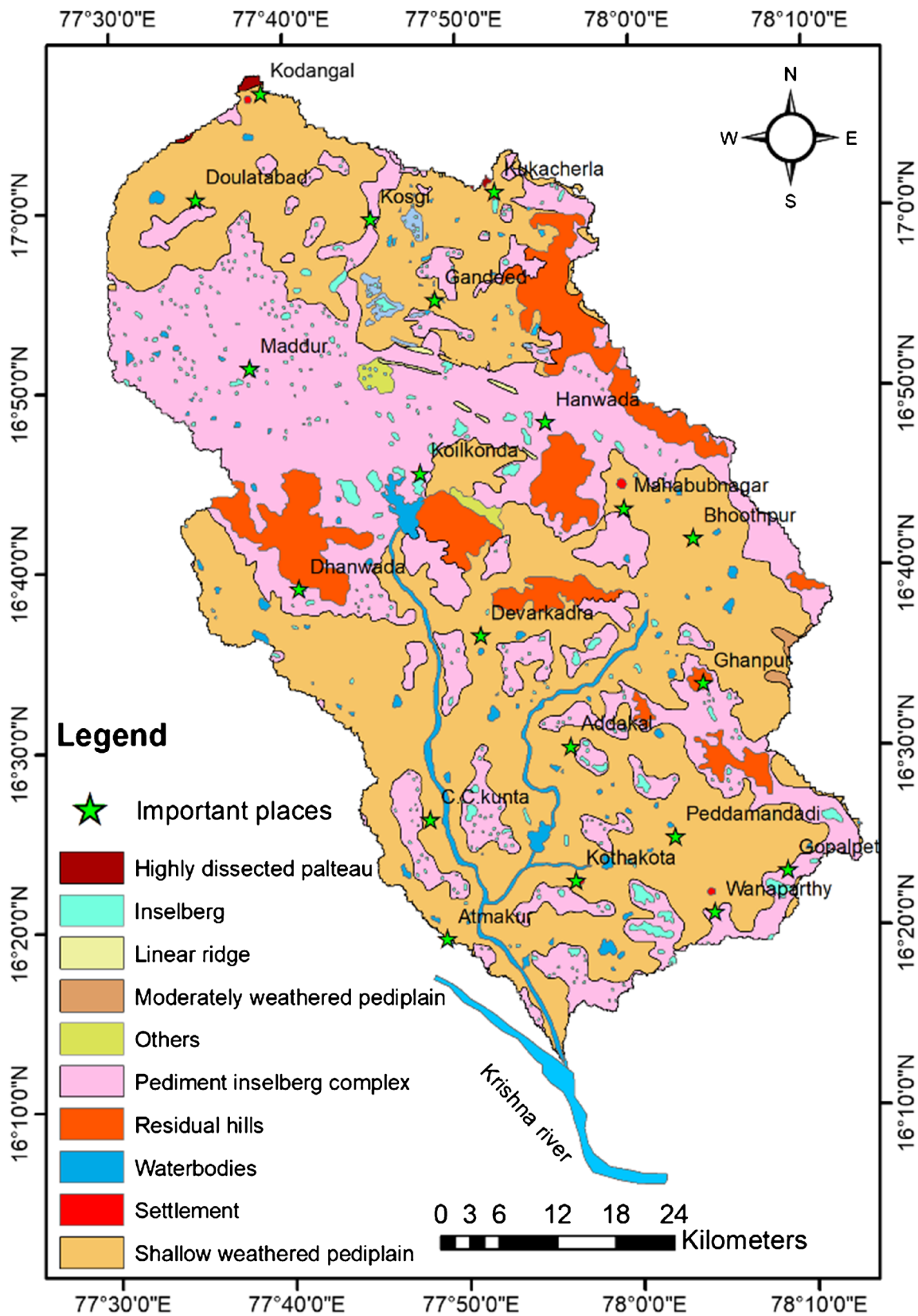


Fig. 3 Geomorphology map of the study area

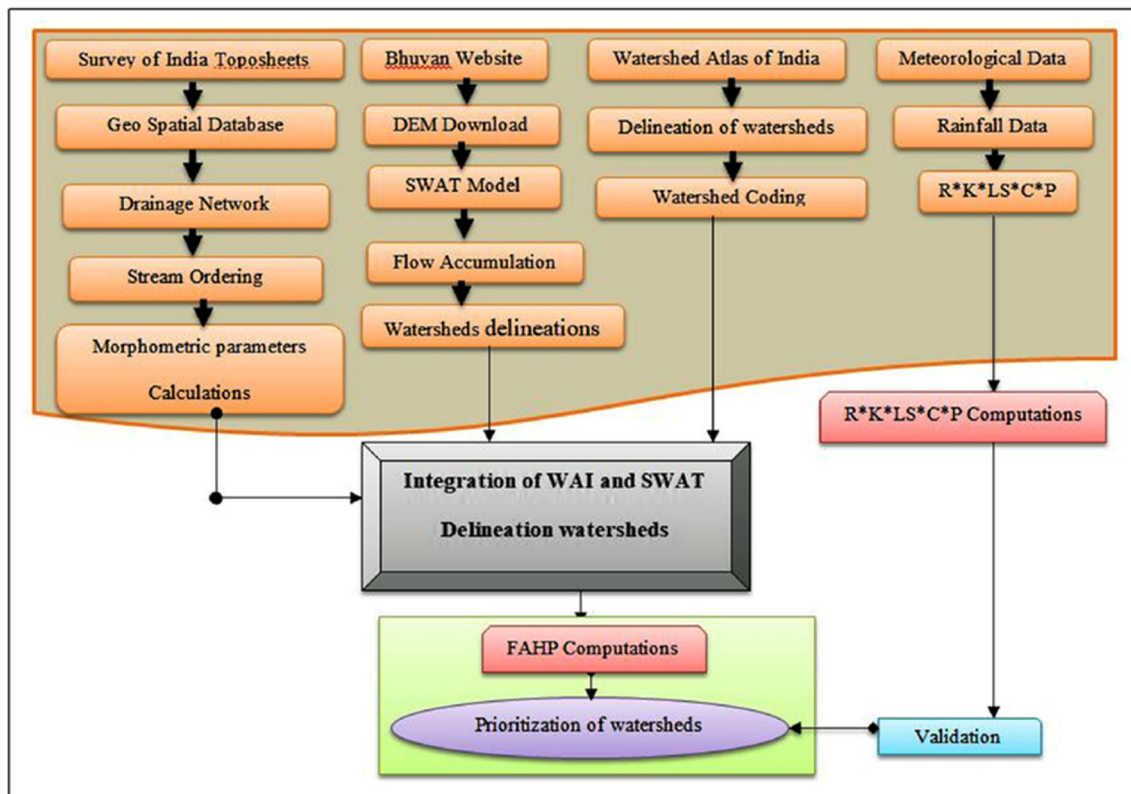


Fig. 4 Flow chart showing the Watersheds Prioritization methodology and validation

## Study area

The Peddavagu river basin is a tributary of the Krishna River located in the Southern Telangana Agro-climatic zone of Telangana state, India. It is situated between  $77^{\circ}28' 33.79''$  to  $78^{\circ} 13' 31.134''$  East longitude and  $16^{\circ} 11' 45.63''$  to  $17^{\circ} 8' 23.744''$  North latitude (Fig. 1). It has a geographical area of 4240.42 sq. km and is spread in 31 subdivisions of the Mahabubnagar district and three subdivisions of the Rangareddy district. The elevation of the basin ranges from 191 to 637 m. The basin's climate transits from tropical to subtropical and has four distinct climatic seasons, such as summer, winter, southwest, and northeast monsoon. The mean annual rainfall of the basin is around 663 mm; it is received mainly during the southwest (June–September) monsoon season. The summers are relatively hot, and the period is from March to May, with temperatures ranging from 32 to 41.5 °C. The winter temperatures range from 16.9 to 19.1 °C, i.e., from November to January. The main livelihoods of rural families are agriculture and allied activities. The region comprises of two agricultural seasons, viz., Kharif (June to October) and rabi (November to March). The major crops grown in the basin are paddy, sorghum, pearl millet, finger millet, maize, groundnut, castor, vegetables, sunflower, chili, and red gram. Kharif crop cultivation is dependent on rainfall and supplemented by groundwater irrigation, while the rabi crop is dependent on only groundwater. Hence, it is imperative to implement soil and water conservation measures in the region,

particularly in critically prioritized watersheds. The basin is spread with soil types like clayey soils, cracking clay soils, gravelly clay soils, gravelly loam soils, and loamy soils.

Figure 2 shows the Peddavagu river basin's geology; the significant portion of the basin is underlain by the archeans crystalline rocks represented by pink and gray granites and gneisses. Granite, migmatites, and genesis rocks are the predominant rock types in the peninsular gneissic complex exposed as high susceptibility hill dolomite and shale. Fine-grained granites and porphyritic granites are quarried near Jadcherla, and Kodangal are used as polishing slabs. The Cuddapah and Kurnool formations comprise of conglomerate, quartzite, and limestone. Figure 3 which shows the river basin's geomorphology was obtained from the State Ground Water Department, Hyderabad, Telangana state. It was further overlaid on the study area to extract and demarcate the exact boundary of the basin using spatial analysis tools in the Arc Map environment. The basin's major geomorphic features are high susceptibility dissected plateau, inselberg, linear ridge, moderate susceptibility weathered pediplain, pediment inselberg complex, residual hills, shallow weathered pediplain, and water bodies.

## Methodology

In the present study, an integrated approach was employed for watershed prioritization after a conscious assessment of the

literature. It was observed that FAHP could improve and automate the watersheds prioritization process along with geospatial tools, hydrological models, and morphometric analysis (Meshram et al. 2019). In this study, the Peddavagu river basin was discretized into watersheds using the SWAT model. Furthermore, these watersheds were coded as per the “Watershed Atlas of India” and morphometry. The first level of classification was based on “Watershed Atlas of India,” where each watershed was assigned with some standard attribute code. The second method included delineating micro-level watersheds using a digital elevation model (DEM) in a SWAT model. Furthermore, morphometric parameters were analyzed for all the watersheds, and FAHP was used to prioritize the watersheds. Figure 4 depicts the adopted method for prioritization of watersheds and validation.

### Delineation of watersheds from “Watershed Atlas of India”

The Peddavagu river basin was identified as part of sheet three of India’s “Watershed Atlas.” The sheet three was scanned using a scanner and was saved in the TIFF format. The scanned map was imported into the ArcMap environment, and was georeferenced.

The rectified map was having an RMSE error of 0.02 decimal degrees within the acceptable limits for soil erosion analysis. Furthermore, the raster map was projected in Arc Map, i.e., from the spherical coordinate system to the plane coordinate system (three-dimensional to the two-dimensional surface) to represent the real-world area units of the study area. To extract the watershed boundaries from the raster map, we have first created a personal geodatabase in the ArcCatalog environment.

Furthermore, the projected raster map was imported into the ArcMap environment, and then it was overlaid with the study area boundary to create a personal geodatabase. Subsequently, the study area’s watershed boundaries were digitized, and relevant attribute data were added into the geodatabase and stored against the same feature class. The digitized watersheds were assigned with codes as per the “Watershed Atlas of India (WAI),” as shown in Fig. 5a. The present study area, i.e., the Krishna river basin, is assigned with 4D code as per the “Watershed Atlas of India.” The current study area, i.e., the Peddavagu river basin, a tributary of the Krishna River, is divided into four watersheds, namely 4D2D1, 4D2D2, 4D2D3, and 4D2D4. The alphanumeric data in the registered codes designate as follows: 4—Region, D—Krishna River, 2—Catchment number, D—Sub-catchment number, and 1—Watershed number.

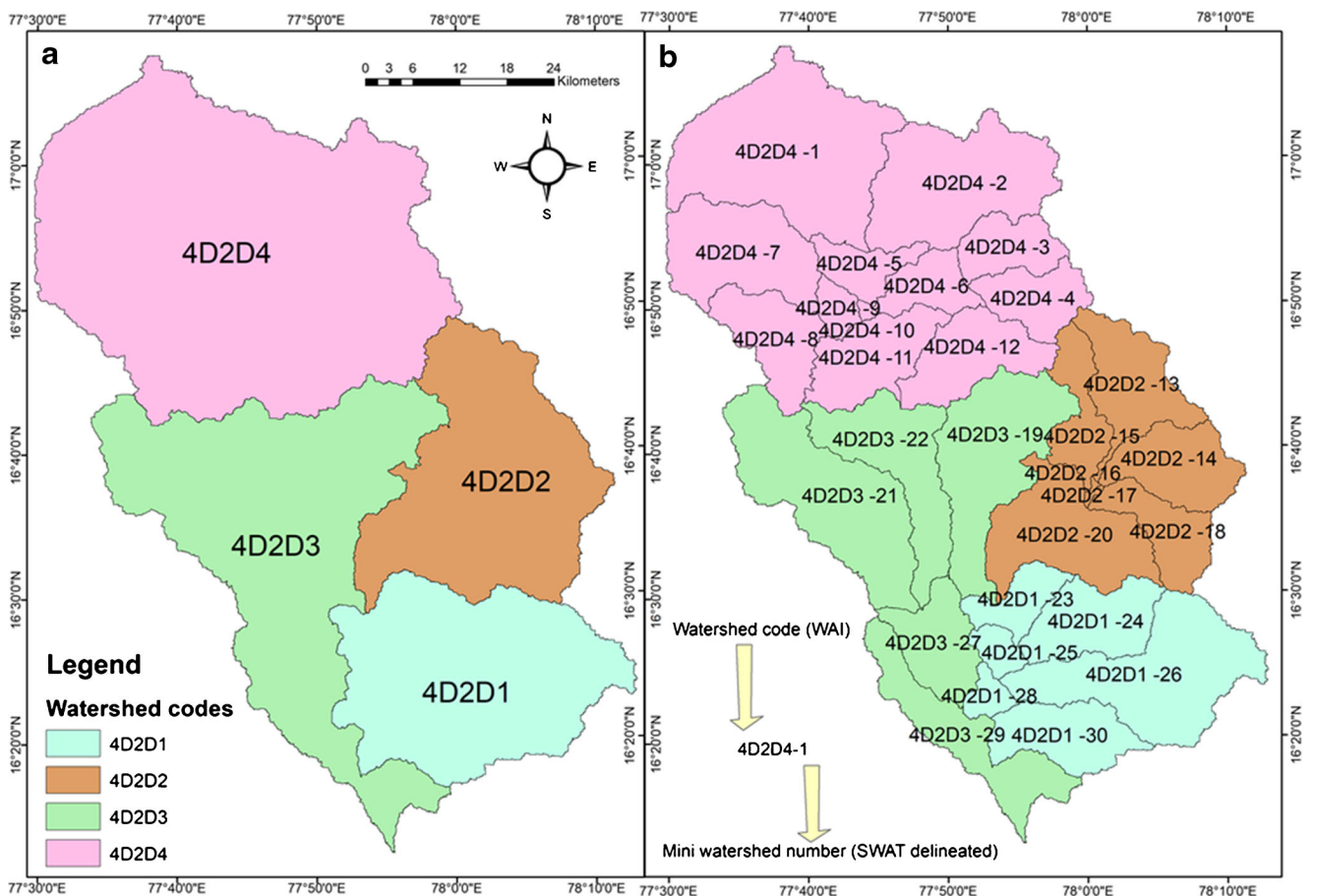


Fig. 5 a WAI delineated codes. b SWAT mapped to WAI codes

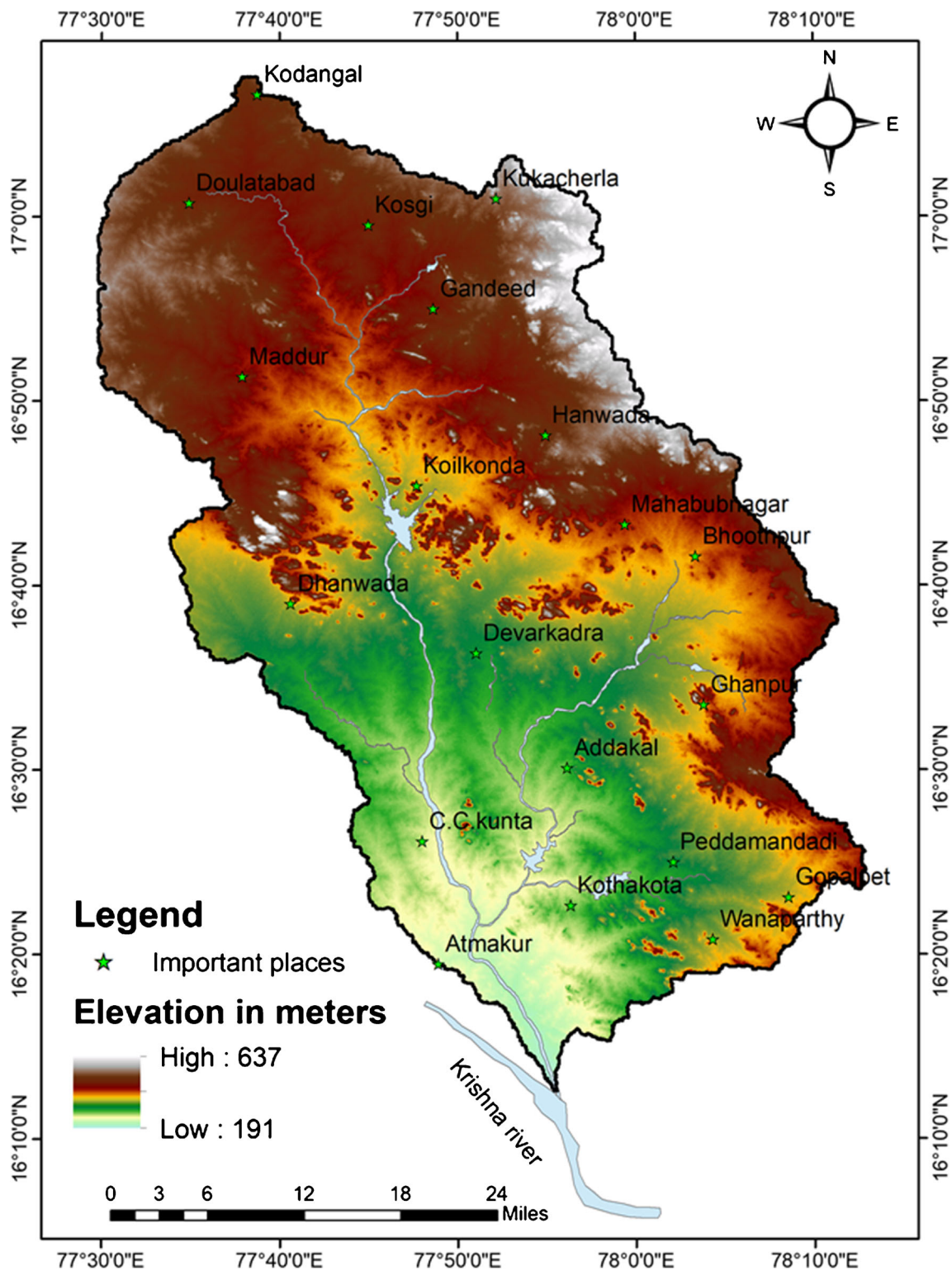


Fig. 6 Digital Elevation Model (DEM) of the study area

**Discretization of watersheds using the SWAT model**

The sub-watersheds delineated using WAI were further discretized into micro-watersheds using a DEM in the SWAT model. To accomplish this, CartoDEM (Digital

Elevation Model) version of Cartosat-1 was downloaded from Bhuvan portal (<https://bhuvan-app3.nrsc.gov.in/data/download/index.php>), National Remote Sensing Center (NRSC), Government of India. NRSC-generated DEM from the stereo images were obtained using two panchromatic



cameras—one near nadir looking aft (Band A) with a tilt of  $-5^\circ$  and the other looking forward (Band F) positioned at  $+26^\circ$ , collecting the stereo coverage of the terrain. It has a spatial resolution of 2.5 m, spectral resolution ranging from 0.5 to 0.85  $\mu\text{m}$  with a swath width of 30 km (Pan-F) and 25 km (Pan-A). The orthorectification process is carried out using ground control points (GCPs). It was observed that the basin has a high elevation and lowest elevation values of 637 and 191 m, respectively, as shown in Fig. 6. The study area's northern and eastern regions have high susceptibility elevation contours, while the southern part is mostly plain. CartoDEM was used as an input to the SWAT model to generate flow accumulation and flow direction raster datasets of the Peddavagu river basin. Furthermore, these rasters' were used to generate vector files of the stream network as well as watersheds (Parupalli et al. 2018).

The hydrological modeling software was used to generate watershed boundaries in vector format from flow direction and flow accumulation rasters'. However, the watershed area's delineation depends on the threshold value provided and the inflow accumulation map. Based on the drainage outlet point, the hydrological model creates watershed boundaries along with area, slope, watershed ids, minimum and maximum elevation, slope length, etc. Generally, the hydrological models are capable of accurately delineating the watershed boundaries. But they lack the provision to incorporate the alphanumeric codes of specific countries or regions. So, for the proper planning of watersheds, it was observed that the nomenclature of watersheds plays a crucial role; the codes were curated in the GIS attribute data. Hence, the watersheds were segmented into micro-watersheds using DEM and drainage maps in the SWAT model. The SWAT model generated 31 (31) micro-watersheds, and these micro-watersheds were sub-coded, as shown in Fig. 5b.

### Stream ordering and SWAT watershed codes designation

In the present study area, the visual interpretation technique was used for digitizing the drainage network by georeferencing and mosaicking the topographic maps in the GIS environment. The drainage lines were extracted from the Survey of India topographical maps of 1:50,000 scales, surveyed by the Government of India during 1965–1969 and 1983–1990, and were digitized in the GIS environment. They were substantiated using the DEM data acquired from satellite imagery using image interpretation. Strahler's (1957) stream ordering method was used to assign the stream order numbers to the streams in the stream network map. In this stream ordering method, the stream order increases when streams of the same order intersect. The overland flow influences the first-order streams. Thus, these stream areas have been more beneficial from the riparian buffers than other areas

of the watersheds. It was observed that the drainage is well developed and has dendritic to the sub-dendritic pattern. The Peddavagu River is a seventh order basin having drainage lines of different stream orders and lengths, as shown in Table 1.

Table 2 shows the mapping of SWAT delineated watersheds with the watershed codes as per the "Watershed Atlas of India." The coding helps in easy identification of the micro-watersheds, prioritization, and management.

### Morphometric assessment of micro-watersheds

The study area's drainage map was generated along with stream order, as shown in Fig. 7, and was further used for morphometric analysis. The linear morphometric parameters such as basin length ( $L_b$ ), the total number of streams of all orders ( $N_u$ ), total stream length of all orders ( $L_u$ ), bifurcation ratio ( $R_b$ ), and aerial aspects like drainage density ( $D_d$ ), stream frequency ( $F_s$ ), drainage texture ( $T$ ), elongation ratio ( $R_e$ ), circularity ratio ( $R_c$ ), form factor ratio ( $R_f$ ), and compactness coefficient ( $C_c$ ) formulae were presented in Table 3. These formulas were used to determine the above parameters for all the micro-watersheds delineated using the SWAT model.

### Prioritization of watersheds using fuzzy analytical hierarchy approach

Micro-watersheds are prioritized to identify the critical watersheds, and accordingly, management plans such as soil and water conservation measures are implemented. Several researchers have used the compound parameter method, fuzzy analytical hierarchy process (FAHP), Kohonen neural network (KNN) method, quantitative and statistical approaches. Among these methods, FAHP was the best method as it deals with fuzziness, uncertainty, and vagueness (Ahmed et al. 2018; Rahaman et al. 2015). Zadeh (1965) developed the fuzzy logic concept 1965; this concept explains the relationship between fuzzy membership functions and fuzzy sets, real numbers with intervals ranging from 0 to 1; these numbers are

**Table 1** Peddavagu river basin stream ordering (Strahler) and stream lengths

S. no	Stream order	Stream no's	Stream length (km)
1	1	7157	4662.2
2	2	1873	1787.6
3	3	545	1670.1
4	4	164	513.8
5	5	53	384.5
6	6	19	89.9
7	7	13	87.0

**Table 2** Watershed Atlas of India codes mapped to SWAT watershed IDs

S. no	Watershed Atlas Code	SWAT model delineated watershed ids
1	4D2D1	23, 24, 25, 26, 28, 30
2	4D2D2	13, 14, 15, 16, 17, 18, 20
3	4D2D3	19, 21, 22, 27, 29, 31
4	4D2D4	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12

different from the crisp set (Wijitkosum and Sriburi 2019). The triangular fuzzy comparison matrix was used to obtain the crisp priority vector through FAHP to prioritize watersheds based on the erodibility (Ahmed et al. 2018; Rahaman et al. 2015; Aher et al. 2013). In this study, erodibility was used as the primary decision parameter to prioritize the watersheds using FAHP analysis.

In FAHP analysis, it is essential to organize the watershed parameters in equal size (i.e., row and column) in the comparison matrix. The following parameters such as basin length (BL), drainage density ( $D_d$ ), stream frequency ( $F_s$ ), form factor ratio ( $R_f$ ), circularity ratio ( $R_c$ ), elongation ratio ( $R_e$ ), texture ratio ( $T$ ), bifurcation ratio ( $R_b$ ), and compactness coefficient ( $C_c$ ) were considered to set up the comparison matrix. Furthermore, these parameters were scaled and plotted to express the relative importance in fuzzy triangular sets, as shown in Fig. 8. These fuzzy sets and reciprocal values, which were converted from stage scale based on the definition of linguistic, are shown in Table 4 as defined by Saaty’s rating scale (Alonso and Lamata 2006). The triangular fuzzy set values shown in the matrix were used to classify the watersheds as follows: one means equal importance and is categorized as, 1.25 as moderate susceptible, 1.5 as high susceptibility, 1.75 as very high susceptibility, and the values in reciprocals of (1/1.25, 1/1.5 and 1/1.75) are deemed to be less critical than others in the descending order.

Each parameter’s fuzzy set values are shown in the pairwise comparison matrix, which was constructed based on the erodibility factor. These constructed pairwise comparison matrix values help assess each watershed parameter’s fuzzy weighted values and normalized weight value. The generated normalized values were verified for consistency and validated if the range is within the acceptable limits or not by using the consistency index. The consistency ratio check depends on the framed matrix size; for the present study, a nine by nine matrix was chosen so that the consistency ratio value could be 1.45, as shown in Table 5.

**Consistency index**

The consistency index measures deviation or degree of consistency using the formula proposed by Saaty (Wijitkosum and Sriburi 2019). The FAHP method evaluates the consistency ratio (CR) and consistency Index (CI). If the CR value evaluation shows less than 10%, it indicates that the decision can be considered consistent or not (Jaiswal et al. 2014):

$$CR = (CI/RI) \times 100$$

Saaty’s proposed equation for CI is as shown below, which is a unitless number and depends on the size of the matrix, as shown in Table 5 (Jaiswal et al. 2014):

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

where  $\lambda_{max}$  is the principal Eigen value and  $n$  is the matrix size.

The normalized weighted value is multiplied with watershed characteristics to determine the fuzzy rank of each watershed. To assess each watershed’s final fuzzy rank, the cumulative and mean values of  $D_d$ ,  $L_b$ ,  $F_s$ ,  $R_f$ ,  $R_c$ ,  $R_e$ ,  $T$ ,  $R_b$ , and  $C_c$  parameters were estimated. The values obtained in the fuzzy ranks were used to determine the priority of micro-

**Table 3** Morphometric parameters, formula, and references

S. no	Basin parameter	Formula	References
1	Basin length ( $L_b$ )	$L_b = 1.312 \times (A)^{0.568}$	Nookaratnam et al. (2005).
2	Drainage density ( $D_d$ )	$D_d = Lu/A$	Horton (1945).
3	Stream frequency ( $F_s$ )	$F_s = N/A$	Horton (1945).
4	Form factor ( $R_f$ )	$R_f = A/(L_b)^2$	Horton (1945).
5	Circularity ratio ( $R_c$ )	$R_c = 4\pi A/P^2$	Miller (1953).
6	Elongation ratio ( $R_e$ )	$R_e = (2/L_b) \times (A/\pi)^2$	Schumm (1956).
7	Drainage texture ( $T$ )	$T = (Nu/P)$	Horton (1945).
8	Bifurcation ratio ( $R_b$ )	$R_b = Nu/Nu+1$	Schumm (1956).
9	Compactness coefficient ( $C_c$ )	$C_c = 0.2821 \times P/(A)^{0.5}$	Horton (1945).

A area of the basin (km<sup>2</sup>),  $Lu$  total stream length of all orders,  $L_b$  basin Length (km),  $N$  total number of streams,  $P$  perimeter of the basin (km),  $Nu$  total number of streams of all order,  $Nu+1$  number of stream segment of next higher order

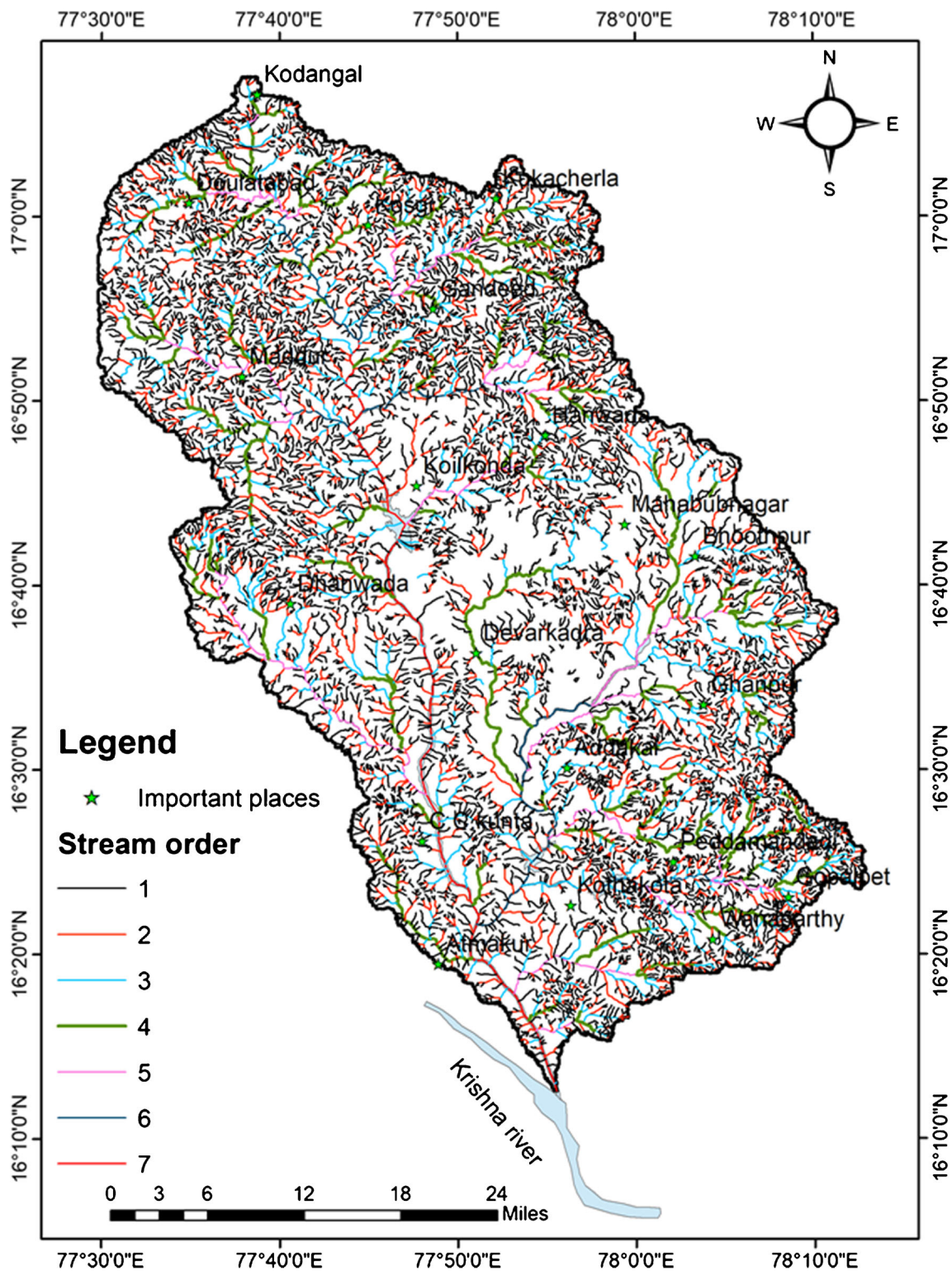


Fig. 7 Stream network map of the river basin

watershed as low, medium, severe, and very high susceptibility. So, in the present study, to classify the watersheds, a fuzzy limit of 0 to 1 (Table 6) was considered. If the simulation values range between 0 and 0.4 then watershed priority was deemed to be of low susceptibility; if it was between 0.4–0.55

then the priority was moderate susceptibility; if the range was between 0.56–0.65 then the priority was high susceptibility and when the range was greater than 0.65 the priority was very high susceptibility. Table 6 shows the relative erosion influence and the fuzzy ranges; if the fuzzy rank values range

**Table 4** Saaty's rating scale definition and explanation

Stage of scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	Favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed

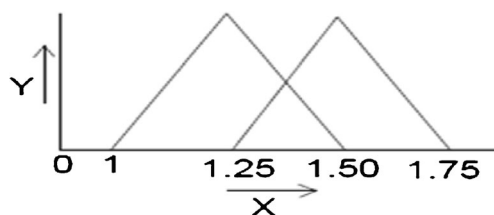
from 0 to 0.4 then the watershed erosion status is 40%, and priority was classified as low susceptibility. When the value lies between 0.4 and 0.55, the erosion status is 40 to 55%, and priority was classified as a moderate susceptibility if the value lies between 0.56 and 0.65 (56% to 65%) the erosion status is high susceptibility. If the value is greater than 0.65 (65%), the erosion status is very high susceptibility.

It was observed that there are no exact rules for the classification of ranges for prioritization of watersheds based on the fuzzy ranks as shown in Table 7 (Rahaman et al. 2015; Aher et al. 2013; Arami et al. 2017; Sangma and Guru 2020; Jaiswal et al. 2015; Mishra et al. 2018; Nitheshnirmal et al. 2019). So, four classes were considered, as shown in Table 6, which were further used to correlate the FAHP outcomes with soil erosion estimated using USLE.

To correlate the data, the organization of soil erosion classes were considered as follows: soil erosion of 0–5 t/ha/year is considered as low susceptibility, 5–20 t/ha/year as moderate susceptibility, 20–30 t/ha/year as high susceptibility, and greater than 30 t/ha/year as a very high susceptibility class; the value 20 was taken as median from the left and right sides as shown in Fig. 9.

### Comparison of the FAHP method using the universal soil loss equation MODEL

The outcomes of the FAHP analysis were finally compared by estimating the soil erosion of watersheds using the USLE model. The USLE model was used to assess the soil erosion

**Fig. 8** Fuzzy triangular sets

using thematic maps such as R-factor, K-factor, LS-factor, C-factor, and P-factor were produced from various sources. The R-factor map was generated from the rainfall data, which was collected from the local meteorological stations. The K-factor map was created using soil map, LS-factor was created using DEM, C- and P-factors were generated using land use and land cover maps, respectively (Jaiswal et al. 2015; Mishra et al. 2018).

Rainfall erosivity ( $R$ ) factor of the study area was computed using the below equation proposed by Singh et al. 1981. The rainfall data has been collected from 20 (20) rain gauge stations located at Koilkonda, Hanwada, Bhoothpur, Mahabubnagar, Addakal, Kodangal, Maddur, Doulatabad, Kosgi, Dhanwada, Atmakur, Devarkadra, C.C.kunta, Wanaparthi, Kothakota, Peddamandadi, Ghanpur, Gopalpet, Kukacherla, and Gandeed sub-districts of the study area for the period 2013 to 2019. R-factor values were computed for each station and were used to generate spatial variation (i.e., R-factor map (Fig. 10)) using the Inverse Distance Weightage (IDW) method in the ArcMap environment:

$$R\text{-factor} = 79 + 0.363 \times P$$

where  $P$  is the mean annual rainfall in millimeters.

Soil erodability factor ( $K$ ) was estimated from the study area's soil map obtained from the National Bureau of Soil Survey, and Land use planning, Nagpur (NBSSLUP). The soil map taxonomy was classified into clayey Soils, cracking clay soils, gravelly clay soils, gravelly loam soils, and loamy soil. Soil erodability factor ( $K$ ) values were collected from the Agricultural department of Telangana state, India, and are presented in Fig. 11.

LS (Slope Length) factor was prepared using the slope map; the study area's slope map has been made from DEM using a 3D analyst in the ArcMap environment. The slope length map was computed from the percentage of slope steepness using the raster calculator and the below equation in the

**Table 5** Average consistency ratios of different sizes of matrices

No. of Erosion hazard parameters (EHPs ( <i>n</i> ))	3	4	5	6	7	8	9	10
Random consistency ratio (RI)	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

spatial analyst tool of the GIS environment. The slope length map of the study area is shown in Fig. 12:

$$LS = (\text{Flow accumulation} \times \text{cell size}/22.13)0.4 \times (\sin \text{slope}/0.0896)1.3$$

where cell size is 30 m; Sin slope means the value of slope in degrees.

The C- and P-factors were obtained from the land use and land cover (LU/LC) of the study area. The LU/LC map was prepared using the normalized difference vegetation index (NDVI) in the ERDAS digital image processing software to assess C- and P-factors' spatial distribution. The C-factor is called the cover and management factor (C), which is estimated using the ratio of soil loss from an area with a specific cover and management under "clean-tilled continuous fallow" (Wischmeier and Smith 1978). The major land use and land cover classes found in the study area are agricultural lands, fallow land, barren land, water bodies, and forest area. The P-factor is called support practice factor, which is estimated using the ratio of soil loss under a particular soil conservation practice (e.g., contouring, terracing) to upslope and downslope area tillage (Renard et al. 1997). The P-factor map shows the loss of soil from an area due to adopted practices; for example, agricultural land has 0.25 while other practices have one (Ahmed et al. 2018). The C- and P-factor maps are shown in Figs. 13 and 14, respectively. Finally, all the above data are used in the USLE equation for deriving the soil erosion of the watersheds and are further used to validate the FAHP results. Finally, the results of the Fuzzy AHP and USLE models were compared using the non-parametric Spearman rank correlation coefficient test (Arabameri et al. (2020); Szmidski and Kacprzyk (2011); Chitsaz and Banihabib 2015):

Universal soil loss equation (USLE),  $A = R \times K \times LS \times C \times P$

*A* = soil loss assessment - t/ha/year, *R* = rainfall-runoff erosivity factor—MJ mm/ha/h/year, *K* = soil erodability factor— $\text{ha}^{-1} \text{MJ mm}^{-1}$ , *LS* = slope length factor—unit less, *C* = cover and management factor—unit less, *P* = support practice factor—unit less.

### Results and discussions

Morphometric analysis is generally employed for the prioritization of watersheds and soil erosion risk assessment.

Moreover, the status of the watersheds is categorized based on the cumulative assessment of all the morphometric parameters using either of the approaches: weighted analysis, overlay analysis, ranking, etc. (Chowdary et al. 2013), while the most recent strategy has been neural networks (Aher et al. 2014). In the current study, we have implemented the fuzzy analytical hierarchical process (AHP) as it is a promising approach to assign weights for criteria by the decision-makers and ranking the watersheds. The Peddavagu river basin was classified into four sub-watersheds based on the Watershed Atlas of India (WAI). These watersheds were coded as per the watershed atlas guidelines and were further used to code the 31 mini watersheds generated using the SWAT model. Such coding (Fig. 5a, b) and integration help define a watershed and support in implementing, monitoring, and managing various watershed development operations. The watersheds were generated using the SWAT model, and stream network was used to analyze morphometric parameters. Furthermore, these values were analyzed, cumulated, and were ranked using fuzzy analytical hierarchical processes to prioritize the mini-watersheds.

### Outcomes of morphometric analysis

Morphometric assessment included the assessment of drainage density (*D<sub>d</sub>*), stream frequency (*F<sub>s</sub>*), drainage texture (*T*), bifurcation ratio (*R<sub>b</sub>*), etc., as shown in Table 8 and Table 9. Among the above parameters, the linear parameters such as drainage density (*D<sub>d</sub>*), frequency (*F<sub>s</sub>*), texture (*T*), and bifurcation ratio (*R<sub>b</sub>*) have shown a direct influence on soil erosion or erodibility. If the linear parameter (*s*) has a high value, it indicates high erodibility and vice versa; high erodibility indicates high importance, and a low value indicates low importance (Rahaman et al. 2015). The stream network analysis of each sub-watershed using morphometric equations (Table 3) has shown varying impacts on the watersheds due to the variations in drainage density (*D<sub>d</sub>*), drainage hierarchy ordering, etc. High bifurcation ratio (*R<sub>b</sub>*) values of more than 5 indicated

**Table 6** Relative erosion range and erosion susceptibility status

S. no	Range	Erosion status
1	0–0.4	Low susceptibility
2	0.4–0.55	Moderate susceptibility
3	0.56–0.65	High susceptibility
4	> 0.65	Very high susceptibility

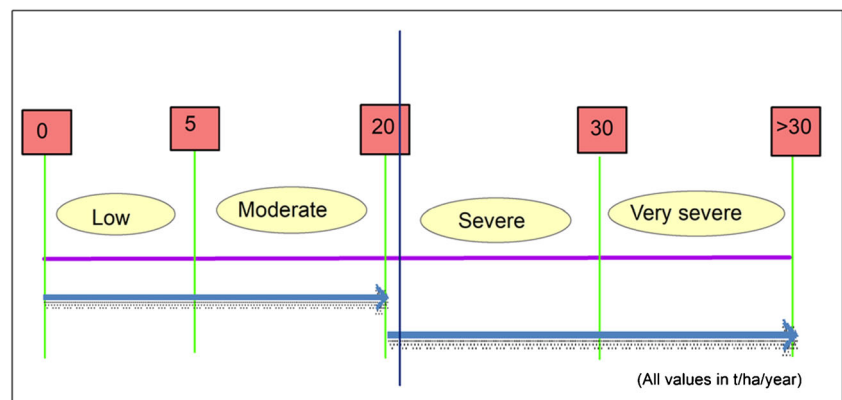
**Table 7** Prioritization classes and ranges considered by various authors

Priority types	Very high	High	Medium	Low	Very low	Author and year
Priority levels	> 0.112	0.109–0.111	0.0851–0.108	0.0791–0.085	< 0.79	Rahaman et al. 2015
	> 0.568	0.511–0.568	0.454–0.511	0.397–0.454	0.057–0.397	Aher et al. 2013
	> 0.568	0.567–0.514	0.513–0.454	0.453–0.397	0.396–0.057	Arami et al. 2017
	0.1818–0.2691	0.1112–0.1818	0.0645–0.1112	0.0466–0.0645	0.0442–0.0466	Sangma and Guru 2020
	More than 0.50	0.37–0.50	0.25–0.37	0.20–0.25	< 0.20	Jaiswal et al. 2015
	> 0.567	0.514–0.567	0.454–0.513	0.397–0.453	0.057–0.396	Meshram et al. 2019
	Exceeding 0.45	0.38–0.45	0.34–0.38	0.29–0.34	< 0.29	Mishra et al. 2018
	0.357–0.458	0.240–0.326	0.098–0.213	0.088–0.096	–	Nitheshnirmal et al. 2019

that the terrain consists of streams strongly controlled by the local geological structures (Kanhaiya et al. 2019). The drainage density ( $D_d$ ) of the basin has an essential relationship with the slope gradient and precipitation in determining the surface runoff. Sub-basins with a higher drainage density of 2.01 to 3.3 (Babu et al. 2016); (Abdulkareem et al. 2018) indicates more precipitation and associated runoff. At the same time, drainage density is due to the materials' underlain resistance leading to coarse drainage texture. In the study area, high drainage density was found in micro-watershed WS-2 with a drainage density of 4.88 km per km<sup>-2</sup> and was lowest in WS-16 with a value of 0.71 km per km<sup>-2</sup>. Low stream frequencies ( $F_s$ ) in parts of the basin infer high susceptibility surface runoff due to fewer structural disturbances. The lowest stream frequency ( $F_s$ ) of 1.07 was found in WS-19, and the high frequency of 3.53 was found in WS-31. The fine drainage texture regions have lower runoff and more infiltration, while coarse drainage texture regions have more runoff (Fenta et al. 2017). The form factor ( $R_f$ ) of the micro-watersheds varied from 0.25 (WS-1) to 0.55 (WS16); this implies that these watersheds are more elongated in shape and have a high runoff. The high elongation ratio ( $R_e$ ) of more than 0.57(WS1) to 0.84 (WS16) indicates high infiltration capacity (Soni 2017). A low circularity ratio ( $R_c$ ) of 0.13 was found in WS22, and the high value of 0.84 was found in WS16; a value less than

one implies that the shape of the micro-watershed will be an elongated circle shape, which is influenced by the length and frequency of streams, geological structures, etc. Watersheds with high priority indicate a greater degree of erosion, and management measures such as soil and water conservation structures have to be recommended and implemented on priority (Parupalli et al. 2018).

Several studies have been conducted on the prioritization of watersheds using compound parameter rank. The ranks to the watersheds were generally assigned based on the cumulative weightage of all the morphometric parameters like basin length ( $L_b$ ), drainage density ( $D_d$ ), stream frequency, bifurcation ratio ( $R_b$ ), texture ( $T$ ), elongation ratio, etc. The watersheds were prioritized based on the watersheds' cumulative weights as follows: lower rank watersheds were categorized as a high priority and high ranks as less priority. Based on research, it was observed that the compound parameter method is based on the weights, summation, division, and simple mathematics, but it is not clear which parameter has to be considered to take as a logical factor (runoff or erodability) for watershed prioritization. In this context, the present study was undertaken to resolve the ambiguity of prioritization of watersheds using a fuzzy approach. In the current study, hydrological parameter erosion was considered to solve the fuzziness or vagueness in the watershed prioritization.

**Fig. 9** Organization of soil erosion classes

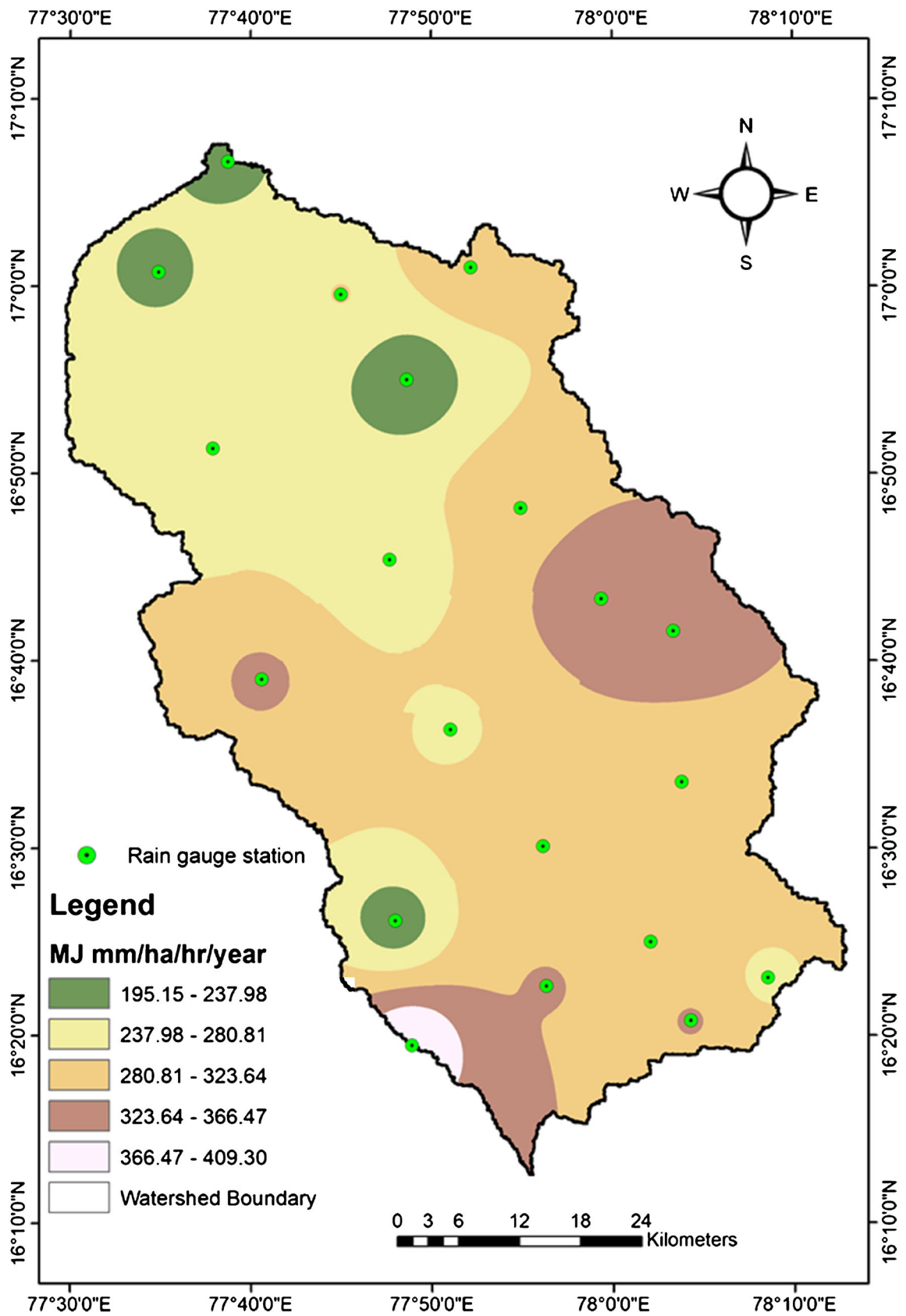


Fig. 10 R-factor map

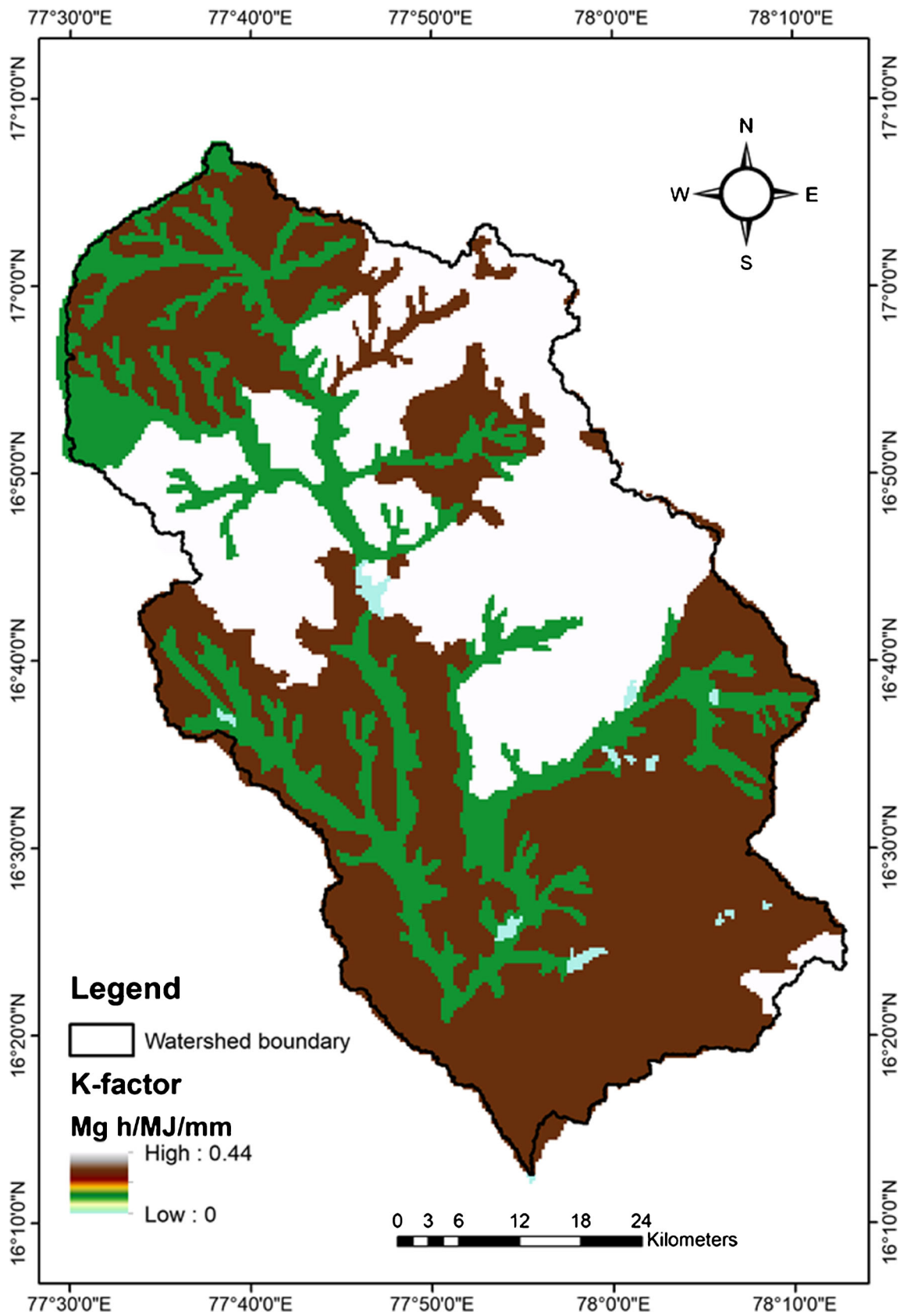


Fig. 11 K-factor map



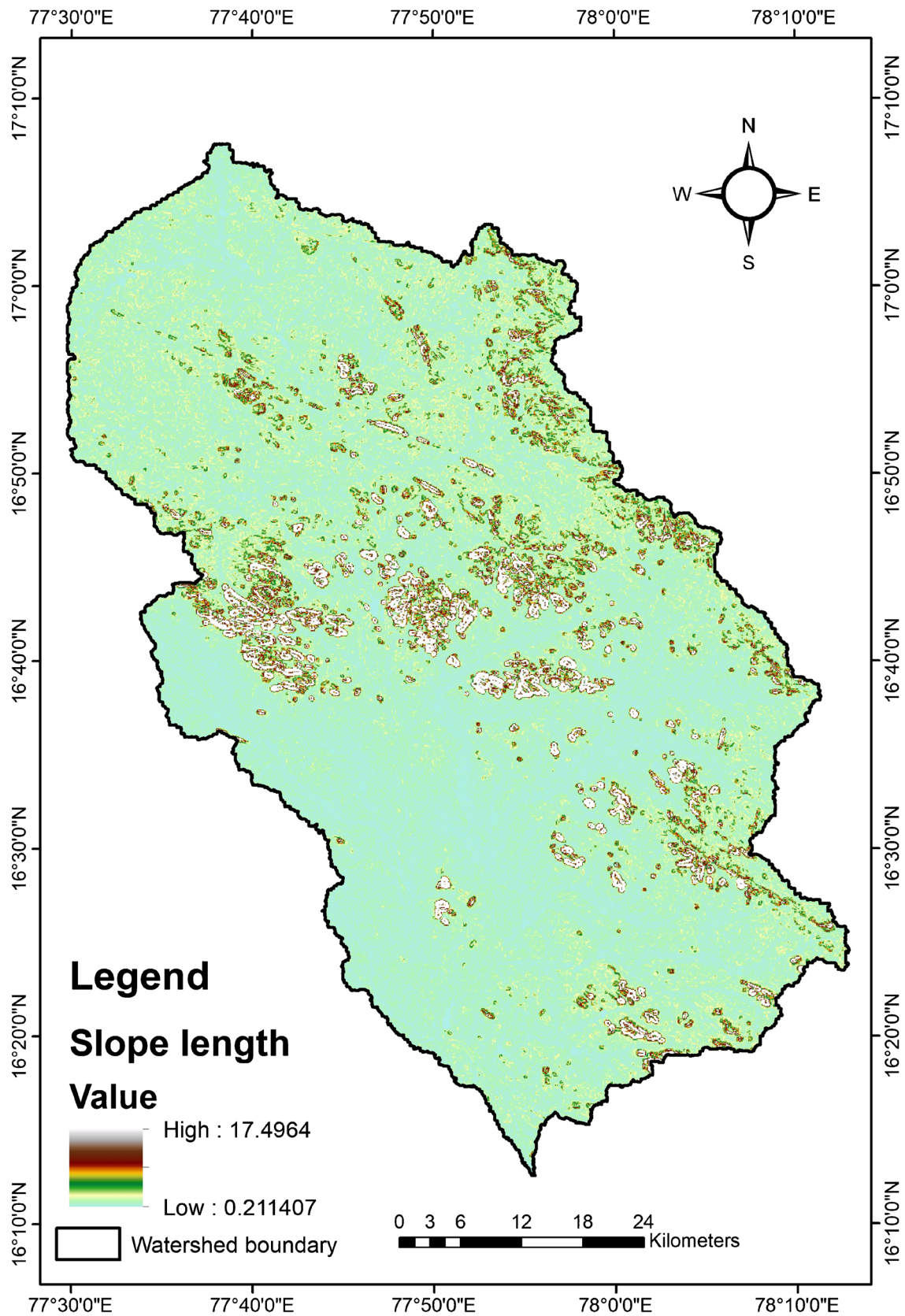


Fig. 12 Slope length map

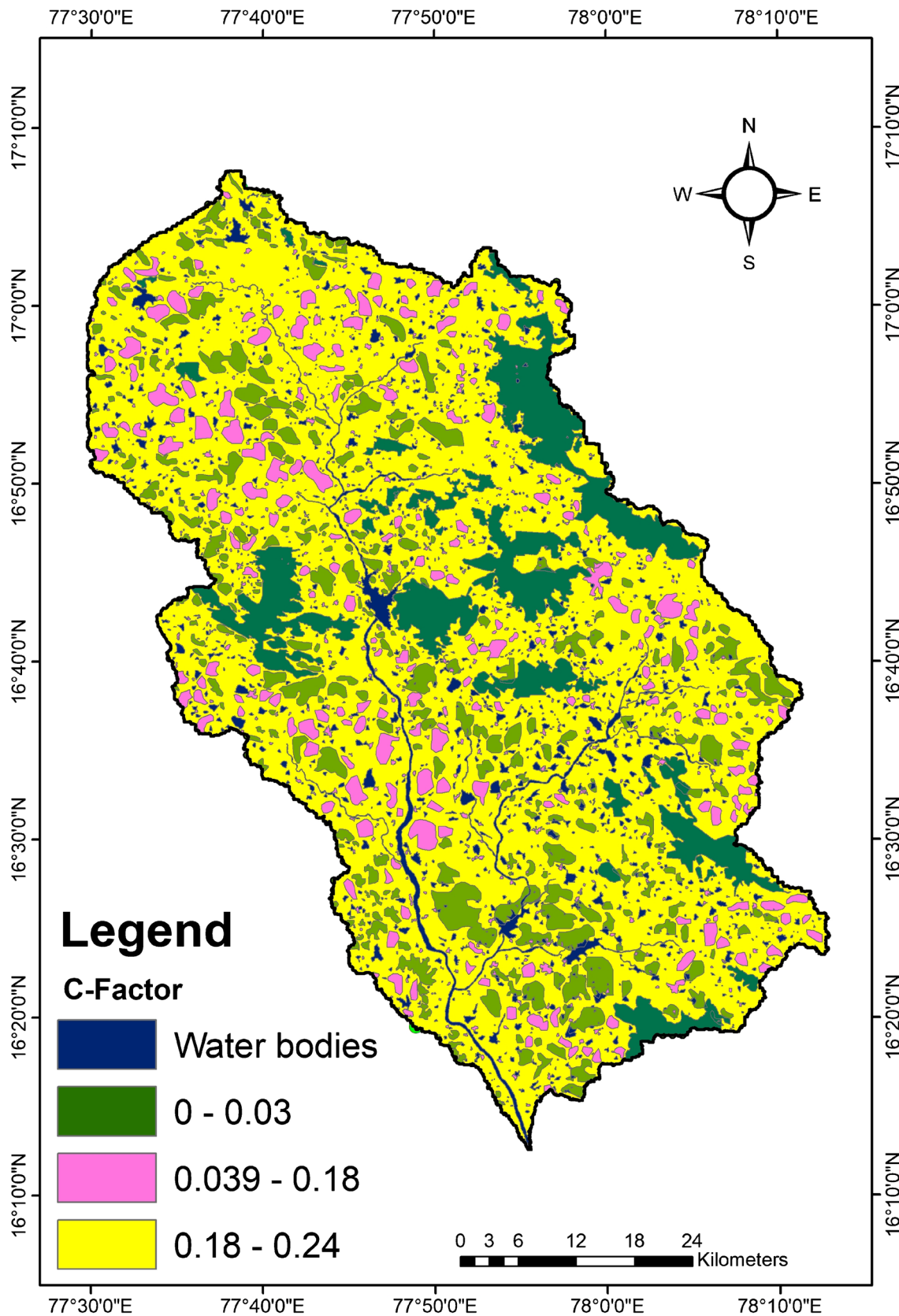


Fig. 13 C-factor map

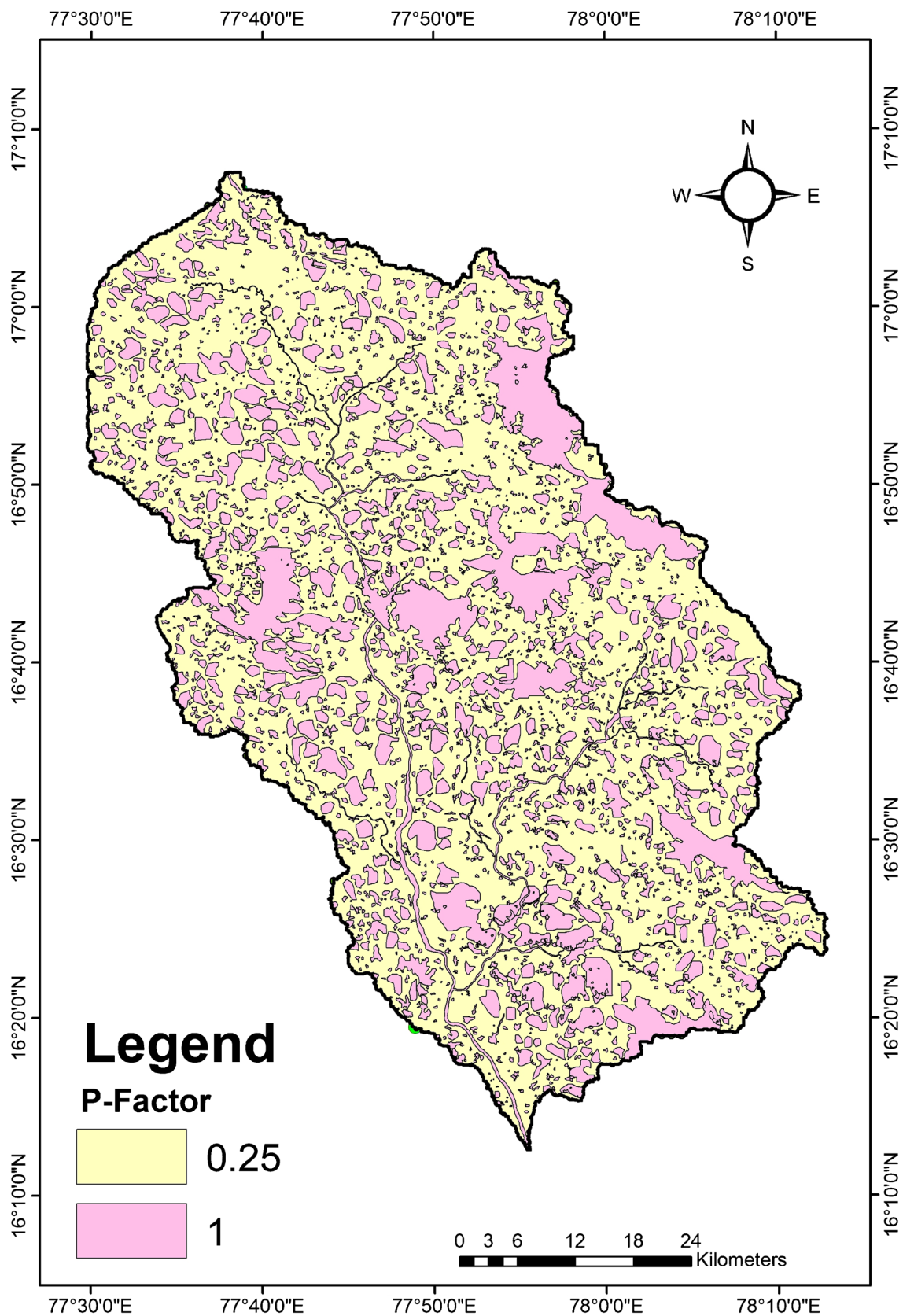


Fig. 14 P-factor map

**Table 8** Characteristics of linear features of Peddavagu Sub-watersheds

Sub-watersheds	No of streams in different stream orders							Order wise total stream lengths (Km)						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
WS1	861	217	59	20	5	1		543.5	227.5	91.9	72.6	183.8	16.8	
WS2	702	179	60	20	2	1		421.9	149.8	813.1	45.5	20.2	5.8	
WS3	224	43	14	8	4			140.9	43.6	22.1	14.1	7.5		
WS4	163	40	11	7	5	1		117.6	46.2	15.5	12.9	8.9	0.1	
WS5	128	32	9	1	0	2	1	83.5	24.6	21	6.3	0	0.6	8.1
WS6	144	34	7	3	0	1	1	95.4	28.1	13.4	5.1	0	13.8	0.3
WS7	376	90	27	9	3			274.1	91.7	46.7	22.6	19.2		
WS8	210	63	20	7	1			157.3	57.7	28.1	23.9	3		
WS9	44	15	4	0	2	2		31	11.1	10.5	0	0.1	6.1	
WS10	5	1	0	0	0	2	2	2.3	1.8	0	0	0	0	2.3
WS11	175	43	14	2	0	0	2	137.2	51.6	25.5	7.4	0	0	11
WS12	236	63	21	5	4	0	2	168.8	49.2	37.6	9.3	15.8	0	2.8
WS13	123	38	13	6				101.9	55.8	31.9	22.7			
WS14	216	62	16	4	1			141.2	62.1	38.5	20.6	9.4		
WS15	133	29	5					105.1	32.5	8.7				
WS16	0	0	1	1	1			0	0	0.3	0.1	0.7		
WS17	1	0	2	0	1			0		1	0	2.7		
WS18	204	61	19	5	1			112.9	56.7	48.9	8.7	0.5		
WS19	223	47	13	6				171.3	67.5	25	33.6			
WS20	274	63	17	8	4	1		197.7	66.8	31.5	24.1	23.1	13.9	
WS21	398	125	50	11	5			303.5	144.9	73	33.3	39.1		
WS22	265	73	20	4	1	0	1	178.3	66.4	31.5	11.2	0	0	28
WS23	98	23	11	2	0	1		56.3	25.1	22.7	2.4	0	7.6	
WS24	308	85	26	7	1	1		160.9	67.4	33.8	32.6	13.1	0.9	
WS25	44	10	3	0	0	1		31.8	9.7	5.3	0	0	4.8	
WS26	803	224	58	14	5	2		439.7	167.6	93.9	52.6	17.5	13	
WS27	191	54	4	1	1	1		119.8	39.9	34.6	10.2	0.1	0	14
WS28	29	8	1	0	0	1	1	23.7	10.3	0.2	0	0	6.6	1.2
WS29	163	43	10	4	0	1	1	113	44.7	14.7	18.1	0	0	9.2
WS30	247	60	16	4	4	0	1	148	58.3	28.4	16.4	15.4	0	0.2
WS31	169	48	14	5	2	0	1	83.3	28.9	20.8	7.6	4.6	0	11

**Prioritization of watersheds using FAHP**

In this study, to prioritize the watersheds of the Peddavagu river basin, the FAHP method was applied, nine morphometric parameters, namely basin length ( $L_b$ ), stream frequency ( $F_s$ ), drainage density ( $D_d$ ), circularity ratio ( $R_c$ ), elongation ratio ( $R_e$ ), drainage texture ( $T$ ), bifurcation ratio ( $R_b$ ), and compound parameter ( $C_c$ ), were selected for the analysis. Generally, for FAHP analysis, the morphometric parameters are arranged in a matrix of equal sizes, a minimum of  $3 \times 3$  size or a maximum of  $10 \times 10$  size, as shown in Table 10. Moreover, the matrix's size is generally determined by the number of parameters used by the user or available expert inputs (Jaiswal et al. 2014). Table 9 shows each cell

designated with a value as per the linguistic form. The main element of erodability is categorized as follows: M as moderate susceptibility, S as high susceptibility, and VS as very high susceptibility. The linguistics showed in Table 4, and fuzzy triangular numbers (Fig. 5) are major constraints of the FAHP process. The fuzzy triangular numbers were used to generate a pairwise comparison matrix, which was further classified as follows : one means equal importance, 1.25 as moderate susceptibility, 1.5 as high susceptibility, 1.75 as very high susceptibility, and the reciprocals were classified as less important as shown in Table 10. The values shown in each cell were used to derive the watershed's FAHP weights, as represented in Table 11 and the values of morphometric parameters were further normalized by multiplying with FAHP weights of the

**Table 9** Morphometric characteristics of Peddavagu sub-watersheds

Watershed	Area (km <sup>2</sup> )	$L_b$	$D_d$	$F_s$	$R_f$	$R_c$	$R_e$	$T$	$R_b$	$C_C$
WS1	447.3	42.02	2.54	2.60	0.25	0.22	0.57	7.30	3.92	2.12
WS2	298.5	33.40	4.88	3.23	0.27	0.22	0.58	7.40	4.38	2.13
WS3	86.8	16.56	2.63	3.37	0.32	0.25	0.64	4.46	3.01	1.99
WS4	95.6	17.50	2.10	2.37	0.31	0.25	0.63	3.26	3.14	2.01
WS5	64.4	13.97	2.24	2.69	0.33	0.18	0.65	2.62	3.71	2.33
WS6	71.8	14.87	2.17	2.64	0.32	0.23	0.64	3.01	2.49	2.10
WS7	211.3	27.45	2.15	2.39	0.28	0.25	0.60	4.91	3.38	2.00
WS8	129.5	20.78	2.09	2.32	0.30	0.20	0.62	3.37	4.09	2.21
WS9	30.1	9.07	1.95	2.23	0.37	0.29	0.68	1.85	1.92	1.86
WS10	4.5	3.08	1.41	2.23	0.47	0.30	0.78	0.73	2.00	1.83
WS11	142.3	21.92	1.63	1.66	0.30	0.19	0.61	2.41	3.54	2.32
WS12	144.4	22.11	1.96	2.29	0.30	0.21	0.61	3.58	2.44	2.17
WS13	151.5	22.72	1.40	1.19	0.29	0.15	0.61	1.61	2.78	2.56
WS14	135.8	21.35	2.00	2.20	0.30	0.26	0.62	3.72	3.84	1.95
WS15	92.8	17.20	1.58	1.80	0.31	0.13	0.63	1.74	5.19	2.81
WS16	1.4	1.62	0.71	2.08	0.55	0.23	0.84	0.34	0.67	2.09
WS17	2.7	2.32	1.36	1.46	0.51	0.19	0.80	0.30	0.00	2.27
WS18	102.8	18.23	2.21	2.82	0.31	0.20	0.63	3.62	3.84	2.23
WS19	271.0	31.61	1.10	1.07	0.27	0.15	0.59	1.92	3.51	2.58
WS20	226.0	28.51	1.58	1.62	0.28	0.17	0.60	2.81	3.24	2.45
WS21	324.9	35.04	1.83	1.81	0.26	0.18	0.58	3.93	3.11	2.35
WS22	202.6	26.80	1.56	1.80	0.28	0.13	0.60	2.55	3.26	2.83
WS23	66.2	14.20	1.72	2.04	0.33	0.17	0.65	1.93	2.96	2.43
WS24	139.1	21.64	2.22	3.08	0.30	0.23	0.62	4.89	3.72	2.09
WS25	31.1	9.25	1.66	1.86	0.36	0.30	0.68	1.60	2.58	1.84
WS26	314.0	34.37	2.50	3.52	0.27	0.18	0.58	7.53	3.38	2.34
WS27	116.7	19.59	1.87	2.16	0.30	0.20	0.62	2.98	4.61	2.21
WS28	27.7	8.66	1.52	1.44	0.37	0.26	0.69	1.10	3.16	1.95
WS29	108.9	18.83	1.83	2.04	0.31	0.15	0.63	2.30	2.32	2.61
WS30	131.2	20.94	2.03	2.53	0.30	0.22	0.62	3.84	2.57	2.13
WS31	67.6	14.37	2.30	3.53	0.33	0.21	0.65	3.76	2.45	2.18

watershed shown in Table 12. The Eigenvector weight ( $\lambda_{max}$ ) value of the Peddavagu watershed was estimated to be 9.45 by

using the geometric computations. The Consistency Index (CI) of the study area was estimated using  $\lambda_{max}$  and  $n$  values,

**Table 10** Linguistics conversion matrix

	$L_b$	$D_d$	$F_s$	$R_f$	$R_c$	$R_e$	$T$	$R_b$	$C_C$
$L_b$	1	1/VS	1/VS	VS	VS	VS	M	S	M
$D_d$	VS	1	VS	1/VS	1/VS	1/VS	1/M	S	1/M
$F_s$	VS	1/VS	1	S	S	S	S	S	1/M
$R_f$	1/VS	VS	1/S	1	S	M	M	M	M
$R_c$	1/VS	VS	1/S	1/S	1	S	M	M	M
$R_e$	1/VS	VS	1/S	1/M	1/S	1	1/M	1/M	1/M
$T$	1/M	M	1/S	1/M	1/M	M	1	1/M	1/M
$R_b$	1/S	1/S	1/S	1/M	1/M	M	M	1	M
$C_C$	1/M	M	M	1/M	1/M	M	M	1/M	1

**Table 11** Pairwise comparison matrix of Peddavagu watersheds

	$L_b$	$D_d$	$F_s$	$R_f$	$R_c$	$R_e$	$T$	$R_b$	$C_C$
$L_b$	1	0.57	0.57	1.75	1.75	1.75	1.25	1.5	1.15
$D_d$	1.75	1	1.75	0.57	0.57	0.57	0.8	1.5	0.87
$F_s$	1.75	0.57	1	1.5	1.5	1.5	1.5	1.5	0.87
$R_f$	0.57	1.75	0.66	1	1.5	1.25	1.25	1.25	1.15
$R_c$	0.57	1.75	0.66	0.66	1	1.5	1.25	1.25	1.25
$R_e$	0.57	1.75	0.66	0.8	0.66	1	0.8	0.8	0.8
$T$	0.8	1.25	0.66	0.8	0.8	1.25	1	0.8	0.8
$R_b$	0.66	0.66	0.66	0.8	0.8	1.25	1.25	1	1.25
$C_C$	0.8	1.25	1.25	0.8	0.8	1.25	1.25	0.87	1
	8.47	10.55	7.87	8.68	9.38	11.32	10.35	10.47	9.14

**Table 12** FAHP Weights of the Peddavagu watersheds

$L_b$	$D_d$	$F_s$	$R_f$	$R_c$	$R_e$	$T$	$R_b$	$C_C$
0.129	0.114	0.137	0.116	0.109	0.093	0.096	0.095	0.106

where the  $n$  value is nine as the parameter data are arranged in  $9 \times 9$  matrixes. The  $\lambda_{max}$  and  $n$  values, i.e., 9.45 and 9, were substituted in the Consistency Index formula (discussed in section 3.4), the CI value was estimated to be 0.05. Finally, the consistency ratio (CR) of the study area was computed using the Consistency Index, Random Index (RI), and multiplied with 100. When the CI is 0.05, the RI is 1.45, as per Table 5, further substituted in the CR formula. The value of consistency ratio (CR) was found to be 0.038 or 3.8

percentage ( $0.038 \times 100 = 3.8\%$ ). The CR value can be used for priority assessment as the estimated (3.8%) consistency ratio of the FAHP analysis is less than 10% and within acceptable limits (Wijitkosum and Sriburi 2019). The sum of all the morphometric parameters considered for the FAHP ranking varied from 0.49 to 0.80. Furthermore, these values were categorized into three categories, i.e., from 0.4 to 0.55 as moderate susceptibility, 0.56 to 0.65 as high susceptibility, and greater than 0.65 as very high susceptibility zones in the Peddavagu watershed, as shown in Table 13.

The 4D2D4 watershed contains 4D2D4-1, 4D2D4-2, 4D2D4-3, 4D2D4-4, 4D2D4-5, 4D2D4-6, 4D2D4-7, 4D2D4-8, 4D2D4-9, 4D2D4-10, 4D2D4-11, and 4D2D4-12 micro-watersheds; from the FAHP ranking, the micro-watersheds priority was observed to be very high

**Table 13** Normalized values with prioritization of the Peddavagu Watersheds based on fuzzy ranks

Watershed	$L_b$	$D_d$	$F_s$	$R_f$	$R_c$	$R_e$	$T$	$R_b$	$C_C$	Fuzzy ranks	Priority
WS1	0.13	0.06	0.10	0.05	0.08	0.06	0.09	0.07	0.08	0.72	Very high susceptibility
WS2	0.10	0.11	0.13	0.06	0.08	0.06	0.09	0.08	0.08	0.80	Very high susceptibility
WS3	0.05	0.06	0.13	0.07	0.09	0.07	0.06	0.06	0.08	0.67	Very high susceptibility
WS4	0.05	0.05	0.09	0.07	0.09	0.07	0.04	0.06	0.08	0.60	High susceptibility
WS5	0.04	0.05	0.11	0.07	0.07	0.07	0.03	0.07	0.09	0.60	High susceptibility
WS6	0.05	0.05	0.10	0.07	0.09	0.07	0.04	0.05	0.08	0.59	High susceptibility
WS7	0.08	0.05	0.09	0.06	0.09	0.07	0.06	0.06	0.08	0.65	High susceptibility
WS8	0.06	0.05	0.09	0.06	0.08	0.07	0.04	0.07	0.08	0.61	High susceptibility
WS9	0.03	0.05	0.09	0.08	0.11	0.08	0.02	0.04	0.07	0.55	Moderate susceptibility
WS10	0.01	0.03	0.09	0.10	0.11	0.09	0.01	0.04	0.07	0.54	Moderate susceptibility
WS11	0.07	0.04	0.06	0.06	0.07	0.07	0.03	0.06	0.09	0.56	High susceptibility
WS12	0.07	0.05	0.09	0.06	0.08	0.07	0.05	0.04	0.08	0.59	High susceptibility
WS13	0.07	0.03	0.05	0.06	0.06	0.07	0.02	0.05	0.10	0.50	Moderate susceptibility
WS14	0.07	0.05	0.09	0.06	0.10	0.07	0.05	0.07	0.07	0.62	High susceptibility
WS15	0.05	0.04	0.07	0.07	0.05	0.07	0.02	0.10	0.11	0.57	High susceptibility
WS16	0.01	0.02	0.08	0.12	0.09	0.09	0.00	0.01	0.08	0.50	Moderate susceptibility
WS17	0.01	0.03	0.06	0.11	0.07	0.09	0.00	0.04	0.09	0.49	Moderate susceptibility
WS18	0.06	0.05	0.11	0.07	0.08	0.07	0.05	0.07	0.08	0.63	High susceptibility
WS19	0.10	0.03	0.04	0.06	0.06	0.07	0.02	0.06	0.10	0.53	Moderate susceptibility
WS20	0.09	0.04	0.06	0.06	0.06	0.07	0.04	0.06	0.09	0.57	High susceptibility
WS21	0.11	0.04	0.07	0.05	0.07	0.06	0.05	0.06	0.09	0.61	High susceptibility
WS22	0.08	0.04	0.07	0.06	0.05	0.07	0.03	0.06	0.11	0.56	High susceptibility
WS23	0.04	0.04	0.08	0.07	0.06	0.07	0.02	0.05	0.09	0.54	Moderate susceptibility
WS24	0.07	0.05	0.12	0.06	0.09	0.07	0.06	0.07	0.08	0.67	Very high susceptibility
WS25	0.03	0.04	0.07	0.08	0.11	0.08	0.02	0.05	0.07	0.54	Moderate susceptibility
WS26	0.11	0.06	0.14	0.06	0.07	0.06	0.10	0.06	0.09	0.74	Very high susceptibility
WS27	0.06	0.04	0.08	0.06	0.08	0.07	0.04	0.08	0.08	0.60	High susceptibility
WS28	0.03	0.04	0.06	0.08	0.10	0.08	0.01	0.06	0.07	0.52	Moderate susceptibility
WS29	0.06	0.04	0.08	0.07	0.06	0.07	0.03	0.04	0.10	0.54	Moderate susceptibility
WS30	0.06	0.05	0.10	0.06	0.08	0.07	0.05	0.05	0.08	0.60	High susceptibility
WS31	0.04	0.05	0.14	0.07	0.08	0.07	0.05	0.04	0.08	0.63	High susceptibility

**Table 14** Watersheds susceptibility classification based on FAHP analysis

WAI watersheds	SWAT watersheds	FAHP analysis	Area in sq. km	Percent of occupancy
4D2D1	24, 26	Very high susceptibility	453.06	63.86
	30	High susceptibility	131.2	18.49
	23, 25, 28	Moderate susceptibility	125.08	17.63
4D2D2	14, 15, 18, 20	High susceptibility	557.73	78.21
	13, 16, 17	Moderate susceptibility	155.72	21.83
4D2D3	21, 22, 27, 31	High susceptibility	711.85	65.2
	19, 29	Moderate susceptibility	379.91	34.79
4D2D4	1, 2, 3	Very high susceptibility	832.64	48.22
	4, 5, 6, 7, 8, 11, 12	High susceptibility	859.35	49.77
	9, 10	Moderate susceptibility	34.56	2.00

susceptibility except for micro-watersheds 4D2D4-9 and 4D2D4-10 which were categorized as moderate susceptibility. The watershed’s morphometric computations have shown that it is elongated in shape with a coarser drainage pattern and high drainage density. Simultaneously, the maximum and minimum elevations were found to be 438 and 327 m, respectively. The FAHP results have shown that the “very high susceptibility” to “high susceptibility” micro-watersheds must be improved by implementing the soil and water conservation measures and enhancing the vegetation cover to reduce the runoff sediment yield within a watershed.

The 4D2D3 watershed contains micro-watersheds 4D2D3-19, 4D2D3-21, 4D2D3-22, 4D2D3-27, 4D2D3-29, and 4D2D3-31, which were found to be elongated in shape with medium drainage density. Simultaneously, the maximum and minimum elevations were found to be 306 and 192 m, respectively. The FAHP results have shown that the micro-watersheds 4D2D3-21, 4D2D3-22, 4D2D3-27, and 4D2D3-31 are high susceptibility eroded except 4D2D3-29, which is moderate susceptibility. It was observed from morphometric analysis that the basin length and elevation differences had shown lesser values compared to other watersheds even though drainage density has a medium value.

The 4D2D2 watershed contains micro-watersheds 4D2D2-13, 4D2D4-14, 4D2D4-15, 4D2D4-16, 4D2D4-17, 4D2D4-18, and 4D2D2-20; the maximum and minimum elevations were found to be 425 and 264 m. Among the seven micro-watersheds, 4D2D2-14 and 4D2D2-18 micro-watersheds were classified as “very high susceptibility” as it is more

impacted by erodibility as per FAHP analysis. The main reasons for the severe erodibility in the two micro-watersheds were dendritic drainage patterns and high drainage density compared to other watersheds. So, the government must immediately implement soil and water conservation measures in the following micro-watersheds: 4D2D2-14 and 4D2D2-18.

The 4D2D1 watershed has six mini watersheds, namely 4D2D1-23, 4D2D4-24, 4D2D4-25, 4D2D1-26, 4D2D1-28, and 4D2D1-30, with minimum and maximum elevations of 248 to 453 m, respectively. It was evident from FAHP analysis that the micro-watersheds severity was classified as follows: 4D2D1-23, 4D2D1-25, and 4D2D1-28 as moderate susceptibility, 4D2D1-24, and 4D2D1-26 as very high susceptibility, and 4D2D1-30 as high susceptibility. However, from the morphometric analysis and FAHP priority ranking, the micro-watersheds 4D2D1-24, 4D2D1-26, and 4D2D1-30 showed significant erodibility and were classified as very high susceptibility micro-watersheds. Hence, the concerned government authorities are recommended to implement the soil and water conservation measures in these micro-watersheds.

The spatial distribution of critical watersheds of the study area has been classified into three classes, viz., moderate susceptibility, high susceptibility, and very high susceptibility, as shown in Fig. 15. Tables 14 and 15 show the watersheds susceptibility classification based on FAHP analysis for WAI and SWAT delineated watersheds. The spatial distribution map of critical watersheds is shown in Fig. 15 with the area in percentage and square kilometers in Table 15. It is observed that more than 30.32% of the basin is under very

**Table 15** Watersheds susceptibility classification of WAI and SWAT Watersheds

Prioritization description	WAI watersheds	SWAT delineated watersheds	Total area in sq. kms
Very high susceptibility	4D2D1 and 4D2D4	1, 2, 3, 24, and 26	1285.7
High susceptibility	4D2D1, 4D2D2, 4D2D3, and 4D2D4	4, 5, 6, 7, 8, 11, 12, 14, 15, 18, 20, 21, 22, 27, 30, and 31	2259.73
Moderate susceptibility	4D2D1, 4D2D2, 4D2D3, and 4D2D4	9, 10, 13, 16, 17, 19, 23, 25, 28, and 29	695.29

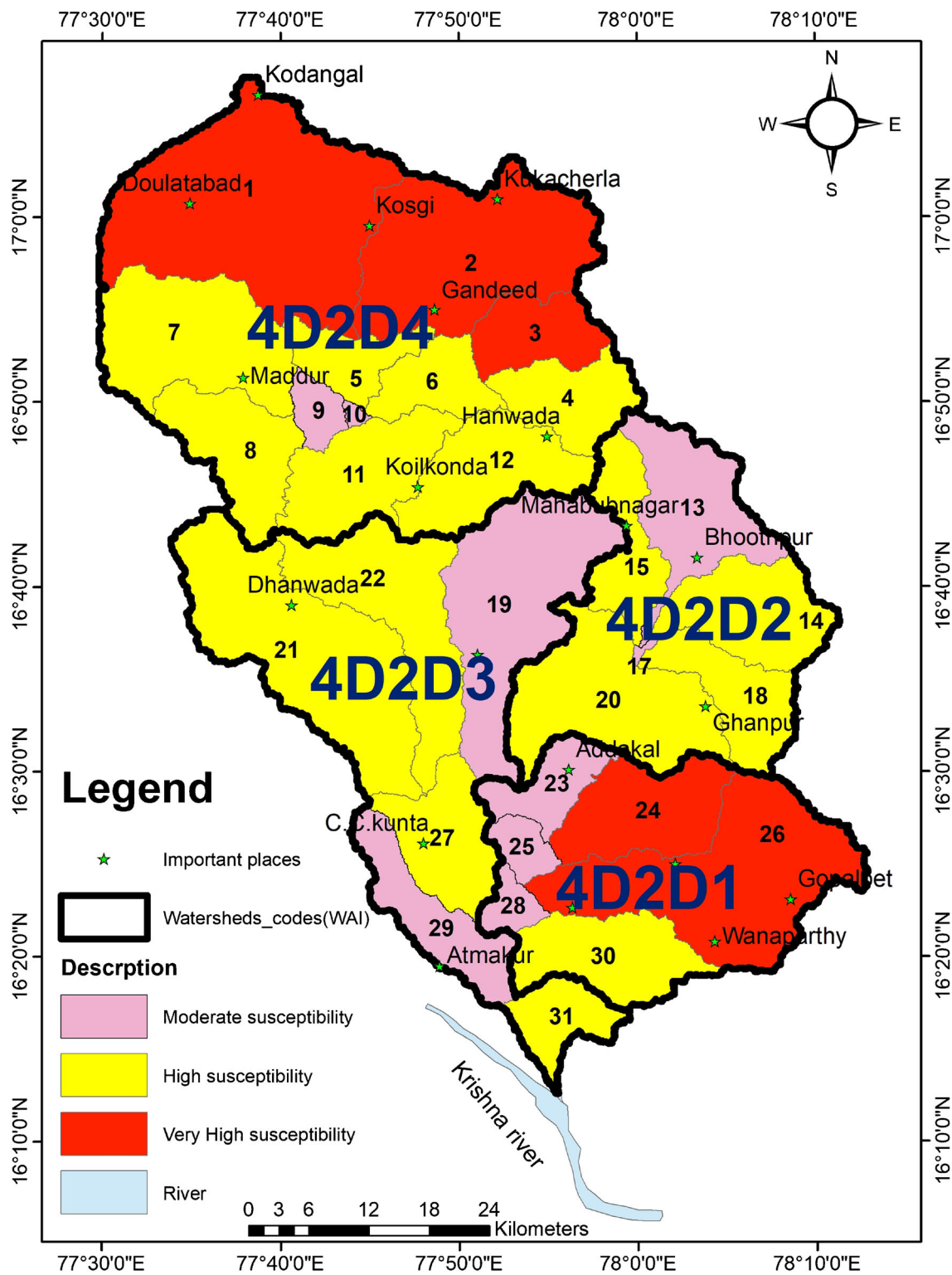


Fig. 15 Delineated critical watersheds using FAHP analysis

high susceptibility to erosion and needs an immediate implementation of management measures, followed by 53.28% area under high susceptibility to severe and 16.4% as moderate susceptibility to erosion. The results obtained from the FAHP analysis were further validated for assessing the fitment

of the above-developed method with the help of the USLE soil loss estimation method (Jaiswal et al. 2015; Mishra et al. 2018).

Finally, to evaluate and compare the FAHP analysis outcomes, the USLE equation was applied to the whole basin and



**Table 16** Watershed wise soil loss assessment and susceptibility classification

WAI watersheds	SWAT watersheds	USLE (t/ha/year)	FAHP analysis	WAI watersheds	SWAT watersheds	USLE (t/ha/year)	FAHP analysis
4D2D4	1	38.65	Very high susceptibility	4D2D2	17	15.07	Moderate susceptibility
4D2D4	2	51.59	Very high susceptibility	4D2D2	18	24.19	High susceptibility
4D2D4	3	43.96	Very high susceptibility	4D2D3	19	13.30	Moderate susceptibility
4D2D4	4	23.84	High susceptibility	4D2D2	20	24.26	High susceptibility
4D2D4	5	24.59	High susceptibility	4D2D3	21	27.77	High susceptibility
4D2D4	6	26.57	High susceptibility	4D2D3	22	26.82	High susceptibility
4D2D4	7	25.03	High susceptibility	4D2D1	23	11.54	Moderate susceptibility
4D2D4	8	24.47	High susceptibility	4D2D1	24	52.44	Very high susceptibility
4D2D4	9	8.74	Moderate susceptibility	4D2D1	25	8.6	Moderate susceptibility
4D2D4	10	8.64	Moderate susceptibility	4D2D1	26	54.96	Very high susceptibility
4D2D4	11	24.32	High susceptibility	4D2D3	27	26.83	High susceptibility
4D2D4	12	25.01	High susceptibility	4D2D1	28	11.70	Moderate susceptibility
4D2D2	13	9.56	Moderate susceptibility	4D2D3	29	15.11	Moderate susceptibility
4D2D2	14	26.06	High susceptibility	4D2D1	30	28.50	High susceptibility
4D2D2	15	24.6	High susceptibility	4D2D3	31	30.00	High susceptibility
4D2D2	16	6.02	Moderate susceptibility				

individual watersheds using inputs R-factor, K-factor, LS-factor, C-factor, and P-factors. The soil erosion statuses of all the sub-watersheds are presented in Table 16 and Fig. 16. The minimum and maximum R-factor values (i.e., erosivity) were found in Ganded and Atmakur with erosivity of 195.08 and 409.33 MJ mm ha<sup>-1</sup> h<sup>-1</sup> per year, respectively. Figure 16 contains the final soil loss map obtained from thematic layers R-factor, K-factor, LS-factor, C-factor, and P-factor. From the visual comparison of Figs. 15 and 16, along with USLE and FAHP severity levels, it is visible that the severity levels are in good agreement. The soil erosivity of a very high susceptibility class is >30 t/ha/year, the high susceptibility class is between 20 and 30 t/ha/year, and the moderate susceptibility class is between 5 and 20 t/ha/year. The comparison of results in Tables 14 and 16 show that very high susceptibility to erosion is found in 4D2D1-24 with soil loss of 54.96 t/ha/year, high susceptibility is found in 4D2D3-22 with a soil erosion of

28.04 t/ha/year, and moderate susceptibility was found in 4D2D3 with a soil erosion of 15.11 t/ha/year.

The results obtained from the USLE and FAHP analysis were correlated using the Spearman’s rank correlation coefficient. To compute the ranks, we have used the following tool available at <https://geographyfieldwork.com/SpearmanRankCalculator.html>. In the below equation, dataset A represents USLE ranks and data set B FAHP analysis ranks. The correlation strength depends on the value of coefficient “Rs” which can be within -1 or + 1. For FAHP analysis, the susceptibility ranks were classified as very high susceptibility as 5, high susceptibility as 4, and moderate susceptibility as 3 while for USLE, 0–5 t/ha/year is 1, 5–20 t/ha/year is 2, 20–30 t/ha/year 3, and > 30 t/ha/year is 4. The different ranks simulations of FAHP and USLE models showed a robust positive correlation value (Rs) of +0.93 for the study area:

$$\begin{aligned}
 \text{Data set A} &= \{4, 4, 4, 3, 3, 3, 3, 3, 2, 2, 3, 3, 2, 3, 3, 2, 2, 3, 3, 3, 2, 4, 2, 4, 3, 2, 2, 3, 4\} \\
 \text{Data set B} &= \{5, 5, 5, 4, 4, 4, 4, 4, 3, 3, 4, 4, 3, 4, 4, 3, 3, 4, 4, 4, 3, 5, 3, 4, 3, 3, 3, 4, 4\} \\
 \text{Number (n) of pairs in data set} &: 31 \\
 \text{Rs value} &: 0.9306
 \end{aligned}$$

### Conclusions

The prioritization of watersheds is crucial for implementing the soil and water conservation measures, which are useful for catchment area treatment (Jaiswal et al. 2015). The FAHP method was developed to prioritize watersheds along with

morphometric analysis and SWAT model outcomes. Furthermore, this method was validated with the outcomes of the USLE assessment method. The SWAT tool was used to accurately delineate and attribute the physical properties (Id, area, length slope, length of the slope, etc.,) of micro-watersheds associated with WAI codes (registers of rivers).

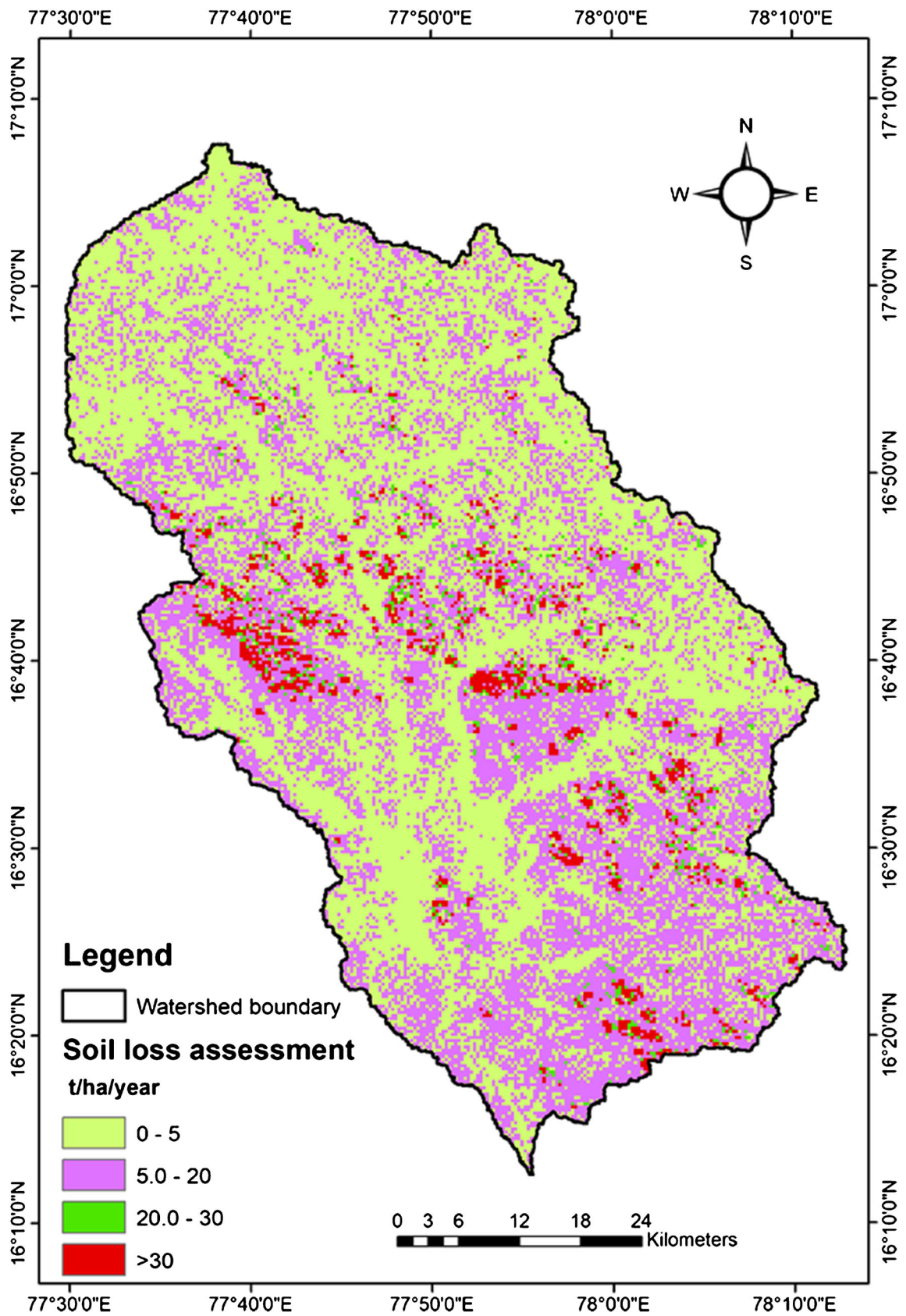


Fig. 16 Soil loss assessment map

The FAHP analysis outcomes were excellent as the consistency ratio was 3.8%, which was within the acceptable range, as suggested by Saaty's. The consistency ratio has shown that the methodology developed is statistically acceptable. Furthermore, we have also compared the current approach with the standard soil loss estimation method, i.e., the USLE approach. The visual comparison of the USLE model outcomes, i.e., the soil loss assessment map (Fig. 16) and the FAHP map (Fig. 15), shows good agreement.

The results of the FAHP analysis and USLE have demonstrated that five watersheds have very high susceptibility to erosion (30.32%), 16 watersheds have high susceptibility (53.28%), and the remaining 10 watersheds have moderate susceptibility (16.4%) to erosion. It implies that the "very high susceptibility category" watersheds need immediate implementation of the soil and water conservation measures followed by the "high susceptibility" and "moderate susceptibility" categories. The spatial distribution map of critical watersheds shown in Fig. 15 is quite useful for soil and water resources conservation, planning, and management. Moreover, the methodology developed could be used in other case studies as the outcomes have agreed with the standard USLE method validated using Spearman Rank Correlation Coefficient.

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