Prioritization of watersheds using multi-criteria evaluation through fuzzy analytical hierarchy process

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Abstract: Conservation of available natural resources through demarcation of potential zones at micro level are primary necessitate for sustainable development, particularly in the fragile semi-arid tropics. Delineation of potential zones for implementation of conservation measures above the entire watershed at similar occurrence is inaccessible as well as uneconomical; consequently it is a prerequisite to apply viable technique for prioritization of sub-watersheds (SWDs). Keeping this in view, the present research attempted to study various morphological characteristics and to implement Geographical Information System (GIS) and Multi Criteria Decision Making (MCDM) through Fuzzy Analytical Hierarchy Process (FAHP) techniques for identification of critical sub-watersheds situated in transaction zone between mountainous and water scarcity region of Western Part of India. The morphometric characterization was obtained through the measurement of three distinct linear, areal and relief aspects over the eight sub-watersheds. The morphometric characterization showed imperative role in distinguishing the topographical and hydrological behavior of the watershed. Each hydrological unit was ranked with respect to the value and weightages obtained by deriving the relationships between the morphometric parameters obtained through classification of the SWDs by associating the robustness of fuzzy logic and the Analytical Hierarchy Processes (AHP). Based on FAHP approach, sub-watersheds were evaluated as vulnerability assessment zones and alienated into five prioritization levels: very less, less, medium, high and very high classes. The evaluated results illustrated that 60.85% of sub-watersheds (five sub-watersheds) were in the medium to high susceptible zones, which depicted potential areas for necessity of establishment of conservation interventions for the sustainable watershed management planning. The FAHP based technique is a viable approach in illustrating the dilemma particularly over data hungry and complex conventional soil and water risk assessment methods and will be useful to various stakeholders (rural extension community, agriculturists and water resources managers) for better decision making with an obliging rule based system for implementing various assessment measures.

Keywords: fuzzy analytical hierarchy process, geographic information system, multiple criteria decision making, watershed prioritization

1 Introduction

Sustainable development and management of natural resources is in crucial need of the hour, particularly in the fragile arid and semi-arid tropics (SATs), which is associated with eminent spatio-temporal variation in hydrological and climatic variables. Watershed is an ideal unit calling for multidisciplinary approach to the resources management for insuring continuous benefits on sustainable basis (Srivastava et al., 2010). Therefore, the key issues of natural resources declination, such as water scarcity, degradation of land, drought, water extremities/flood, etc. are accomplished through management of development regions or micro watershed units. Analysis of drainage network characteristics such as, morphometric properties, hydrogeology, terrain, etc. plays a significant role in allocation, design and implementation of the conservation measures over the

small scale hydrological unit of the watershed.

In the past researches, prioritization of watershed was accomplished through different approaches to instance soil erosion or sediment yield indexing (SYI), morphological characterization, socio-economic aspects, etc. Adinarayana et al. (1995) generated Integrated Resources Units (IRUs) through semi-quantitative method of the SYI model for progression of priority classes of sub-watersheds in western plateau and hilly agro-climatic region of the Indian Peninsula. Similarly, some other studies focused on soil erosion and SYI modeling aspects by classifying the erosion affected priority areas (Suresh et al., 2004; Ratnam et al., 2005; Kalin and Hantush, 2009; Pandey et al., 2009; Niraula et al., 2011; Pai et al., 2011). In some other researches, socioeconomic aspects (Patil, 2007; Gosain and Rao, 2004; Newbold and Siikamäki, 2009; Kanth and Hassan, 2010) and land deterioration as well as land use change impacts were also measured for evaluation of prospective zones of watersheds (Adinarayana, 2003; Deb and Talukdar, 2010; Kanth and Hassan, 2010; Javed et al., 2011; Sarma and Saikia, 2011).

GIS and remote sensing (RS) techniques are proved to be proficient tools for morphometric characterization of sub-watersheds (Singh, 1994; Grohmann, 2004; Sreedevi et al., 2009; Aher et al., 2010; Rao et al., 2011). Mishra et al. (2007) carried out prioritization of sub-watersheds through morphological characteristics by using Soil and Water Assessment Tool (SWAT) model in the small multi-vegetated watershed of a sub-humid subtropical region in India. In some other researches, prioritization of sub-watersheds (SWD) was carried out through compound parameter technique (Venkateswarulu et al., 2003; Thakkar and Dhiman, 2007; Hlaing et al., 2008; Paul and Inayathulla, 2012). In these methods priority ranking was based on the compound or average value of the morphological characteristic variable, and biasness in weights associated with individual variable was thrust aside, which may leads to erroneous variation. Assessment of different vulnerability producing factors is the decision making process associated with formation of system knowledge database which involves multiple criteria and alternatives, which results in great degree of complexity. Therefore, in this research an attempt has been made for prioritization of sub-watersheds through analysis of the natural drainage system that implements a novel approach by investigating the fuzzy analytical hierarchy process (FAHP) to circumvent the complex information associated with various morphological characteristics by accomplishing better accuracy in identification and prioritization of SWDs with earlier approaches.

2   Materials and methods

2.1   Study area and data sources

The multi-criteria decision making analysis through FAHP was demonstrated over a watershed situated at Pimpalgaon Ujjaini village of western part of India (Figure 1). The watershed is located between 74°45′00″ E to 74°51′00″ E longitude and 19°08′43″ N to 19°11′31″ N latitude, and consists of an area about 3,109 ha. The watershed lays under the Survey of India topographic sheet number 47 I/16 (1:50000 scale) and comes in transition zone between mountainous and water scarcity region of Central Plateau Region. The study region is assorted by eight distinct land use classes viz. agriculture land, fallow land, water body, land under plantation, scrub land, reserved forest built-up land, and barren land. Agriculture practices are performed primarily with single cultivation season i.e. *kharif* (June-October) or *rabi* (November-March) with few immunities under double cropping cultivations.
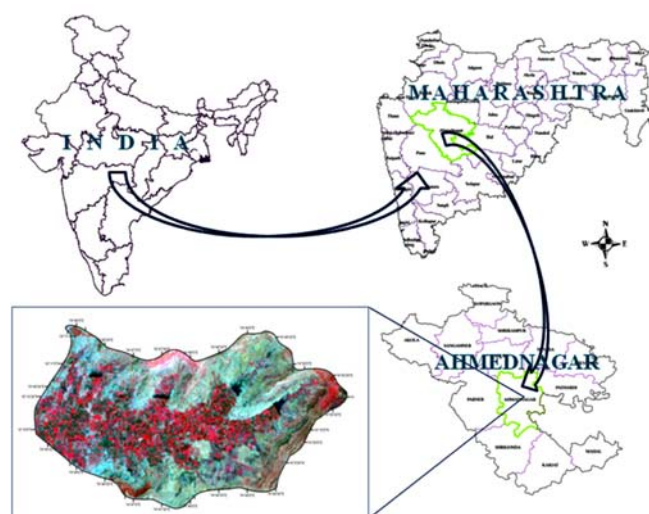

Figure 1   Study area map of the Pimpalgaon Ujjaini Watershed, Ahmednagar (MH), India.

Climatically the study region is governed by semiarid tropics with hot and dry air circulations. The weather is characterized by having the mean maximum (35°C) and minimum (11°C) temperatures in summer and winter seasons along with an annual rainfall of 650 mm. The physico-chemical analysis of the soil properties indicated that the soil is sandy loam to clay texture having moderate permeability with moderate organic carbon, highly available potassium, less available nitrogen, and phosphorous content in which the soil moisture availability to crops is one of the most important restraining factors prevailing the crop yield.

Various landforms of the study region were elucidated through preparation of False Colour Composite (FCC) from the Landsat 7 Enhanced Thematic Matter (ETM+) satellite imageries (path: 146 and row: 46) for the monsoon (kharif) as well as post-monsoon (rabi) agriculture seasons. The SOI topographical sheet (47 I/16) was utilized for demarcation of the watershed and to acquire various resource maps such as sub-watershed map, base map, and drainage network map, etc. Furthermore, ground survey data at various sample sites of the watershed and pertinent reports of the study region were also used as an auxiliary source of information for accomplishing the analysis in GIS environment.

2.2 Drainage system analysis

The watershed of the study region represented dendratic pattern of the drainage system in which the morphometric analysis was performed through measurements of linear, areal and relief aspects. The natural drainage network system analysis was obtained through deriving the drainage data from SOI topographic sheet which was updated by using FCC acquired from Landsat ETM+ where Horton's law (Horton, 1932) was used for stream ordering. The sub-watershed boundaries were demarcated with respect to the water divide, contours, and topographical variables accomplished through the analysis of hydro-geo-morphology features of terrain and digital elevation model (DEM). Consequently, Pimpalgaon Ujjaini watershed was demarcated into eight sub-watersheds (SWDs) and allocated as SWD-1 to SWD-8. The morphometric characterization in the form of linear, areal and relief aspects for the delineated sub-watersheds was evaluated based on the formulae given in Aher et al. (2010).

2.3 Prioritization of sub-watersheds

In 1980s the Analytical Hierarchical Process (AHP) method was proposed by Saaty (1980). It is based on subjective approach in which weightages are assigned by pair wise comparison between various criteria obtained through policies by decision makers. Multi-criteria Decision Making (MCDM) process could provide the optimum solution in which the uncertainties associated with evaluating criteria were ranked on the basis of overall performance of various input decision options with respect to the multiple objectives for the complex, fuzzy and linguistic characteristics.

In the present research, Fuzzy Analytical Hierarchy Process (FAHP) with extent analysis method (Saaty, 1980) which uses triangular fuzzy numbers for pair wise comparison scale is implemented and is endowed below:

Let $X = \{x_1, x_2 \ldots . . x_n\}$ and $Z = \{z_1, z_2 \ldots . . z_m\}$ be an object and goal sets, respectively. According to the extent analysis method, for each objective function, extent analysis is carried out with respect to each goal set. Hence, m extent analysis values for every object set is:

$$M_{g_i}{}^1, M_{g_i}{}^2, \ldots, M_{g_i}{}^m \qquad i = 1, 2 \ldots . . n \qquad (1)$$

where, $M_{gi}{}^j$ ($j = 1, 2, \ldots, m$) are triangular fuzzy numbers (TFNs). Now, the value of fuzzy synthetic extent with respect to the ith object is defined by Equation (2) as:

$$FS_i = \sum_{j=1}^{m} M_{g_i}{}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}{}^j \right]^{-1} \qquad (2)$$

For calculation of priority vectors of FAHP, fuzzy pairwise comparison matrix $A = (a_{ij})_{m*n}$ is considered, in which $a_{ij} = (r_{ij}, s_{ij}, t_{ij})$ where r, s and t are defined as the lower, modal and upper value of the triangular fuzzy number (M), respectively. In this the triangular fuzzy numbers ($\sum_{j=1}^{m} M_{g_i}{}^j$) can be accomplished by fuzzy addition operation for the m extent analysis values in such a way that

$$\sum_{j=1}^{m} M_{g_i}{}^j = \left(\sum_{j=1}^{m} r_{ij}, \sum_{j=1}^{m} s_{ij}, \sum_{j=1}^{m} t_{ij} \right) \qquad i = 1, 2 \cdots n$$

$$(3)$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m}M_{g_i}^{\ j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m}t_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m}s_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m}r_{ij}}\right) \quad (4)$$

In the next step, the degree of possibility of $M_2 = (r_2, s_2, t_2) \geq M_1 = (r_1, s_1, t_1)$ can be expressed as

$$V(M_2 \geq M_1) = \sup_{x \geq y}[\min(\mu_{M1}(x), \mu_{M2}(y))] \quad (5)$$

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M2}(d) =$$

$$\begin{cases} 1, & if & s_2 \geq s_1 \\ 0, & if & r_1 \geq t_2 \\ \dfrac{r_1 \geq t_1}{(s_2 \geq t_2) - (s_1 \geq r_1)}, & otherwise \end{cases}$$

$$(6)$$

where, d is the ordinate of the highest intersection point of the triangular fuzzy network between μ_{M1} and μ_{M2}. Furthermore, an extent of possibility for a convex fuzzy number to be larger than k convex fuzzy number M_i for $i = 1, 2 \ldots k$ can be calculated as:

$$V(M \geq M_1, M_2, \ldots M_k) = V(M \geq M_1) \ and \ (M \geq M_2)\ldots and(M \geq M_k)$$
$$= \min V(M \geq M_i) \qquad for \ (i = 1, 2, \ldots k)$$

$$(7)$$

Now, assume that

$$d'(A_i) = \min V(FS_i \geq FS_k) \ for \ (k = 1, 2, \ldots n) \ and \ k \neq 1$$

$$(8)$$

Subsequently, the value of weight vector (W') for $H_i = 1, 2, \ldots, n$; for n number of elements can be expressed as:

$$W' = (d'(H_1), \ d'(H_2), \ldots, \ d'(H_n))^T \quad (9)$$

After normalization of Equation (9), a non-fuzzy number (W) is represented as given below:

$$W = (d(H_1), \ d(H_2), \ldots, \ d(H_n))^T \quad (10)$$

Thus, prioritization rating by FAHP analysis technique was demonstrated for all of the sub-watershed in Pimpalgaon Ujjaini watershed.

3   Results and discussion

Morphometric characterization was performed through the analysis of linear, areal and relief aspects of the watershed. Horton (1932) nomenclature system was used for ordering the stream network drainage system which was dendratic in nature and observed to be of 5th order. Table 1 illustrates the sub-watershed wise morphometric variables used for pair-wise comparison matrix in fuzzy analytical hierarchy process.

Table 1   Comparison matrix of morphometric properties of Pimpalgaon Ujjaini watershed.

Watershed Code	Circulatory Ratio C-1	Bifurcation Ratio C-2	Drainage Texture C-3	Form Factor C-4	Drainage Density C-5	Compactness Constant C-6	Basin Shape C-7	Stream Frequency C-8	Elongation Ratio C-9
SWD-1	0.502	2.583	1.963	0.339	3.065	1.411	0.094	4.383	0.657
SWD-2	0.541	2.222	1.699	0.327	3.474	1.359	0.029	4.472	0.645
SWD-3	0.570	2.333	1.965	0.416	3.475	1.325	0.128	5.322	0.728
SWD-4	0.604	2.583	2.808	0.616	4.206	1.287	0.157	8.205	0.885
SWD-5	0.768	2.867	3.405	0.640	4.035	1.141	0.228	7.904	0.902
SWD-6	0.796	2.944	4.202	0.488	4.154	1.121	0.098	8.449	0.789
SWD-7	0.511	2.000	1.183	0.338	2.908	1.398	0.066	2.645	0.656
SWD-8	0.511	2.93	2.071	0.280	2.842	1.399	0.024	4.218	0.597

Watershed behaves differently as per its characteristic features for different vulnerability assessment factors, and therefore demarcation of priority decisive zone for demonstration of conservation measures is of crucial importance. Watershed shape and other linear parameters possess negative and positive correlation, respectively with risk assessment factors such as runoff, soil erosion, etc. (Thakkar and Dhiman, 2007). In this study, eight sub-watersheds (SWDs) were identified for

the evaluation of FAHP process.

MCDM is the systematic process that provides multi-criteria decision analysis for the given set of various alternatives with respect to the evaluation criteria in spatial/non-spatial behavior through assessment of scores or ranks based on the input factors. For the objective function of prioritization of sub-watersheds, nine morphometric evaluation variables in the form of circulatory ratio, bifurcation ratio, texture ratio, form

factor, drainage density, compactness constant, basin shape, stream frequency and elongation ratio were decided as criteria's C-1 to C-9 over the given set of sub-watersheds (SWD-1 to SWD-8), and were depicted as alternatives Alt-1 to Alt-8 (Figure 2).
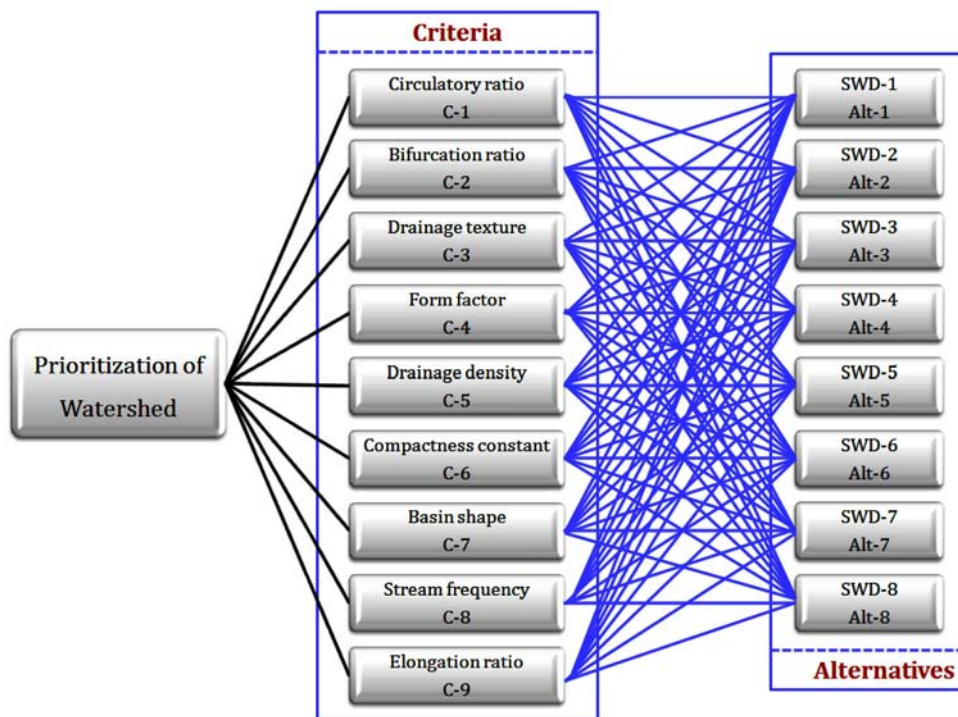

Figure 2   Multi-criteria evaluation by FAHP for prioritization of sub-watersheds

According to Chang's extent analysis FAHP method (Chang, 1996), each morphometric criteria was evaluated through formation of pair wise comparison matrix based on the fuzzy linguistic scale and weightages were obtained through normalization of fuzzy measures (Table 2). Furthermore, ranking obtained from alternative weightages and morphological characteristics criteria were overlaid in GIS environment (Figure 3) to formulate the integrated risk assessment map for implementation of preferential conservation measures.

In this research, FAHP analysis value aligns between 0.340 and 0.625 (Table 2). Prioritization of each characteristic variable was carried out on the basis of FAHP analysis score where the first rank is assigned to the SWD having the highest analysis value; in the same

way ranks were assigned to each decisive/priority zone. Thus, SWD-4 was allocated with the highest priority (Priority-1) having FAHP analysis value of 0.625 pursued by SWD-5, SWD-6, SWD-3, and likewise SWD-8 received merest ranking (Priority-8).

Based on the multi-criteria decision analysis, the integrated vulnerability assessment map of the Pimpalgaon Ujjaini demonstration zone obtained over eight sub-watersheds is illustrated in Figure 4. SWD-4, SWD-5 and SWD-6 obtains the highest priority rankings (Priority-1, 2 and 3, respectively) which becomes potential area for application of the best management practices caused due to greater extent of natural resources degradation.

Table 2   Prioritization rankings of the sub-watersheds.

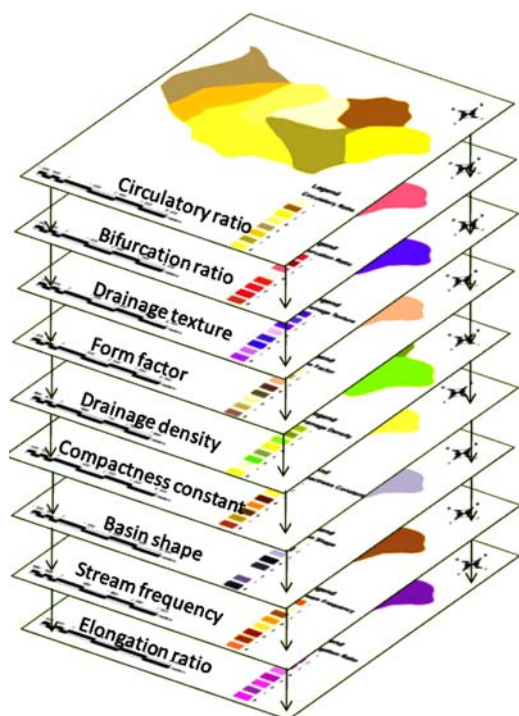| Sub-watersheds	Alternatives							
	SWD-1	SWD-2	SWD-3	SWD-4	SWD-5	SWD-6	SWD-7	SWD-8
Score based on FAHP	0.407	0.365	0.541	0.625	0.609	0.570	0.474	0.340
Prioritization Ranks	6	7	4	1	2	3	5	8

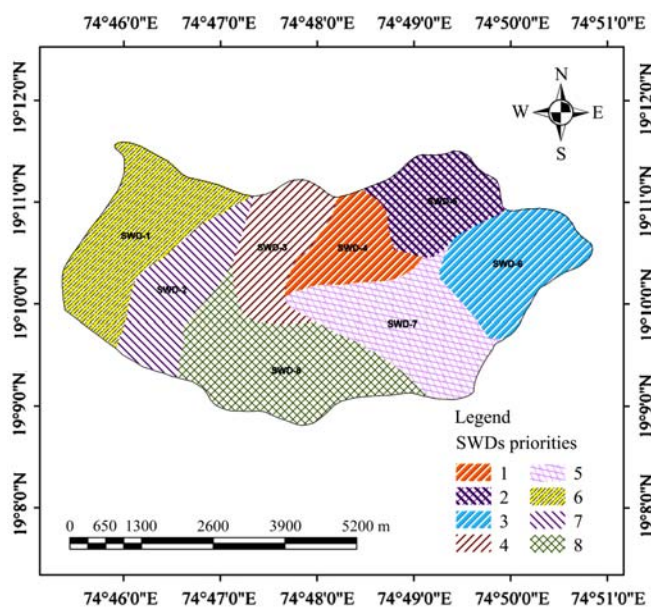Figure 3   Assignment of weightages for overlay analysis

Figure 4   Prioritization of sub-watershed by FAHP analysis

Furthermore, the sub-watersheds were alienated into five priority classes from very less to very high based on the overall weightages assigned to the categorized of morphometric parameters from MCDM through FAHP analysis (Table 3).

In comparison with the above classification, it was found that 60.85% of Pimpalgaon Ujjaini region approaches medium to very high priority zones.

The highland prominence portion of the Pimpalgaon

Ujjaini zone is constituted by medium to high risk zone (Figure 5) and is occupied by SWD-4, SWD-5, SWD-3, SWD-7 and SWD-6.   However, comparatively low sensitivity regions were characterized by SWD-1, SWD-2 and SWD-8 with an area extent of 39.15%.

Table 3   Alienation of FAHP scores into different priorities

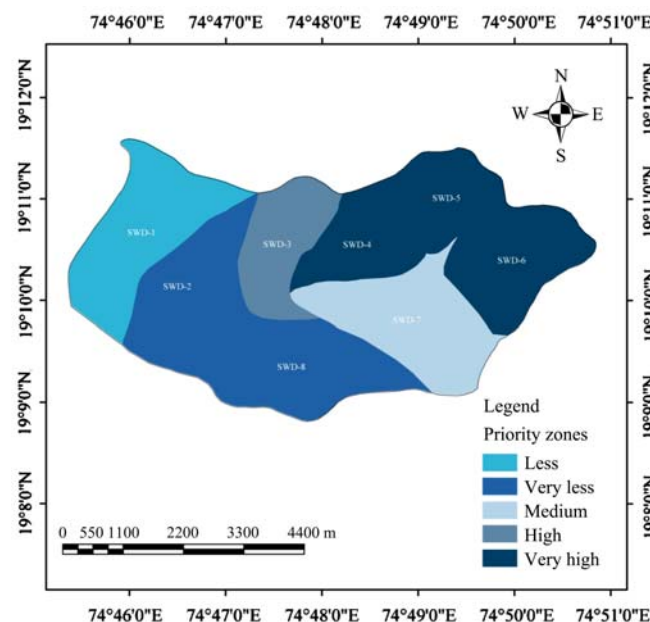| S. No.	Priority Types	Priority Levels	Sub-watersheds	Percentage of Area
1	Very Less	0.057 to 0.397	SWD-2, SWD-8	23.27
2	Less	0.397 to 0.454	SWD-1	15.88
3	Medium	0.454 to 0.511	SWD-7	10.61
4	High	0.511 to 0.568	SWD-3	09.61
5	Very High	>0.568	SWD-4, SWD-5 and SWD-6	40.64

Figure 5   Demarcation of natural resources degradation susceptibility zones

The intended multi-criteria based FAHP technique is a viable approach for identification of the sensitive priority zones and is useful for better decisions making through accomplishment of best management practices such as implementation of land and water conservation engineering measures, forestation, etc.

4   Conclusions

This research demonstrates the applicability of remote sensing, GIS, and multi-criteria decision making through Fuzzy Analytical Hierarchy Process (FAHP) techniques in prioritization as well as morphometric

characterization for planning and management of sub-watersheds.

In this study, a novel and logical approach of MCDM processes i.e. FAHP analysis based prioritization was formulated successfully which plays an imperative role in illustrating the dilemma through integration of risk assessment factors causing natural resources degradation. This may be one of the viable and efficient techniques, particularly over the data hungry conventional watershed prioritization approaches for designing and developing the efficient sustainable development and management practices, especially for the scarce/unavailable data

conditions. The MCDM process plays an imperative role when the complexity is involved due to several quantitative and qualitative criteria.

The pertinence of the demonstrated FAHP technique in delineation of decisive zones for implementation of efficient watershed management planning strategies over the heterogeneous hydro-geo-morphological conditions of the watershed will be useful to various stakeholders such as agriculturists, rural extension community, natural resources managers, etc. for better decisions making through classification and management of conceivable regions.

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