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Watershed prioritization using multi-criteria decision analysis tool for Bhopal (upper) lake catchment, Madhya Pradesh

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ABSTRACT

Watershed prioritization involves the identification of critical areas that are vulnerable to soil erosion and produce higher sediment yield. These areas need conservation activities on a priority basis. The soil erosion and subsequent yield from different watershed areas depend on multiple factors, so the selection of watershed based on a single factor may have the potential risk of wrong selection. The multi-criteria decision support-based analytical hierarchical process can be used conveniently for prioritization of watershed, where erosion process relies on various interdependent and spatially distributed factors. For prioritization, Bhopal Lake catchment was divided into twenty-four sub-watersheds (SW-1 to SW-24) and ten erosion hazard parameters (EHPs) were analysed for all sub-watersheds, which were used as inputs in a decision support system for the identification of erosion-prone areas. Based on susceptibility to erosion and sediment yield, the sub-watersheds were classified into five priority categories: very high, high, medium, low, and very low for the conservation and management of sub-watersheds. The sub-watersheds SW-19 and SW-24 have been characterized as a very high erosion area covering about 26 km^2 area, which is 7% of the total study area where immediate implementation for soil and water conservation (SWC) measures are required.

1. INTRODUCTION

Land and water are the most precious and indispensable resources essentially required to sustain life and for a region's economic and social progress. The hydrological flow regime and physiography of watershed parameters like soil type, elevation and land cover play an essential role in a watershed. Soil erosion from watershed areas and the succeeding dumping in water bodies are of great concern. At first, the fertile soil erodes from watershed areas, reduces the reservoir capacity and degrades the water quality at lower reach. Consequently, soil conservation and watershed management programs are required to cut back on watershed damage and soil erosion problems. In this regard, watershed prioritization is used to identify appropriate areas and suggest proper SWC measures to minimize sediment yield (SY) and maintain proper functioning of the reservoir / watershed. Estimating morphometric parameters are of enormous use in river basin analysis, watershed characterization, and natural resources management (Thakur *et al.,* 2019). Morphological analysis is a significant way to understand a watershed's topographical and hydrological condition. Morphological parameters with a specific value range indicate runoff generation intensity and erosion hazard. To visualize the drainage basins and for evaluation of morphological parameters, it necessitates preparation of thematic maps *viz.* drainage map, ordering of various streams, measurement of watershed area and parameters, length of the drainage channel, drainage density, stream frequency, form factor, and circularity ratio (Ranjan *et al.,* 2014). The information acquired from a watershed's morphometric analysis can be used for watershed prioritization, water resource management and planning, mapping and conservation of components like soil erosion, sedimentation, landslide susceptibility, and groundwater potential assessment.

Watershed prioritization is the process of ranking different sub-watersheds of a watershed area conferring to an order in which they have to be selected for SWC treatment. Morphometric analysis of watershed can be used for prioritization by analysing different linear and areal parameters even without accessing the soil maps (Patel *et al.,* 2013; Singh *et al.,* 2014; Farhan *et al.,* 2017). Implementing similar SWC measures over the entire watershed is inappropriate and expensive; thus, it is necessary to apply a feasible technique to prioritize the watershed. The feasible technique to treat the watershed is meaningful if the watershed is divided into sub-units, which are ideal for watershed management planning (Mishra *et al.,* 2018; Balasubramani *et al.,* 2019). The erosion process depends on various inter-dependent and spatially distributed parameters. It can be recognized by considering the possible set of multiple spatially distributed parameters or constraints under a multiple criteria decision analysis (MCDA) to obtain suitable weights that can ultimately identify sensitive areas in a watershed (Jaiswal *et al.,* 2015; Song and Chung, 2017). Numerous empirical models based on the geomorphological parameters were developed in the past to quantify sediment yield. Among them, the sediment yield index (SYI) method (Bali and Karale, 1977; Nookaratnam *et al.,* 2005) and universal soil loss equation (USLE) (Wischmeier and Smith, 1978; Chowdary *et al.,* 2013; Kar *et al.,* 2022) are extensively utilized for sedimentation and annual soil loss (SL) estimation from watersheds.

Technologies like remote sensing (RS) and geographical information system (GIS) have made it possible to automate the traditional approach of watershed prioritization (Malik *et al.,* 2019). De Steiguer *et al.* (2003) used the Analytic Hierarchical Process (AHP) to assist in implementing integrated watershed management, and plan the selection process to solve watershed management issues. The objective of the present study was to prioritize sub-watersheds based on erosion hazard parameters (EHPs) using RS and GIS techniques through the MCDA technique. Watershed prioritization needs analysis of various morphological, topographical, soil, and land-use based characteristics in GIS and MCDA techniques for identification of critical sub-watersheds in the study area (Saaty, 1980; De Steiguer *et al.,* 2003; Pareta and Pareta, 2011; Ranjan *et al.,* 2014; Jaiswal *et al.,* 2015; Mallick *et al*., 2018). The EHPs were estimated by measuring three distinct linear, areal, and relief aspects (Sreedevi *et al.,* 2009; Sarcar *et al.,* 2013) of geomorphology, topography, soil loss and SY of twenty-four sub-watersheds. Average annual soil loss is an essential parameter for identifying erosion-sensitive area, and its spatial distribution in the watershed has been determined using the USLE) (Wischmeier and Smith, 1965; Nasre *et al.,* 2013).

2. MATERIALS AND METHODS

Study Area

Bhopal lake is one of the largest freshwater lakes in India, and it falls on western part of Bhopal, Madhya Pradesh. It contains a significant amount of drinking water for the residents and supplies nearly 30 million imperial gallons per day to serve the city's daily needs of 40% of the population (Prasad and Tiwari, 2018). The capacity of Bhopal lake has reduced from 101.6 MCM to 75.72 MCM (Prasad and Tiwari, 2018) and is further reducing day by day due to soil erosion in its catchment; therefore, suitable conservation measures need to be implemented immediately according to priority.

The lake is lies in 77°0′00″ to 77°30′00″E longitudes and 23°5′00″ to 23°20′00″N latitudes, and is surrounded by Van Vihar National Park, human settlements, and agriculture fields. It contains a significant amount of potable water and contributes nearly 40% of potable water supply in a normal weather year (Virha *et al.,* 2011). The study area is spread in toposheets number 55E/3, 55E/4, 55E/7, and 55E/8 on a 1:50,000 scale. The Bhopal lake has a catchment area of 364.96 km^2, out of which, 20.07 km^2 is submerged by water. The present study area comes under the moderate subtropical climate, where the temperature ranges from 7°C to 45°C. The location map, sub-watershed map, drainage map and LULC map of the study area are shown in Fig's 1, 2, 3, and 4, respectively.

Erosion Hazard Parameters (EHPs)

Watershed is a natural geohydrological unit, where several streams drain through a common outlet (Srinivas *et al*., 2007; Samanta and Jana, 2020). In the present study, drainage network was derived from the NBSS&LUP and Survey of India toposheets. The sub-watershed boundaries were created with the help of the Arc-Hydro tool in ArcGIS 10.1 using SRTM DEM (30 m) as input. To execute the study's objective, thematic layer of EHPs, which are responsible for the detachment and transportation of soil, were generated in a GIS environment using the universally adopted method as given in Table 1. Subsequently, the Analytical Hierarchical Process was adopted to prioritize sub-watersheds.

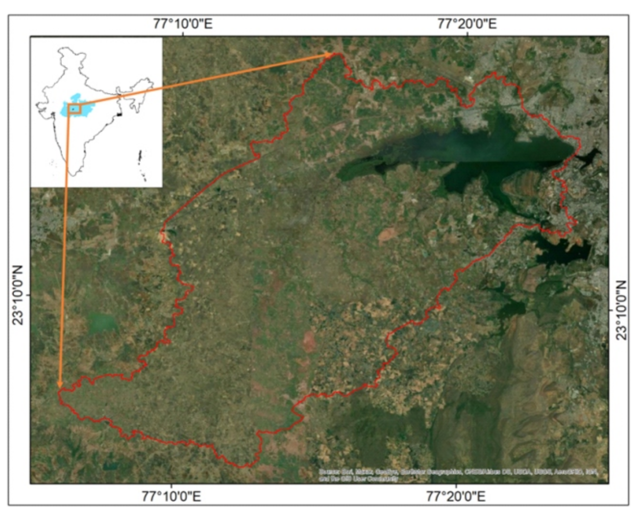

Fig. 1. Location map of Bhopal lake catchment

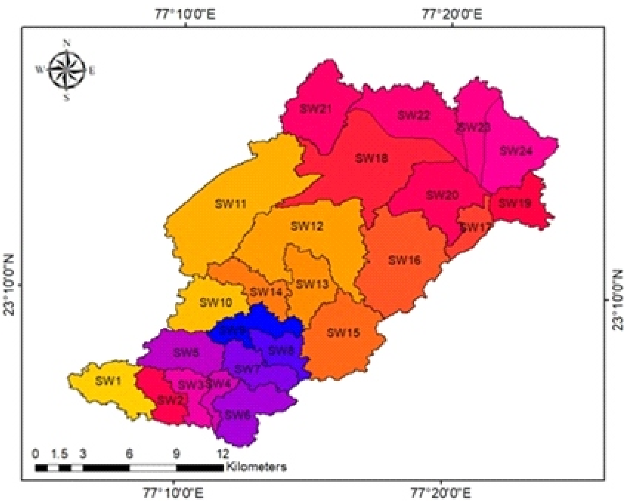

Fig. 2. Sub-watershed map of Bhopal lake catchment

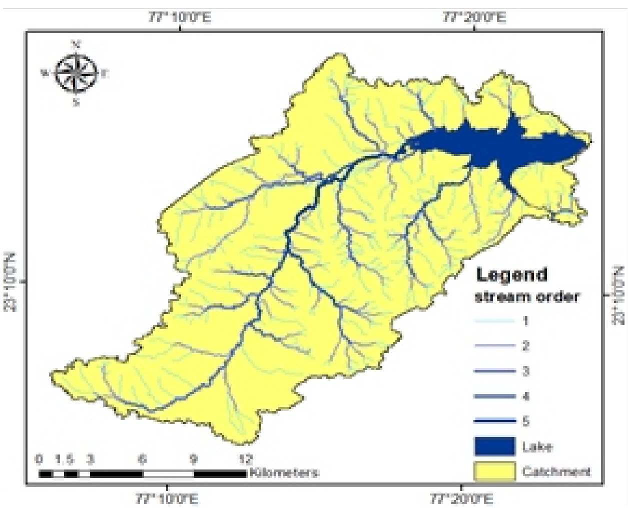

Fig. 3. Drainage map of Bhopal lake catchment

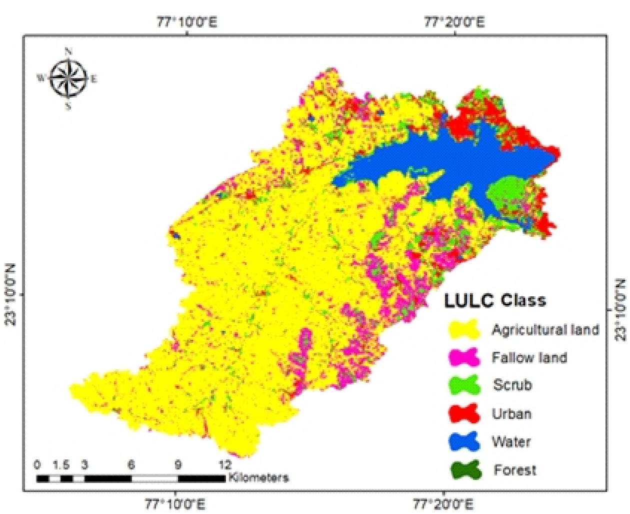

Fig. 4. Land use / land cover map of Bhopal lake catchment

After prioritization, different thematic layers *viz*. priority, erosion, land cover, slope, and drainage were overlayed in the Arc-GIS 10.1 software for identification of suitable conservation measures and their location.

Prioritization

The analytic hierarchy process (AHP) was introduced by (Saaty, 1980; Saaty, 2008). The AHP constructs a matrix of pair-wise comparisons (ratios) between the responsible factors. In the present study, 10 different parameters termed EHP have been selected to construct the AHP matrix (Jaiswal *et al*., 2015; Mishra *et al*., 2015; Kulimushi *et al*., 2020). To fill the AHP matrix, comparisons between parameters were made and scaled from 1 to 9 (Table 2), wherein 1 indicates that both parameters are equally important, while 9 confirms that one factor is significantly important in comparison to the other (Jaiswal *et al.,* 2014). The values 3, 5 and 7 explain the experience and judgment - slightly, strongly and very strongly - favor one over the other, respectively, whereas intermediate values *i.e.* 2, 4, 6 and 8 were used in case of compromise.

Consistency Check

The consistency of a particular decision can be verified by evaluating the consistency ratio (CR) between the consistency index (CI) and the random consistency index. The CR can be computed by the following the equation (Jaiswal *et al.,* 2014):

$$CR = \frac{CI}{RI} \quad ...(1)$$

Where, CI = Consistency index; RI = Random consistency index.

The CI is a measure of consistency that can be estimated using the following equation:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad ...(2)$$

Where, λ_{max} = Principle Eigen value obtained from priority matrix; n = Size of comparison matrix.

Saaty has determined the average random consistency index (RI) based on various sample sizes which is given in Table 2.

If the CR value is smaller or equal to 10%, the consistency is acceptable. If the CR is greater than 10%, we need to devise a subjective judgment (Jaiswal *et al*., 2015; Kulimushi *et al*., 2021).

Priority Assessment

The comparison matrix under AHP depicts the significance between two factors of EHPs that are responsible for the decision (Table 3). For the determination of each sub-watershed's priority, the values of the different EHP factors were normalized on a standard scale between 0 and 1. This

Table: 1
Estimation erosion hazard parameters (EHPs) for sub-watersheds

S.No.	Parameters	Formula	Reference
1.	Drainage density (D_d)	$D_d = \frac{L_u}{A}$ D_d = Drainage density; L_u = Total stream length of all orders A = Area of the basin (km^2)	Horton (1932)
2.	Form factor (R_f)	$R_f = \frac{A}{{L_b}^2}$ R_f = Form factor; A = Area of the basin (km^2) ${L_b}^2$ = Square of basin length	Horton (1932), Kar *et al.* (2018)
3.	Circularity ratio (R_c)	$R_c = \frac{12.57 * A}{P^2}$ R_c = Circularity ratio; A = Area of the basin (km^2) P^2 = Square of the perimeter (km)	Miller (1953)
4.	Drainage texture (D_t)	$D_t = \frac{N_u}{P}$ D_t = Drainage texture; N_u = Total no. of streams of all orders P = Perimeter (km)	Horton (1945)
5.	Channel frequency (F_s)	$F_s = \frac{N_u}{A}$ F_s = channel frequency; N_u = Total number of streams of all orders	Horton (1945)
6.	Soil loss (A)	$A = R \times K \times LS \times C \times P$ A = Average annual soil loss rate (t $ha^{-1} yr^{-1}$); R = Rainfall erosivity factor (MJ-mm ha^{-1} h^{-1} yr^{-1}); K = Soil erodibility factor (t ha^{-1} h^{-1} ha^{-1} MJ^{-1} mm); LS = Soil length and steepness factor; C = Crop cover and management factor; P = Conservation supporting practice factor	Wischmeier and Smith (1965); Thakur *et al.* (2018); Singh *et al.* (2021)
7.	Sediment Production Rate (SPR)	$\log SPR = 4919.8 + 48.64 \log (100 + R_f) - 1337.77 \log (100 + R_c) - 1165.65 \log (100 + C_c)$ SPR = Sediment production rate (ha-m 100 km^{-2} yr^{-1}); R_f = Form factor; R_c = Circulatory ratio; C_c = Compactness coefficient	Josh and Das (1982)
8.	Sediment Transport Index (STI)	$STI = \left(\frac{As}{22.13}\right)^{0.6} \left(\frac{\sin \beta}{0.0896}\right)^{1.3}$ Where, As is the upstream area and β is the slope at a given cell	Moore and Burch (1986); Jaiswal *et al.* (2015)
9.	Sediment Yield (SY)	$SY = 1.067 * 10^{-3} * p^{1.384} * A^{1.292} * D_d^{0.392} * S^{0.129} * F^{2.51}$ SY = Sediment yield (Mm^3 yr^{-1}); P = Annual precipitation (cm) A = Sub-watershed area (km^2); D_d = Drainage density (km km^{-2}) S and F = Average slope and Vegetative cover factor	Rao and Mahabaleswara (1990); Jaiswal *et al.* (2015)
10.	Slope (S)	SRTM DEM	Jaiswal *et al.* (2015)

negates the influence of one factor over others due to its significant variation; eq. 3 has been used for normalization of all the EHP parameters between 0 to 1:

$$N_i = \frac{(U_{nor} - L_{nor})}{(U_{act} - L_{act})}(X_i - L_{act}) \quad ...(3)$$

Where, N_i = Normalized value of a parameter for i^{th} watershed, U_{nor} = Upper value in the standard scale (1); L_{nor} = Lower value in the standard scale (0); U_{act} = Maximum value of the parameters; L_{act} = Minimum value of the parameters; X_i = Observed value of parameters for i^{th} watershed.

After estimating the normalized values and the weight of different EHPs using AHP for various watersheds, the final priority has been analyzed using eq. 4:

$$P_j = \sum_{i}^{1=n} W_i N_{ij} \quad ...(4)$$

Table: 2
Consistency ratios for different size of matrix

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table: 3
AHP weight for different erosion hazard parameters (EHPs) of Bhopal lake catchment

Parameters	SE	SY	STI	SPR	S	Dd	Fs	Rf	Dt	RC
SE	0.33	0.48	0.32	0.25	0.30	0.26	0.23	0.19	0.22	0.22
SY	0.11	0.16	0.32	0.25	0.18	0.15	0.14	0.19	0.16	0.17
STI	0.11	0.05	0.11	0.25	0.18	0.15	0.14	0.11	0.10	0.12
SPR	0.11	0.05	0.04	0.08	0.18	0.15	0.14	0.11	0.10	0.07
S	0.06	0.05	0.04	0.03	0.06	0.15	0.14	0.11	0.10	0.07
D_d	0.06	0.05	0.04	0.03	0.02	0.05	0.14	0.11	0.10	0.07
F_s	0.06	0.05	0.04	0.03	0.02	0.02	0.05	0.11	0.10	0.07
R_f	0.06	0.03	0.03	0.03	0.02	0.02	0.01	0.04	0.10	0.07
D_t	0.05	0.03	0.03	0.03	0.02	0.02	0.01	0.01	0.03	0.07
R_C	0.04	0.02	0.02	0.03	0.02	0.02	0.01	0.01	0.01	0.02
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Where, P_j = Final priority for j^{th} watershed; W_i = Weight of i^{th} EHP; N_{ij} = Normalized value of i^{th} EHP for j^{th} watershed.

After defining the final priority for all sub-watersheds, clustering technique was opted to group these sub-watersheds into five classes of priority, namely, very high, high, moderate, low, and very low.

3. RESULTS AND DISCUSSION

It is challenging to treat the whole watershed at a time due to the involvement of huge costs and resources. It might be uneconomical and useless if the same treatment is applied to the whole watershed. Therefore, the plan of conservation activities must be made on a scientific basis with the identification of priority areas. The present study divided the Bhopal lake catchment into twenty-four sub-watersheds named SW-1 to SW-24 (Fig. 2), and was characterized as a fourth-order catchment by the hierarchical ranking system. The watershed consists of 235, 63, 19, 4 and 1 number of 1st, 2nd, 3rd, 4th and 5th order streams, respectively, and has a mean bifurcation ratio (R_b) of 5.51. The lower values of R_b represent fewer structural disturbances in the sub-basin (Strahler, 1957), and the drainage pattern has not been distorted because of structural disturbances (Nag, 1998). The mean bifurcation ratio of the basin showed that the basin comes under normal condition. The drainage density (D_d) of a watershed depends on the soil type, topography and surface cover of the basin (Snehal and Babar, 2013). The drainage density ranged from 0.95 (SW-22) to 1.72 (SW-4) km km^{-2} for the sub-watersheds of the study area (Fig. 3). The channel frequency (F_s) varied between 0.41 (SW-24) and 1.87 (SW-11), which as per Singh *et al.* (2021) shows low channel frequency. Form factor (R_f) computed for all sub-watersheds varied in the range of 0.21 (SW-23) to 0.93 (SW-21), where 0.21 indicates elongated watershed while a higher value (0.93) indicates circular watershed (Pareta and Pareta, 2011). The circulatory ratio (R_c) was computed to be 0.14 (SW-4, 9) to 0.39 (SW-24). The drainage texture (R_t) for all sub-watersheds varied from 0.31 to 1.28 km^{-1}, depicting very coarse drainage texture as given in Pareta and Pareta (2011). The sediment production rate (SPR) of the study area varies from the lowest near to 0 (SW-9) to the highest 1.048 (SW-24) ha-m 100 km^{-2} yr^{-1}. The average soil loss (SE) from sub-watersheds has been computed and found between 7.13 (SW-18) and 28.93 (SW-19) t ha^{-1}yr^{-1}. The sediment yield (SY) for the study area ranged from 0.2 (SW-4) to 0.94 (SW-11) (Mm^3 yr^{-1}). The sediment transportation index (STI) for the study area varied from 0.001 to 0.007. The slope of the basin was analyzed using the SRTM digital elevation model and it varies from 5.4% to 11.62%.

In the present study, ten EHPs have been taken for the decision where λ_{max} and *CI* have been assessed as 11.29 and 0.143, respectively. The *RI* for the decision was computed as 1.49. The CR for the present decisions has been computed as 0.0962 or 9.62%, which is less than 10%; hence, the discrepancy in the decision is acceptable and the weights acquired can be used for priority valuation (Jaiswat *et al.*, 2015). The values in the above comparison matrix (Table 3) provided for the computation of weights of different parameters using the approximation technique. The weights of EHPs generated and considered for priority assessment are given in Table 4.

It can be seen that SL, SY, SPR and the slope all together got 70% weightage in the decision and are the significant forces among considered EHPs for assessing the priority of sub-watersheds. The weights obtained from AHP based decision support were then utilized to get final priority

Table: 4
EHP weight considered for the priority

SE	SY	SPR	S	D_d	R_f	D_d	F_s	D_t	R_c
0.28	0.18	0.13	0.1	0.08	0.07	0.05	0.04	0.03	0.02

numbers for all sub-watersheds. The final priorities of sub-watersheds have been divided into five categories *i.e.* more than 0.41 as very high, 0.31 to 0.40 as high, 0.25 to 0.30 as moderate, 0.20 to 0.24 as low and less than 0.19 as very low priority, so that environmentally stressed area can be recognized to suggest soil conservation measures. Based on priority, sub-watershed 24 was kept in topmost priority while sub-watershed 13 got the last priority. It has been found that SW-11, SW-16, SW-19, and SW-24 (Fig. 5) in Bhopal lake catchment require prevention measures first before other sub-watersheds are treated. From the analysis, it has been observed that 26% area comes under the very high and high categories, and 58% under the low and very low categories (Table 5). Hence scientifically developed conservation measures should be imposed immediately in the top priority sub-watersheds. A detailed study area survey was conducted for validation of results, and a close resemblance of model results with field conditions was observed.

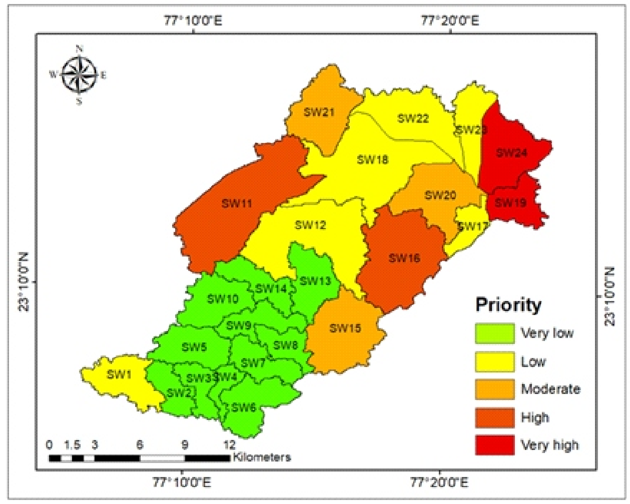

Fig. 5. Priority map of Bhopal lake catchment

Table: 5
Priority index of the study area

Priority	Range	Area (km^2)	Area covered (%)
Very high	0.41 and above	25.86	7
High	0.40 to 0.31	68.95	19
Moderate	0.30 to 0.25	56.52	15
Low	0.24 to 0.20	114.71	31
Very low	Less than 0.19	98.92	27
Total		364.96	100.00

Suitable Soil Conservation Measures for Prioritized Areas

In prioritized area, suitable conservation measures are needed to control the surface runoff, sediment production, and improve the water productivity (Kar *et al.,* 2017). In the present study, suitable conservation measures were identified based on the LU/LC map, erosion map, drainage map, slope map, soil map and priority map (Jaiswal *et al.,* 2013). Soil conservation measures are broadly classified into two types (a) biological measures, and (b) mechanical or engineering measures. The biological measures helpful in checking soil erosion are agronomical practices, agrostological methods, and dry farming practices. Agronomical practices include contour farming, tillage practices, crop rotations, leguminous crops cultivation, mixed cropping, mulching, and strip cropping. Important agrostological practices suggested are cultivating grasses (ley farming), retiring the land, afforestation, reforestation, and checking to overgraze. Mechanical measures for soil conservation are terracing, contour trenching, construction of terrace outlets, gully control structures, check dams, ponds and stream bank protection etc. (Jaiswal *et al.,* 2014; Sinshaw *et al.,* 2021). Keeping these parameters in view, the areas having high and very high priority can be considered for construction of mechanical measures while for low, very low and moderate priority sub-watersheds agronomic / biological measures can be adopted so that runoff can be minimized and may also help in groundwater recharge. The present study area is dominated by agricultural land, and on a priority basis, the maximum area comes under moderate to very low priority; so in this type of area, agricultural measures like strip cropping, mulching, mixed cropping etc. may be helpful to control erosion and manage the watershed. The sub-basin 19 having a scrub-dominated land comes under very high priority, which can be treated by constructing check dams, afforestation and gully plugging. The CAT (catchment area treatment) plan suggested 9 gully plugs, 2 check dams and 4 boulder bunds for the Bhopal lake catchment (Fig. 6). Agronomic measures such as strip cropping, vegetative barriers and afforestation were suggested according to slope and land cover.

4. CONCLUSIONS

Bhopal lake fulfills a huge domestic demand for water. To maintain the lake's capacity and quality of water, there is an urgent need to take suitable action based on prioritization, which can help to undertake optimal decisions for the conservation of the lake. The AHP based decision support with ten spatially distributed EHPs suggested that soil erosion with the weight of 0.28 has the highest influence in the prioritization procedure. In contrast, the circulatory ratio with the weight of 0.02 has the lowest influence on the

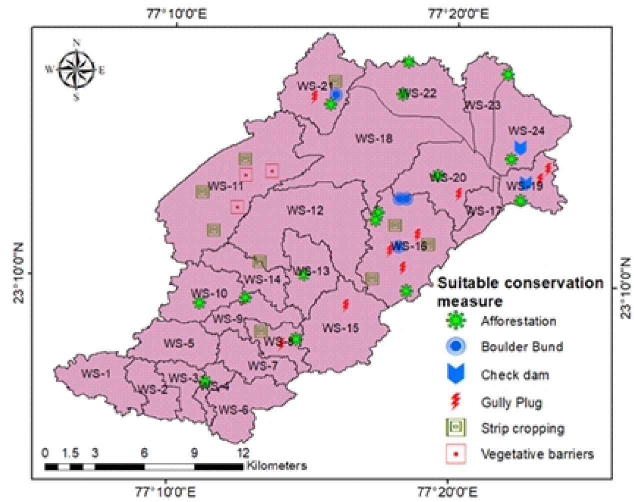

Fig. 6. Suitable conservation measures for Bhopal lake catchment

decision. Nearly 95 km^2 out of 364.96 km^2 of total catchment area of Bhopal lake has been found under very high (WS-19 and 24) and high priorities (SW-11 and 16) where soil conservation measures need to be taken up urgently. Prioritization helps to provide proper planning for SWC, protect the soil from erosion, and maintain the soil's productive capacity as well as the quality of the water. Considering the above scenario of various sub-watersheds, several suitable measures have been suggested for catchment area treatment and reduction of sediment inflow. The CAT plan suggests 9 gully plugs, 2 check dams and 4 boulder bunds for the Bhopal lake catchment.

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