Multi-criteria decision analysis (MCDA) for surface water management plan, a case study of Kansachara sub-watershed, West Bengal, India

Kartic Bera and Pabitra Banik

ABSTRACT

The increasing demands on fresh water resources by our burgeoning population and diminishing quality of existing water resources because of pollution and the additional requirements of serving our spiraling industrial and agricultural growth have led to a situation where the consumption of water is rapidly increasing and the supply of fresh water remains more or less constant. In the context of quality, potable water is always meager for the present and future. The study is an innovative attempt towards the development of the watershed on the earth science platform. Thereafter the balancing of water resources for domestic and agricultural uses is also tried. The focus is mainly on surface water for present use and groundwater for future. This management plan especially includes socially and economically backward demographic conditions. The present study is an integrated approach for a micro-watershed development plan of the Kansachara sub-watershed.

Key words | management plan, MCDM, prioritization, surface water, water balance

Kartic Bera (corresponding author)
Pabitra Banik
Agricultural and Ecological Research Unit,
Indian Statistical Institute,
203 B. T. Road, Kolkata 700108,
West Bengal,
India
E-mail: *1kbrsgis@gmail.com*

INTRODUCTION

Water is the very basis of life and is the foundation for human survival and development. Water is one of the most important elements for any kind of development or planning (Aliyari *et al.* 2018) for the 21st century (Kathpalia & Kapoor 2002). The suitable management of our limited water resources will be essential to ensure food security for our growing population and to eliminate poverty (Bera 2013). It will be essential also to avoid growing conflicts and the possibility of social unrest in the country in future due to water scarcity (Koop & van Leeuwen 2015; Zeng *et al.* 2017). Water security in India is emerging as an issue of extreme urgency. Broadly defined, water concerns are multi-dimensional in nature, combining the sufficient need for quality water for socio-economic uses as well as adequate water to sustain ecosystem functions (Hu & Boyer 2018). Water security for India implies effective responses to changing water conditions in terms of quality, quantity and uneven distribution (IDSA Task Force Report 2010). Watershed management is described by the different natural parameters for making an appropriate action plan (Kumar & Kumar 2011) or implementation. Watershed management (Zhou *et al.* 2018) is a complex attribute of watersheds that has a direct effect on micro-watersheds. Most micro-watershed parameters are determined by the interaction of several characteristics and measurable natural attributes of the region. In this research, only a limited number of parameters have been selected for evaluation. Once the problem has been identified, the set of criteria for evaluation needs to be designated. Since the evaluation criteria are related to geographical entities and the relations between them, they can be approximately represented.

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More than one parameter is equally important for watershed management. These are very much interrelated also. Six standard methods were used and studied briefly to calculate individual parameters of the study area (Ceballos-Silva & López-Blanco 2003). Final priority has been evaluated through the analytical hierarchy process (AHP) method (Saaty 1977), one of the best in multiple-criteria decision-making (MCDM). The AHP method is increasingly used as a decision support method with multiple parameters (Zeng & Huang 2017). AHP is welcomed for supporting procedural justice regarding clearness and equality of decisions. This is useful for water resource management, with diverse multi-parameters for prioritization questions with diverse criteria or for allocation of scarce resources (Malczewski 2006). However, AHP's promises of procedural justice are partly grounded in its supposed numerical accuracy (Kessili & Benmamar 2016). The numerical basis of AHP is not as unequivocal as current 'AHP standard practice' suggests. By contrast, AHP can contribute to the multiple criteria for procedural justice, which may explain AHP's continuing and growing popularity (Chakhar & Mousseau 2008).

METHOD AND DATA

Study area

The study area, Dwarakeswar watershed (also known as Dhalkishor), is geographically located at 23°14′N to 23°20′N latitude and 86°44′E to 86°55′E longitude. It occupies a total area of about 114.34 km^2 (Bera & Bandyopadhyay 2011). In upper Beko the watershed flow has several tributaries; one of them on the left bank tributary is Kansachara (Figure 1). It has 19 micro-watersheds in a 114.34 km^2 area. The study area is bounded by four blocks, i.e. Chhatna, Indpur, Kashipur and Hura of Bankura and Purulia districts respectively. The master slope of the area tends towards the southeast direction. In the extreme northwestern part towards the Chhotonagpur plateau (Bera & Bandyopadhyay 2013), the undulations are more pronounced.

Aim and objective

The aim of the study is remote sensing (RS) and geographic information system (GIS)-based micro-watershed prioritization for water resource management. Objectives of the study are: to prepare a drainage network map, and based on the map, delineate the boundaries of the micro-watersheds; furthermore, to prepare the classified map of land use and land cover of sub-watersheds up to micro-watersheds from satellite imagery; analysis of parameters (Water Scarcity zone, Sediment Yield Index (SYI), Land Capability, Morphometric parameters, Societal condition and Run-off); and to identify site suitability for surface water management (Gu *et al.* 2017).

Methodology

The estimation of the hydrologic characteristics was done by using morphometric parameters. These parameters can be accurately estimated in the GIS environment. One of the most widely used techniques for estimating direct runoff depths from storm rainfall is the United States Department of Agriculture (USDA) Soil Conservation Service's (SCS) Curve Number (CN) method (USDA 1985). The quantitative assessment of soil erosion is a basic aspect of watershed management and therefore using the SYI model one can predict the rate of soil loss by using some empirical formulae (Jaiswal *et al.* 2015). A special emphasis on demographic structure is the best management practice (BMP) in these areas and assessment of BMP implementation is effective for water availability improvement through monitoring strategies. Finally, an AHP-based micro-watershed is categorized into three classes for pursuing the action plan, i.e. first, second and third stages.

Pair-wise comparison techniques are widely used in the multi-criteria decision analysis (MCDA) method. It was developed by Saaty (1977) in the context of a decision-making process known as analytic hierarchy process. The pair-wise comparison (Table 1) of parameters results in the 'importance matrix', which is based on a scale of importance intensities. Table 1 elaborates the scale of importance. The importance matrix can then be analyzed by various methods, the eigenvector method or

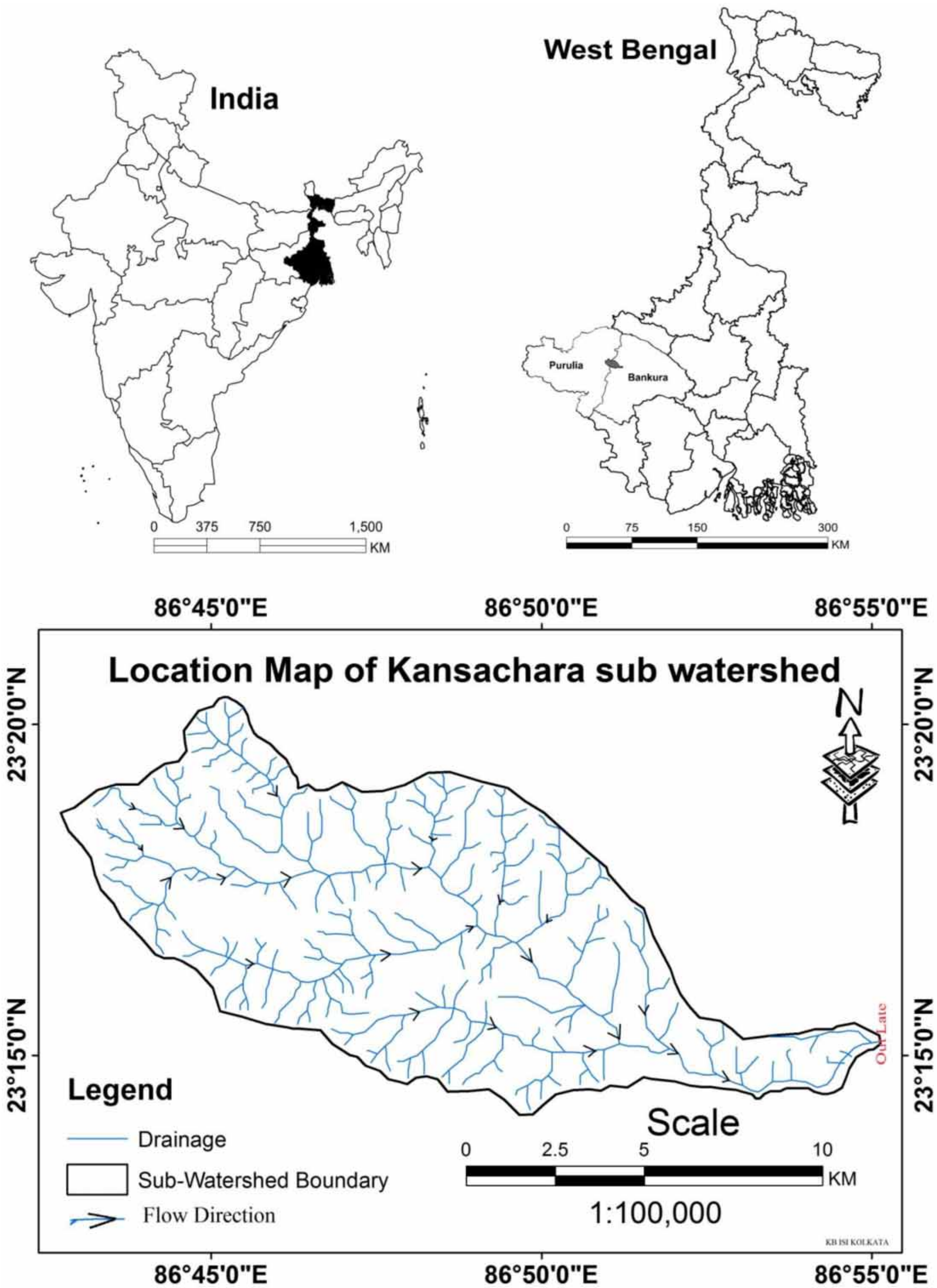

Figure 1 | Study area location.

least squares method, to arrive at the weightages of each parameter in the matrix (Singh *et al.* 2002). However, in the present study, a ratio (reciprocal matrix) is constructed, where each factor or criterion is compared with the other criteria, relative to its importance on a scale from 1 to 9.

Weights are calculated by normalizing the eigenvector associated with the maximum eigenvalue of the matrix. This involves the following operation:

- Computation of the sum of values in each column of the pair-wise comparison matrix (Table 2).

Table 1 | Scale for pair-wise comparison

Assigned value	Definition	Explanation
1	Parameters are of equal importance	Two parameters contribute equally to the objective
3	Parameter j is of weak importance compared with parameter i	Experience and judgment slightly favour parameter i over j
5	Essential or strong importance of parameter i compared with j	Experience and judgment strongly favour parameter i over j
7	Demonstrated importance	Criteria i is strongly favoured over j and its dominance is demonstrated in practice
9	Absolute importance	The evidence favors parameter i over j to the highest possible order of affirmation
2,4,6, and 8	Intermediate values between two adjacent judgments	Judgment is not precise enough to assign values of 1,3,5,7,and 9

Table 2 | Pair-wise comparison of factors for action plan

Factors	Scarcity	SYI	Land capability	Morphometric	Societal	Run-off
Scarcity	1	3	5	7	7	9
SYI	1/3	1	3	5	4	7
Land capability	1/5	1/3	1	2	5	3
Morphometric	1/7	1/5	1/2	1	2	5
Societal	1/7	1/4	1/5	1/2	1	2
Run-off	1/9	1/7	1/3	1/5	1/2	1
Sum	1.928	4.923	10.033	15.7	19.5	27

Table 3 | Normalized matrix with results

Factors	Scarcity	SYI	Land capability	Morphometric	Societal	Run-off	Sum	Priority vector	% of weight
Scarcity	0.519	0.609	0.498	0.446	0.359	0.333	2.765	0.461	46.076
SYI	0.173	0.203	0.299	0.318	0.205	0.259	1.458	0.243	24.295
Land capability	0.104	0.068	0.100	0.127	0.256	0.111	0.766	0.128	12.766
Morphometric	0.074	0.041	0.050	0.064	0.103	0.185	0.516	0.086	8.593
Societal	0.074	0.051	0.020	0.032	0.051	0.074	0.302	0.050	5.026
Run-off	0.058	0.028	0.033	0.013	0.026	0.037	0.195	0.032	3.244

- Normalization of the matrix by dividing each element by its column total.
- Computation of the mean of the elements in each row of the normalized matrix (Table 3).

Saaty (1977) applied the consistency ratio (CR) computed (Table 3) to check the consistency of comparisons by using the flowing formulas:

$$\mathrm{CR} = \frac{\text{Consistency Index (CI)}}{\text{Random Inconsistency Index (RI)}}$$

$$\mathrm{CI} = \frac{\lambda\max - n}{n-1}$$

where λ max (principal eigenvalue) = sum of products

Table 4 | Random inconsistency indices (RI)

Number of criteria (*n*)	Random inconsistency indices (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

between each element of the priority vector and column total, and $n =$ number of comparisons/criteria.

If the consistency ratio CR > 0.10, then some pair-wise values need to be reconsidered and the process is repeated until the desired value of CR < 0.10 is reached (Table 4).

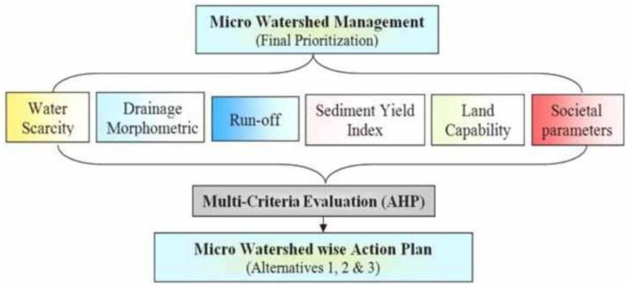

Figure 2 | Flow chart of the work.

Calculation of consistency ratio (CR)

$$\begin{aligned}\lambda \max &= (1.928 \times 46.07632855) + (4.923 \times 24.29530124) \\ &\quad + (10.033 \times 12.76595183) + (15.7 \times 8.592603084) \\ &\quad + (19.5 \times 5.026182866) + (27 \times 3.243632435) \\ &= 6.57014234\end{aligned}$$

$$\mathrm{CI} = (6.57014234 - 6)/(6 - 1) = 0.114028468$$

$$\mathrm{CR} = 0.114028468/1.24 \text{ (six parameters, value of RI} = 1.24) = 0.0919584 \text{ (consistency is acceptable, as CR} < 0.10).$$

Table 5 | AHP (analytical hierarchy process)-based Kansachara sub-watershed final prioritization

Factors / MWC	Scarcity	SYI	Land capability	Morphometric	Societal	Run-off	Total	Action plan
2A2C8F1a	92.15	72.89	38.30	8.59	10.05	9.73	231.71	3
2A2C8F1b	138.23	72.89	38.30	17.19	5.03	9.73	281.36	3
2A2C8F1c	138.23	48.59	12.77	8.59	10.05	9.73	227.96	3
2A2C8F1d	92.15	48.59	38.30	8.59	5.03	9.73	202.39	2
2A2C8F1e	138.23	24.30	38.30	8.59	15.08	9.73	234.22	3
2A2C8F1f	138.23	48.59	38.30	17.19	10.05	9.73	262.09	3
2A2C8F2a	138.23	48.59	12.77	8.59	10.05	9.73	227.96	3
2A2C8F2b	92.15	48.59	12.77	17.19	5.03	9.73	185.45	2
2A2C8F2c	92.15	24.30	12.77	8.59	15.08	9.73	162.62	1
2A2C8F3a	92.15	24.30	12.77	8.59	10.05	6.49	154.35	1
2A2C8F3b	46.08	24.30	12.77	17.19	10.05	6.49	116.86	1
2A2C8F3c	46.08	24.30	25.53	8.59	10.05	6.49	121.04	1
2A2C8F4a	46.08	24.30	38.30	8.59	10.05	3.24	130.56	1
2A2C8F4b	46.08	24.30	25.53	8.59	10.05	3.24	117.79	1
2A2C8F4c	46.08	24.30	38.30	8.59	5.03	3.24	125.53	1
2A2C8F5a	46.08	24.30	38.30	25.78	5.03	3.24	142.72	1
2A2C8F5b	92.15	24.30	38.30	8.59	5.03	3.24	171.61	2
2A2C8F6a	92.15	24.30	12.77	8.59	5.03	3.24	146.08	1
2A2C8F6b	92.15	24.30	25.53	8.59	10.05	6.49	167.11	2

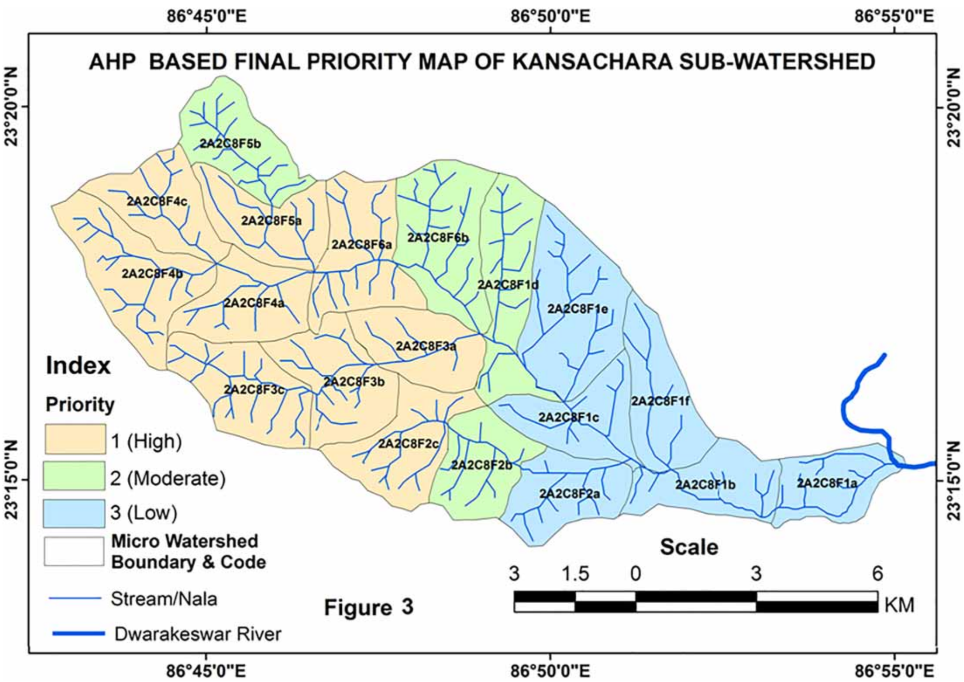

Figure 3 | Final priority map.

RESULTS AND DISCUSSION

The methodology described above has been implemented for the Kansachara sub-watersheds to determine the suitability of the land for micro-watershed development and management. The prioritization at the micro-watershed level for the sub-watersheds was on the following parameters; Water Scarcity, Sediment Yield Index, Land Capability, Morphometric parameters, Societal parameters and Run-off (Figure 2).

As per the analysis in Table 5 of the total 19 micro-watersheds in the sub-watershed, nine micro-watersheds (2A2C8F2c, 2A2C8F3a, 2A2C8F3b, 2A2C8F3c, 2A2C8F4a, 2A2C8F4b, 2A2C8F4c, 2A2C8F5a, 2A2C8F6a) fall under first management stage, four micro-watersheds (2A2C8F1d, 2A2C8F2b, 2A2C8F5b, and 2A2C8F6b) under second management stage and the remaining six micro-watersheds (2A2C8F1a, 2A2C8F1b, 2A2C8F1c, 2A2C8F1e, 2A2C8F1f and 2A2C8F2a) are under third management stage, whereas immediate action is not required for development based on another micro-watershed of Kansachara sub-watershed (Figure 3).

CONCLUSION

Saaty's AHP technique is applied with final decisions and provides a comprehensive framework for structuring a decision problem for evaluating alternative solutions. Furthermore, Saaty's AHP-based MCDA tool is applied for optimum development of land and water resources and to meet the basic minimum needs of people thereby improving their socioeconomic conditions. The present study revealed the characterization of the upper Dwarakeswar basin based on soil, relief, drainage, land use, etc. and other collected information like, climate, geology, local problems, etc. considered for analysis using RS and GIS techniques. The AHP-based prioritization analysis revealed that 54.24 km^2 (nine micro-watersheds) of the Kansachara sub-watershed can be considered for intensified soil conservation measures because of high priorities.

The information generated from such studies can be applied by decision-makers and planners for sustainable development of any watershed area. It is advised to carry out a micro-analysis-supported system with ground truth verification before implementation of these development plans.

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