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Prioritisation of micro-catchments based on morphology

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Two multicriterion decision-making methods, namely 'compromise programming' and the 'technique for order preference by similarity to an ideal solution' are employed to prioritise 22 micro-catchments (A1 to A22) of Kherthal catchment, Rajasthan, India and comparative analysis is performed using the compound parameter approach. Seven criteria – drainage density, bifurcation ratio, stream frequency, form factor, elongation ratio, circulatory ratio and texture ratio – are chosen for the evaluation. The entropy method is employed to estimate weights or relative importance of the criterion which ultimately affects the ranking pattern or prioritisation of micro-catchments. Spearman rank correlation coefficients are estimated to measure the extent to which the ranks obtained are correlated. Based on the average ranking approach supported by sensitivity analysis, micro-catchments A6, A10, A3 are preferred (owing to their low ranking) for further improvements with suitable conservation and management practices, and other micro-catchments can be processed accordingly at a later phase on a priority basis. It is concluded that the present approach can be explored for other similar situations with appropriate modifications.

Notation

A	area
C_a	relative closeness of each alternative a
D_a	difference between ranks U_a and V_a achieved by the same alternative a
D_a^+	separation measure of each alternative a from the ideal solution
D_a^-	separation measure of each alternative a from the anti ideal solution
D_c	degree of diversification of criterion c
D_d	drainage density
D_j	degree of diversification
E_C	entropy of criterion c
E_j	entropy of the set of alternatives for criterion j
F_u	stream frequency
$f'_j(a)$	value of criterion j for alternative a
$f_j(a)$	normalised value of criterion j for alternative a
f_j^*	normalised ideal value of criterion j
f_j^{**}	normalised anti ideal value of criterion j
L	total length of all streams in the micro-catchment
L_b	length of basin
$L_p(a)$	L_p metric for alternative a for the chosen value of parameter p
M_j, m_j	maximum and minimum values of criterion j in the alternative set N
N	number of alternatives
N'	total number of streams
N_1	total number of first-order streams
N_u	number of streams of order u
N_{u+1}	number of streams of order $u + 1$
P	perimeter
p	parameter reflecting the attitude of the decision maker with respect to compensation between deviations
p_{ij}	normalised payoff matrix
R	Spearman rank correlation coefficient
R_b	bifurcation ratio
R_c	circulatory ratio
R_e	elongation ratio
R_f	form factor
T	texture ratio
U_a, V_a	ranks achieved for the same alternative a
w_c	weight of criterion c
w_j	weight assigned to the criterion j

1. Introduction

Water and land resources for irrigation in a global scenario are dwindling exponentially day by day owing to the growth of the human and livestock population, impact of urbanisation, and demands from other sectors that warrant effective and efficient utilisation of the same. This phenomenon is relevant in most of the developing countries, such as India. Rajasthan state (where the chosen catchment lie) is the largest in India, covering 10·5% of the country's geographical area and sharing 1·15% of its water resources (Figure 1). Some 70% of the population of Rajasthan depends mainly on activities related to agriculture (Narain *et al.*, 2005). Recurring and prolonged droughts of a moderate to severe nature, flash floods, low and erratic rainfall, high summer temperatures, low humidity, high-velocity wind, scarce irrigation facilities, and average to poor soil cover along with lack of sufficient soil moisture are not uncommon. Also, growing demand and a shortfall of surface water have burdened the existing ground water resources, and in many cases have led to over-exploitation. It is expected that non-agricultural demand for water will increase substantially in the coming years, whereas per capita water available will decrease (Narain *et al.*, 2005). Narain *et al.* (2005) suggested suitable agronomic and engineering measures for soil and water conservation programmes that can be integrated with land-use practices for both livelihood security and drought mitigation. Developing and improving a catchment is one of the ways to minimise and mitigate the impact of droughts and other related issues. This process of improving the catchments in a multifaceted way ultimately depends not only on the available natural resources but also on the financial resources, which is a serious concern to the participating agencies such as government departments, research institutions, non-government organisations (NGOs) and other stakeholders. In this regard, it is not possible to implement catchment development and management strategies simultaneously in all the catchments. Hence, prioritisation of catchments is imperative to plan the resource-based activities; this includes identifying catchments that need attention immediately. Holistically, this will also enable the provision of employment on a continued basis. It is also expected that continuous improvement of catchments over a long time domain will improve the socio-economic aspects of the region in general and for relevant stakeholders in specific, soil and moisture conservation and water resources by construction of check dams, which accelerate the recharging process (Government of Rajasthan, 2010; Narain *et al.*, 2005; Srinivasa *et al.*, 2008).

The geomorphology of a catchment, which represents geometrical as well as topological properties, has received wide attention and acceptance both from hydrologists and geomorphologists as a result of the ability to analyse a catchment in the absence of adequate data or in an ungauged environment (Rai *et al.*, 2001; Renschler and Harbor, 2002). In this regard, Rai *et al.* (2001) suggested the utilisation of measurable geomorphological parameters in linear and areal perspectives, such as catchment area, basin length, stream slope, drainage density, bifurcation ratio, stream frequency, length of overland flow, form factor, shape factor, elongation ratio, circulatory ratio, compactness coefficient and texture ratio of the catchment. The qualitative/quantitative analyses of these parameters are important in characterising the catchment, along with land-use pattern, soil, rainfall and slope (Rai *et al.*, 2001). These parameters can also be used as the basis to initiate hydrology and water resource related studies (rainfall–runoff), regional unit hydrograph studies, flood frequency analysis and development of a geomorphological instantaneous unit

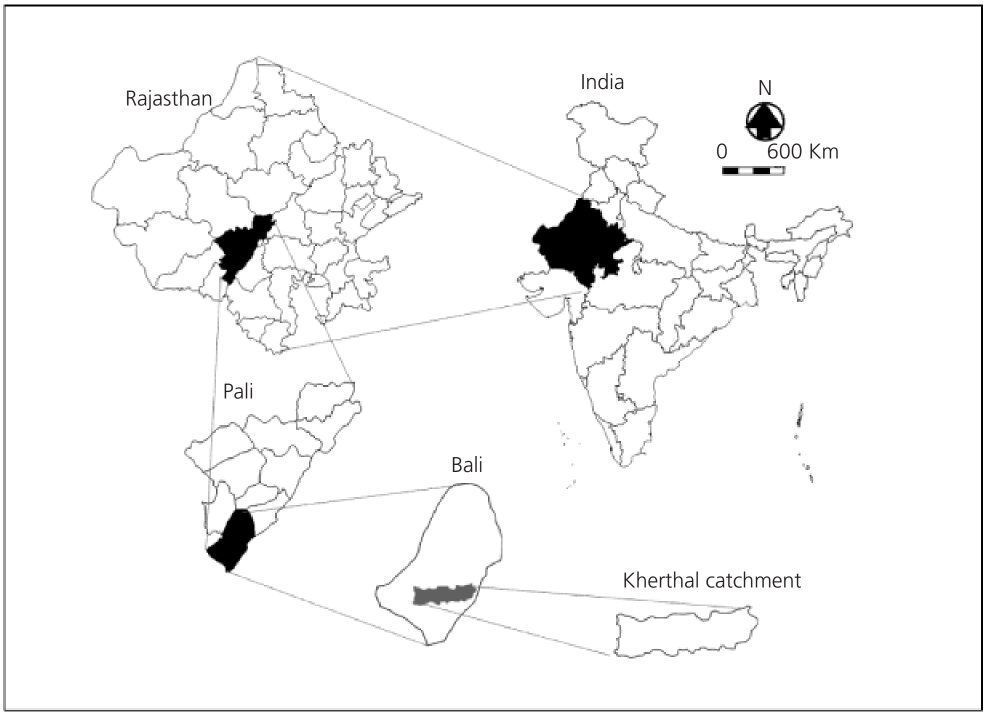

Figure 1. Location map of Kherthal catchment, Rajasthan, India

hydrograph, as well as to develop and prioritise catchment management strategies/policies for effective and sustainable soil and water conservation planning practices.

In this regard, multicriterion decision-making (MCDM) methods (Raju and Nagesh Kumar, 2010) are gaining prominence in prioritising/ranking of catchments. MCDM methods are used for evaluating real-world situations based on various qualitative/quantitative criteria to suggest a suitable alternative among the options available. In the present paper alternatives represent catchments. The present paper is divided into a literature review, description of techniques employed, case study and data analysis, results and discussion, followed by conclusions.

2. Literature review

In the present study only relevant and limited literature is presented. Renschler and Harbor (2002) stressed the role of geomorphologists in the development and implementation of soil erosion assessment tools, and the outcome can be used as the basis for regulatory policies on land management. They opined that soil loss calculations and geomorphological expertise can be used for soil and water conservation planning both through agricultural and local legislation. They concluded that geomorphologists can provide unique perspectives on soil erosion and can continue to affect policy through soil erosion research. Garde (2006) studied river morphology in detail from various perspectives. Table 1 presents a literature review relating to authors and the important parameters employed in their studies. It can be observed from Table 1 that almost all the studies use similar parameters, which were also employed as the basis for choosing the parameters for the present study. Area and perimeter of basins, total length of stream channels, number of streams, stream order and basin length are the fundamental parameters that are required to estimate most of the parameters mentioned in Table 1 and explained in detail in Table 2.

It is noted from the literature review (with the exception of Raju and Nagesh Kumar (2011)) that either comparative analysis is conducted among catchments or a simple rating/compound parameter approach is employed to rank them. However, no study to date has explored either determining weights of the criterion explicitly in a systematic approach or applying MCDM methods for the planning problem, which is the basis for the present paper. In contrast, the present study deals with ranking of catchments using MCDM methods supported by entropy and Spearman rank correlation techniques (which are explained in detail in the objectives of the present study listed below). To the authors' knowledge, this is the first application of MCDM (for ranking catchments) and the entropy method (for weight estimation) in prioritisation studies using morphological parameters. In addition, application of the Spearman rank correlation approach has also assisted in the effective ranking of the chosen catchments.

Adequately addressing the above limitations is the basis for formulating the objectives for the present paper, which can be listed as follows.

(*a*) To explore the applicability of compromise programming (CP) and the technique for order preference by similarity to an ideal solution (Topsis), which are based on 'distance from

Serial No.	Reference	Important parameters analysed
1	Biswas *et al.* (2002)	Bifurcation ratio, drainage density, stream frequency, texture ratio, form factor, circulatory ratio and elongation ratio
2	Ratnam *et al.* (2005)	Bifurcation ratio, drainage density, texture ratio, length of overland flow, stream frequency, compactness coefficient, circulatory ratio, elongation ratio, shape factor and form factor
3	Kouli *et al.* (2007)	Bifurcation ratio, average stream length ratio, drainage density, stream frequency, texture ratio, form factor, elongation ratio and constant of channel maintenance
4	Srinivasa *et al.* (2008)	Drainage density, slope, water capacity, groundwater prospects, soils, wastelands, irrigated area, forest cover, data on agricultural labourers, population and rainfall conditions
5	Sangita and Nagarajan (2010)	Bifurcation ratio, drainage density, drainage frequency, relief ratio, elongation ratio, circulatory ratio and compactness constant
6	Bagyaraj and Gurugnanam (2011)	Bifurcation ratio, drainage density, stream frequency, circulatory ratio, texture ratio, form factor, elongation ratio and constant of channel maintenance and relief parameters
7	Raju and Nagesh Kumar (2011)	Bifurcation ratio, drainage density, stream frequency, length of overland flow, form factor, shape factor, elongation ratio, circulatory ratio, compactness coefficient and texture ratio

Table 1. Comparative analysis of morphological parameters employed by various researchers

Parameter	Definition	Remark	Mathematical expression	Derived values for micro-catchment No. 6
Basin length	Length of basin	—	$L_b = 1{\cdot}312A^{0{\cdot}568}$	2·8834
Drainage density	Ratio of total length of stream segments of all orders per unit area (km^{-1})	Function of time, lithology and represents closeness of channel spacing	$D_d = \frac{L}{A}$	7·985
Bifurcation ratio	Ratio of number of streams of a given order to number of streams of next higher order (no units)	Index of hydrograph shape of basins	$R_b = \frac{N_u}{N_{u+1}}$	1·75, 4·67, 1. Average is 7·42/3 = 2·473
Stream frequency	Total number of stream segments of all orders per unit area (km^{-2})		$F_u = \frac{N'}{A}$	22·25
Texture ratio	Ratio of number of stream segments of first order and perimeter of that catchment (km^{-1})	Index of underlying geology, infiltration rates of rocks and relief characteristics of the catchment	$T = \frac{N_1}{P}$	4·086
Form factor	Ratio of basin area to square of basin length (no units)	Relates shape of the basin, peak flow and duration	$R_f = \frac{A}{L_b^2}$	0·481
Elongation ratio	Ratio of diameter of circle of the same area as the drainage basin and maximum length of basin (no units)	Index of basin shape and hydrological character of a drainage basin	$R_e = 1{\cdot}128\frac{A^{0{\cdot}5}}{L_b}$	0·782
Circulatory ratio	Ratio of area of basin to area of circle having its circumference equal to perimeter of the basin (no units)	Influenced by length and frequency of streams, geological structures, land use/land cover, climate, slope of catchment	$R_c = 12{\cdot}57\frac{A}{P^2}$	0·350

* Other parameters of A6: A is area (km^2) = 4; P is perimeter (km) = 11·993; L is total length of all streams in the MWS = 31·94; N' total number of streams = 89; N_1 is total number of first-order streams = 49; N_u = number of streams of order u = 49, 28, 6, 6; N_{u+1} = number of streams of order u + 1 (28, 6, 6). Stream order is based on hierarchic ranking of streams proposed by Strahler (1957). The first-order streams have no tributaries whereas second-order streams have only first-order streams as tributaries. Similarly, third-order streams have first- and second-order streams as tributaries.

Table 2. Description of various geomorphological parameters and their mathematical expressions with illustration

ideal solution' and 'ideal and anti-ideal solutions' respectively (explained in detail in Sections 3.1 and 3.2), to prioritise 22 micro-catchments (A1 to A22) of Kherthal catchment, Rajasthan, India. Seven parameters, namely drainage density (D_d), bifurcation ratio (R_b), stream frequency (F_u), form factor (R_f), elongation ratio (R_e), circulatory ratio (R_c) and texture ratio (T) are chosen for the evaluation. In both these methods, parameters are simultaneously considered for ranking of micro-catchments.

(*b*) To conduct a comparative analysis with a simple, but effective compound parameter approach (CPAP).
(*c*) To explore the applicability of the entropy method for estimating the relative importance of parameters.
(*d*) To explore the applicability of the Spearman rank correlation coefficient.

3. Techniques employed

3.1 Compromise programming

Compromise programming defines the suitable solution as the one in the set of efficient solutions whose point is at the least distance from an ideal point (Zeleny, 1982). The distance measure used in CP is the family of L_p metrics and expressed as

$$L_p(a) = \left[\sum_{j=1}^{J} w_j^p \left|f_j^* - f_j(a)\right|^p\right]^{1/p} \quad (1)$$

where $j = 1, 2, \ldots, J$; $L_p(a) = L_p$ metric for alternative a for the chosen value of parameter p; $f_j(a)$ is the normalised value of criterion j for alternative a; f_j^* is the normalised ideal value of criterion j; w_j is the weight assigned to the criterion j; p is the parameter reflecting the attitude of the decision maker with respect to compensation between deviations. For $p = 1$, all deviations from f_j^* are taken into account in direct proportion to their magnitudes. For $p = \infty$, the largest deviation is the only one taken into account corresponding to zero compensation between deviations.

3.2 Technique for order preference by similarity to an ideal solution

The technique for order preference by similarity to an ideal solution is based on the principle that the chosen alternative should have the shortest distance from the ideal solution (the same as the CP approach with $p = 2$) and the farthest distance from the anti-ideal solution (Chen and Hwang, 1992; Opricovic and Tzeng, 2004). A brief methodology of Topsis consists of the following steps.

(*a*) Compute the separation measure D_a^+ of each alternative a from the ideal solution, that is the Euclidean distance of each criterion from its ideal value, and summing these for all criteria ($j = 1, 2, \ldots, J$) for a given alternative a, that is

$$D_a^+ = \sqrt{\sum_{j=1}^{J}\left[w_j f_j(a) - w_j f_j^*\right]^2} \quad (2)$$

(*b*) Compute the separation measure D_a^- of each alternative a from the anti-ideal solution, that is the Euclidean distance of each criterion from its anti-ideal value, and summing these for all criteria ($j = 1, 2, \ldots, J$) for a given alternative a, that is

$$D_a^- = \sqrt{\sum_{j=1}^{J}\left[w_j f_j(a) - w_j f_j^{**}\right]^2} \quad (3)$$

where, f_j^{**} is the normalised anti-ideal value of criterion j.

(*c*) Compute the relative closeness C_a of each alternative a with reference to anti-ideal measure D_a^-, that is

$$C_a = \frac{D_a^-}{\left(D_a^- + D_a^+\right)} \quad (4)$$

(*d*) Rank the alternatives based on the C_a values. The higher the C_a value, the better the alternative.

3.3 Entropy method for estimation of relative importance of parameters

The entropy method estimates the weights of the various criteria from the given payoff matrix, that is the matrix representing alternatives against criteria array, and is independent of the views of the decision maker (Pomerol and Romero, 2000). Hwang and Yoon (1981) mentioned that the entropy method is particularly useful to explore contrasts between sets of data and these sets of data can be mapped as a set of alternative solutions in the payoff matrix, where each alternative solution is evaluated in terms of its outcome. The philosophy of the method is based on the amount of information available (can be measured by its entropy value) and its relationship with the importance of the criterion. Pomerol and Romero (2000) and Aomar (2002) explained the entropy method in the following steps.

(*a*) For the given normalised payoff matrix, p_{ij}, entropy E_j of the set of alternatives for criterion j is

$$E_j = -\frac{1}{\ln(N)}\sum_{i=1}^{N} p_{ij}\ln(p_{ij}) \quad \text{for} \quad j = 1, \ldots, J \quad (5)$$

where N is the number of alternatives and j is the number of criterion.

(*b*) Degree of diversification D_j of the information provided by the outcomes of criterion j is $D_j = 1 - E_j$ for $j = 1, \ldots, J$ and normalised weights of the criterion are

$$w_j = \frac{D_j}{\sum_{j=1}^{J} D_j} \qquad (6)$$

If the entropy value is high, the uncertainty contained in the criterion vector is high (step 1), diversification of the information is low (step 2) and correspondingly the criterion is less important. This method is advantageous as it reduces the burden of the decision maker for large-sized problems. It can also be used as a benchmark solution in situations where consensus cannot be reached in a group, while estimating the weights of criterion. Conversely, the role of the decision maker is limited while estimating the relative importance of the criterion.

3.4 Spearman rank correlation coefficient

The Spearman rank correlation coefficient R is useful to determine the measure of association/correlation (including positive or negative direction of a relationship) between ranks achieved by different scenarios for a given set of alternatives. If U_a and V_a denote the ranks achieved by the above situation(s) for the same alternative a, then R is defined as (Gibbons, 1971)

$$R = 1 - \frac{6\sum_{a=1}^{N} D_a^2}{N(N^2 - 1)} \qquad (7)$$

where D_a is the difference between ranks U_a and V_a achieved by the same alternative a, N is the number of alternatives and R values vary between -1 and 1.

4. Case study and data analysis

Kherthal catchment, in Rajastan (Figure 1) lies between latitudes 24°51′ and 24°58′ north and longitudes 73°8′ and 73°19′ east. The area of the catchment (consisting of 25 micro-catchments) is approximately 159 km^2 (Government of Rajasthan, 2000a, 2000b). Relevant and required data are inferred from Indian remote sensing, linear imaging and self-scanning (IRS-LISS-III) imageries of the case study area. In addition, survey of India topographical sheets 45 H/1 and 45 H/5 to a scale of 1:50 000 were also used. The climate of the catchments is semi-arid, and characterised by very hot summers and cold winters. Maximum and minimum temperatures registered are 45°C and 1°C and mean annual rainfall in the region is 490 mm. Maximum and minimum elevation of the catchment is 1090 m and 340 m above mean sea level. Land cover patterns include areas of dense forest, fallow land and a double crop season: crops grown in the Kharif season (summer, i.e. June to October) are bajra, pulses, and in the Rabi season (winter, i.e. November to February) are wheat and mustard. Groundwater is the major source for irrigation, with average withdrawals in the region varying from 40 to 80 m^3/day. The topography of Kherthal catchment is undulating, with nearly level (0 to 1%), very gently sloping (1 to 3%; low-lying areas) and gently sloping areas (3 to 5%); as well as steeper, hilly areas (>5% to >70% slopes). Geologically the area consists of granite, massive and plutonic rocks, and massive limestone. Geomorphologically it consists of structural and denudated hills, pediments, buried pediments and valley fields (Government of Rajasthan, 2000a, 2000b; Raju and Nagesh Kumar, 2011). Seven morphological parameters, namely drainage density (D_d), bifurcation ratio (R_b), stream frequency (F_u), texture ratio (T), form factor (R_f), elongation ratio (R_e) and circulatory ratio (R_c) were chosen for the evaluation. Morphological characteristics have been studied in detail by various researchers (Horton, 1932, 1945; Miller, 1953; Schumm, 1956; Strahler, 1957, 1964).

In the present study, the catchment area, basin length, channel slope, land use and mean basin elevation were measured/estimated/inferred. Also in the present study, 22 out of 25 micro-catchments were chosen for the prioritisation process; details are presented in Table 3. In addition, the seven mentioned parameters were computed for A1 to A22. Descriptions and mathematical expressions for the seven parameters are presented in Table 2, along with corresponding values for A6 as an example (Biswas *et al.*, 2002; Garde, 2006; Ratnam *et al.*, 2005; Strahler, 1957, 1964). Table 3 presents the areas of A1 to A22 and the payoff matrix. Out of the seven criteria, the first four are of ‘maximisation’ in nature and the latter three are of ‘minimisation’ in nature. In any decision-making environment, high values are preferred for maximisation criteria (e.g. benefits) and low values are preferred for minimisation criteria (e.g. cost). However, for compatibility and analysis purposes, a minimisation nature criterion was given a negative sign, so that it could be considered as a maximum for computation purposes and accordingly presented in Table 3 (Biswas *et al.*, 2002; Ratnam *et al.*, 2005). It is noted from Table 3 that drainage density varies between lower and upper values (1·979, 7·985) among A1 to A22. Similarly lower and upper values for bifurcation ratio are (1, 3·764), stream frequency (3·333, 22·250), form factor (0·341, 0·604), elongation ratio (0·658, 0·877), circulatory ratio (0·185, 0·651), and texture ratio (0·556, 4·330).

The estimated parameters are normalised based on the methodology suggested by Pomerol and Romero (2000) and Raju and Nagesh Kumar (2010). The normalisation process helps to ensure that the criterion with a larger range will not dominate the criterion with a smaller range and helps to maintain consistency and uniformity. Even though form factor, bifurcation ratio, elongation ratio and circulatory ratio do not have any units, they are also normalised because of the differences in their variance, relative magnitude. Pomerol and Romero (2000) suggested four methods for normalisation. Out of these

Alternative	Parameter								
	MWS in the field	Area: km^2	D_d: km/km^2	R_b	F_u: No. of streams/km^2	T: km^{-1}	R_f	R_e	R_c
A1	2	50·500	3·392	1·701	6·337	4·152	−0·341	−0·658	−0·422
A2	3	12·500	3·834	3·764	8·480	3·223	−0·412	−0·724	−0·539
A3	4	6·750	5·126	1·898	15·556	4·330	−0·448	−0·755	−0·490
A4	5	3·000	4·577	1·839	14·667	3·118	−0·500	−0·798	−0·587
A5	6	4·250	2·696	3·060	9·647	2·587	−0·477	−0·779	−0·621
A6	7	4·000	7·985	2·473	22·250	4·086	−0·481	−0·782	−0·350
A7	9	2·000	4·477	2·938	12·500	2·304	−0·529	−0·820	−0·593
A8	10	0·750	4·436	2·750	13·333	1·612	−0·604	−0·877	−0·500
A9	11	1·750	3·969	2·200	9·143	1·010	−0·538	−0·828	−0·185
A10	12	10·500	4·700	1·993	13·238	3·783	−0·422	−0·733	−0·274
A11	13	3·200	3·974	2·292	10·625	1·952	−0·496	−0·794	−0·347
A12	14	1·300	3·464	2·667	8·462	1·300	−0·561	−0·845	−0·432
A13	15	2·500	4·464	1·843	11·200	2·303	−0·513	−0·808	−0·651
A14	16	1·500	2·798	2·333	6·667	1·056	−0·550	−0·836	−0·429
A15	17	4·250	4·303	1·720	9·176	1·760	−0·477	−0·779	−0·414
A16	18	14·000	4·071	2·224	8·929	3·507	−0·406	−0·719	−0·482
A17	19	2·500	4·870	2·150	12·800	2·460	−0·513	−0·808	−0·587
A18	20	6·750	3·520	1·775	6·074	1·447	−0·448	−0·755	−0·336
A19	21	2·250	3·385	1·000	5·333	0·840	−0·520	−0·814	−0·554
A20	23	4·500	1·979	3·400	3·333	0·556	−0·473	−0·776	−0·216
A21	24	13·550	2·814	2·567	4·576	1·841	−0·408	−0·720	−0·446
A22	25	2·250	3·829	2·167	8·444	1·643	−0·520	−0·814	−0·452
Maximum		50·500	7·985	3·764	22·250	4·330	−0·341	−0·658	−0·185
Minimum		0·750	1·979	1·000	3·333	0·556	−0·604	−0·877	−0·651

Table 3. Micro-catchment areas and payoff matrix

$$\frac{f'_j(a)}{\sum_{a=1}^{N} f'_j(a)}$$

termed M1 from now on, is used for the entropy approach and

$$\frac{f'_j(a) - m_j}{M_j - m_j}$$

termed M2 from now on, is used for CP and Topsis application, as suggested by Pomerol and Romero (2000) and Raju and Nagesh Kumar (2010). Here, $f'_j(a)$ is the value of criterion j for alternative a and M_j and m_j are maximum and minimum values of criterion j in the alternative set N.

5. Results and discussion

5.1 Entropy method

Table 4 presents weights of the criteria obtained by the entropy method – that is, based on the normalisation approach

$$\frac{f'_j(a)}{\sum_{a=1}^{N} f'_j(a)}$$

for the data presented in Table 3 and steps 1 to 2 described in the entropy method (Section 3.3). It can be noted from Table 4 that among seven parameters, texture ratio is given high importance (0·366), which means that its effect on prioritisation of A1 to A22 is very significant, followed by F_u (0·255), R_c (0·126), D_d (0·116), R_b (0·106), R_f (0·0237), R_e (0·006) and the combined contribution of R_f and R_e is less than 0·03. Texture ratio is given

Parameter	Entropy value, E_C	$D_c = 1 - E_C$	Weights of criteria $w_c = \frac{D_c}{\sum D_c}$	Rank
D_d	0·988	0·01238	0·116	4
R_b	0·989	0·01130	0·106	5
F_u	0·973	0·02712	0·255	2
T	0·961	0·03890	0·366	1
R_f	0·997	0·00252	0·0237	6
R_e	0·999	0·00065	0·006	7
R_c	0·987	0·01346	0·126	3
		$\sum D_c = 0{\cdot}10632$		

Table 4. Entropy values and weights of criteria

three times the importance as compared to circulatory ratio. Stream frequency is almost twice that of circulatory ratio. Entropy studies also provided an opportunity to differentiate the relative importance of morphological parameters (instead of assuming they are equal) which ultimately affect the prioritisation of A1 to A22; relevant aspects are discussed in the coming sections. Moreover, as weights of parameters are independent of the views of the decision maker (as dependent only on payoff matrix), it is expected to reduce bias in the estimation, if any, which is the added advantage of the entropy method. To the best of the present authors' knowledge, this is the first application of the entropy method in morphological studies related to the catchment management environment.

5.2 Compromise programming

In the CP approach, minimum, maximum and ideal values for each criterion are chosen from Table 3 and normalised as per the equation

$$\frac{f'_j(a) - m_j}{M_j - m_j}$$

Accordingly, the maximum value is assigned as one and the minimum value is assigned zero, and the optimal value is the maximum value. Table 5 presents L_p metric values for $p = 1$, 2, ∞ and corresponding ranking pattern based on Equation 1 and weights estimated by the entropy method (from now on termed varying weights, VW). A small change in the L_p metric value is also accounted for here while inferring ranking and computation of Spearman rank correlation coefficient values. All three sets $p = 1$, 2, ∞ show different ranking patterns. However, the first three positions are consistently occupied by A6, A3, A10 and they can be considered for treatment immediately for possible improvements. L_p (for $p = 1$) values for A6, A3, A10 are 0·1342, 0·3126, 0·3399. These are 0·0721, 0·1527, 0·1640 for $p = 2$ and 0·0512, 0·0942, 0·1216 for $p = \infty$. In all three sets of p, A19, A20 occupied higher ranks, which means that no immediate attention is necessary for these micro-catchments for possible improvements. Spearman rank correlation coefficient R (based on Equation 7) values presented in Table 6 between $p = 1$ and 2 (0·9684), $p = 1$ and ∞ (0·9018), $p = 2$ and ∞ (0·9706) indicate reasonably good correlation.

A study was also conducted to analyse CP with equal weights (EW) assigned to all parameters, namely 0·1428 each. In this case, L_1, L_2, $L\infty$ values for top ranking A6 and A10 are 0·2835, 0·3786; 0·1394, 0·1569; 0·0853, 0·0937 (Table 5). Spearman R values between $p = 1$ and 2 (i.e. 0·9198) and p = 2 and ∞ (i.e. 0·8848) indicate good correlation and satisfactory correlation for $p = 1$ and ∞ (i.e. 0·6838). R values between varying and equal weight scenarios are presented in Table 7.

5.3 Technique for order preference by similarity to an ideal solution

D_a^+ (corresponding to Equation 2 is the same as that of CP with $p = 2$), D_a^- (corresponding to Equation 3) and C_a (Equation 4) for the A1 to A22 in VW and EW scenarios as presented in Table 8. In the VW scenario, A6, A3 and A10 occupied the first three positions (with C_a values of 0·8608, 0·7274, 0·6789), and A20 and A19 occupied the last two positions with C_a values of 0·1685 and 0·0976. Similar analysis was carried out for the EW scenario and the results are also presented in Table 8. In this case, A6, A10 and A3 occupied the first three positions with C_a values of 0·6594, 0·5776, 0·5538. Spearman R values between ranking pattern obtained by Topsis between VW and EW scenarios is 0·8509. These values for CP ($p = 2$) for VW, EW and Topsis for VW and EW scenarios are 0·9898, 0·9141, indicating good correlation between CP ($p = 2$) and Topsis for both weight scenarios.

5.4 Compound parameter approach

In the CPAP, seven parameters were ranked individually for each micro-catchment and these were averaged to obtain the compound parameter for each micro-catchment, as presented in Table 9. The lowest compound parameter is given the highest priority and can

Alternative	Varying weight (VW) scenario						Equal weight (EW) scenario					
	L_p ($p = 1$)	Rank	L_p ($p = 2$)	Rank	L_p ($p = \infty$)	Rank	L_p ($p = 1$)	Rank	L_p ($p = 2$)	Rank	L_p ($p = \infty$)	Rank
A1	0·4645	4	0·2543	7	0·2146	11	0·4154	3	0·2075	6	0·1267	11
A2	0·4778	5	0·2485	6	0·1858	8	0·4348	5	0·1935	5	0·1165	7
A3	0·3126	2	0·1527	2	0·0942	2	0·4299	4	0·1806	3	0·1022	3
A4	0·4872	7	0·2150	4	0·1242	4	0·5846	9	0·2299	8	0·1256	10
A5	0·6026	11	0·2878	10	0·1819	7	0·6098	13	0·2452	14	0·1400	17
A6	0·1342	1	0·0721	1	0·0512	1	0·2835	1	0·1394	1	0·0853	1
A7	0·5599	8	0·2722	9	0·1968	9	0·6093	12	0·2394	12	0·1289	12
A8	0·6069	12	0·3131	13	0·2635	16	0·6893	19	0·2741	20	0·1536	21
A9	0·6591	15	0·3806	19	0·3219	20	0·6189	16	0·2549	16	0·1322	14
A10	0·3399	3	0·1640	3	0·1216	3	0·3786	2	0·1569	2	0·0937	2
A11	0·5834	10	0·2985	12	0·2310	12	0·5719	8	0·2194	7	0·1060	4
A12	0·7016	17	0·3677	17	0·2940	18	0·7003	20	0·2714	19	0·1355	15
A13	0·6339	13	0·2953	11	0·1979	10	0·6773	18	0·2616	17	0·1439	19
A14	0·7731	20	0·4035	20	0·3179	19	0·7434	21	0·2861	21	0·1405	18
A15	0·6532	14	0·3293	14	0·2499	13	0·6122	14	0·2338	9	0·1143	6
A16	0·4827	6	0·2333	5	0·1796	5	0·4706	6	0·1929	4	0·1074	5
A17	0·5600	9	0·2622	8	0·1819	6	0·6142	15	0·2367	11	0·1255	9
A18	0·7140	19	0·3752	18	0·2817	17	0·6080	11	0·2413	13	0·1292	13
A19	0·8826	22	0·4428	21	0·3390	21	0·8242	22	0·3143	22	0·1532	20
A20	0·7750	21	0·4614	22	0·3668	22	0·6056	10	0·2697	18	0·1595	22
A21	0·7045	18	0·3636	16	0·2570	14	0·5694	7	0·2345	10	0·1388	16
A22	0·6816	16	0·3439	15	0·2614	15	0·6682	17	0·2536	15	0·1193	8

Table 5. L_p metric values (for $p = 1, 2, \infty$) and ranking pattern obtained by compromise programming (VW and EW scenarios)

Varying weight (VW) scenario			Equal weight (EW) scenario		
Method	Method	Spearman *R* value	Method	Method	Spearman *R* value
CP ($p = 1$)	CP ($p = 2$)	0·9684	CP ($p = 1$)	CP ($p = 2$)	0·9198
	CP ($p = \infty$)	0·9018		CP ($p = \infty$)	0·6838
	Topsis	0·9785		Topsis	0·9424
	CPAP	0·9153		CPAP	0·8791
CP ($p = 2$)	CP ($p = \infty$)	0·9706	CP($p = 2$)	CP ($p = \infty$)	0·8848
	Topsis	0·9898		Topsis	0·9141
	CPAP	0·9265		CPAP	0·8961
CP ($p = \infty$)	Topsis	0·9435	CP ($p = \infty$)	Topsis	0·6589
	CPAP	0·9028		CPAP	0·6612
Topsis	CPAP	0·9277	Topsis	CPAP	0·9446

Table 6. Spearman rank correlation coefficient values for varying and equal weight scenario

Method (VW scenario)	Method (EW scenario)	Spearman rank value
CP ($p = 1$)	CP ($p = 1$)	0·7391
CP ($p = 2$)	CP ($p = 2$)	0·8407
CP ($p = \infty$)	CP ($p = \infty$)	0·7221
Topsis	Topsis	0·8509
CPAP	CPAP	0·8780

Table 7. Spearman rank correlation coefficient values between varying and equal weight scenarios

be provided with immediate soil conservation measures. Table 9 presents two scenarios, namely VW and EW. In the VW scenario, A6, A3, A4, A10 with compound parameter values 3·03, 5·54, 6·36, 6·74 respectively occupied the first four positions and A19, A20 with compound parameter values 18·73 and 18·44 occupied the last two positions. In the case of the EW scenario, A6, A10, A3, A2 occupied the first four positions, indicating that weights of parameters were playing a major role, which significantly affects the decision-making process for prioritisation. Spearman *R* value between VW and EW scenarios is 0·8780.

Spearman *R* values between various combinations of methods with two weight scenarios are presented in Tables 6 and 7; these are self-explanatory. It can be observed from Table 6 that correlation between CP ($p = \infty$) with other methods in the VW scenario is above 0·9, whereas in the EW scenario, the *R* values between CP ($p = \infty$) and CP ($p = 1$), CP ($p = 2$), Topsis, CPAP are 0·6838, 0·8848, 0·6589, 0·6612, which indicates that the results pattern of CP ($p = \infty$) is not compatible with the other methods. It can be noted from Table 7 that the *R* value between CP ($p = 1$), CP ($p = \infty$) for both VW and EW scenarios is 0·7391 and 0·7221, which is not satisfactory for two different weight scenarios for the same method. Similar inferences can be drawn from Tables 6 and 7.

It is observed that all three approaches CP, Topsis and CPAP provide comparable results, as observed by their individual ranking pattern and inferences drawn from the Spearman rank correlation coefficient values.

5.5 Sensitivity analysis

The value of each weight of criterion is increased and then decreased as much as possible without changing the order of the criterion. Stream frequency is the second largest criterion, with relative importance of 0·255. The adjacent values are 0·365 (texture ratio) and 0·126 (circulatory ratio). Therefore two sensitivity runs were performed for this criterion to investigate the influence of values up to 0·364 and 0·127 on the ranking, respectively. This represents the range that maintains the same order. Similar analysis was also conducted for other criteria. A total of 12 combinations of weight scenarios were evaluated and almost all of the 12 combinations showed similar trends.

5.6 Decision making in a multimethod environment

In the present study, the average ranking approach suggested by Bui (1987) is employed by considering ranking pattern of CP ($p = 1,\ 2$), Topsis and CPAP (excluding the outcome of CP ($p = \infty$) owing to incompatibility and to maintain consistency for a group decision-making perspective) to obtain a more meaningful analysis of the outcome. The average ranking pattern is presented in Table 9, which can be used as the basis for a soil and water conservation programme with an holistic view, depending on the perception of department officials (Sharma, 2004). Figures 2 and 3 present the ranking pattern of micro-catchments by various methods for both varying and equal weight scenarios. The average ranking (represented by notation AV) is also shown.

6. Summary and conclusions

In total, seven parameters, namely drainage density (D_d), bifurcation ratio (R_b), stream frequency (F_u), texture ratio (T), form factor (R_f), elongation ratio (R_e) and circulatory ratio (R_c) were

Alternative	Varying weight (VW) scenario				Equal weight (EW) scenario			
	D_a^+	D_a^-	C_a	Rank	D_a^-	D_a^+	C_a	Rank
A1	0·2543	0·3539	0·5818	4	0·2497	0·2075	0·5461	5
A2	0·2485	0·2908	0·5392	7	0·2343	0·1935	0·5477	4
A3	0·1527	0·4076	0·7274	2	0·2241	0·1806	0·5538	3
A4	0·2150	0·2978	0·5807	5	0·1682	0·2299	0·4225	8
A5	0·2878	0·2294	0·4435	10	0·1693	0·2452	0·4084	9
A6	0·0721	0·4462	0·8608	1	0·2698	0·1394	0·6594	1
A7	0·2722	0·2279	0·4557	9	0·1606	0·2394	0·4014	10
A8	0·3131	0·1883	0·3755	12	0·1375	0·2741	0·3341	17
A9	0·3806	0·1087	0·2222	18	0·1036	0·2549	0·2890	19
A10	0·1640	0·3468	0·6789	3	0·2145	0·1569	0·5776	2
A11	0·2985	0·1791	0·3750	13	0·1377	0·2194	0·3856	12
A12	0·3677	0·1223	0·2496	17	0·1094	0·2714	0·2873	20
A13	0·2953	0·2083	0·4136	11	0·1333	0·2616	0·3375	16
A14	0·4035	0·0854	0·1747	20	0·0879	0·2861	0·2350	21
A15	0·3293	0·1510	0·3143	14	0·1317	0·2338	0·3603	14
A16	0·2333	0·3029	0·5649	6	0·2072	0·1929	0·5179	6
A17	0·2622	0·2356	0·4733	8	0·1518	0·2367	0·3907	11
A18	0·3752	0·1042	0·2174	19	0·1345	0·2413	0·3579	15
A19	0·4428	0·0479	0·0976	22	0·0724	0·3143	0·1872	22
A20	0·4614	0·0935	0·1685	21	0·1578	0·2697	0·3691	13
A21	0·3636	0·1416	0·2802	16	0·1768	0·2345	0·4298	7
A22	0·3439	0·1387	0·2873	15	0·1120	0·2536	0·3064	18

Table 8. Ranking pattern obtained by Topsis approach (VW and EW scenarios)

considered as evaluation criteria for prioritising 22 micro-catchments of Kherthal catchment, Rajasthan, India. The entropy method was employed to determine the weights of the criteria. CP, TOPSIS and the CPAP were employed to prioritise the micro-catchments, as exploring more than one method enhances the decision-making ability for selection of the most suitable option (Duckstein *et al.*, 1994). This also provided an opportunity to understand the application potential of the methods employed. The average ranking approach suggested by Bui (1987) was employed herein to aggregate the ranking pattern. The resulting patterns may change with the addition of further geomorphological parameters, a change in relative importance of the criteria or the normalisation approach. However, the methodology presented can be applied to similar problems with great ease, which is the main focus of the present paper.

The following conclusions/inferences are drawn from the present studies.

(*a*) It is the first complete MCDM application in morphological studies incorporating extensive sensitivity analysis and a simple but effective weight estimation procedure, the entropy method.
(*b*) Quantitative evaluation of morphometric parameters is found to be extremely useful in situations with an ungauged environment, such as Kherthal, where prioritisation of micro-catchments is essential for implementing soil and water conservation programmes. This also provided an opportunity for improved understanding of the geomorphological and hydrological characteristics of the micro-catchments.
(*c*) It is observed that all the three approaches CP, Topsis and CPAP give comparable results, as shown by their individual ranking pattern and inferences drawn from Spearman rank correlation coefficient values.
(*d*) Average ranking pattern along with related sensitivity analysis reveals that A6, A3 and A10 are consistently ranked as the highest priority for soil and water conservation programmes.
(*e*) Among the seven parameters, texture ratio is given high importance (0·366), which means that its effect on prioritisation of micro-catchments is very significant, followed by F_u (0·255), R_c (0·126), D_d (0·116), R_b (0·106), R_f (0·0237), R_e (0·006) and the combined contribution of R_f and R_e is less than 0·03.
(*f*) The ranking pattern provided by the two MCDM methods and the CPAP suggested that weights of criteria play a major role. However, the present study can be used as the basis for further refining the weight estimation procedure in a fuzzy environment.
(*g*) Spearman rank correlation coefficient is found to be a good

Alternative	D_d	R_b	F_u	T	R_f	R_e	R_c	Varying weight		Equal weight		Average ranking	
								Ave	Rank	Ave	Rank	VW	EW
A1	17	20	18	2	1	1	1	9·58	8	8·57	5	5	5
A2	13	1	14	6	4	4	16	9·53	7	8·29	4	6	4
A3	2	15	2	1	6	6	21	5·54	2	7·57	3	2	3
A4	5	17	3	7	13	13	2	6·36	3	8·57	6	4	7
A5	21	3	10	8	9	9	10	9·78	9	10·00	8	10	10
A6	1	8	1	3	11	11	3	3·03	1	5·43	1	1	1
A7	6	4	7	10	18	18	18	9·38	5	11·57	12	8	11
A8	8	5	4	16	22	22	20	11·52	13	13·86	16	13	19
A9	12	12	12	20	19	19	5	14·25	15	14·14	18	17	17
A10	4	14	5	4	5	5	15	6·74	4	7·43	2	3	2
A11	11	10	9	12	12	12	6	10·15	12	10·29	9	12	9
A12	16	6	15	18	21	21	11	14·93	17	15·43	19	18	20
A13	7	16	8	11	14	14	4	9·50	6	10·57	10	11	16
A14	20	9	17	19	20	20	13	16·81	20	16·86	21	20	21
A15	9	19	11	14	10	10	17	13·44	14	12·86	14	14	13
A16	10	11	13	5	2	2	19	9·94	11	8·86	7	7	6
A17	3	13	6	9	15	15	22	9·79	10	11·86	13	9	12
A18	15	18	19	17	7	7	7	15·82	19	12·86	15	19	14
A19	18	21	20	21	16	16	9	18·73	22	17·29	22	22	22
A20	22	2	22	22	8	8	14	18·44	21	14·00	17	21	15
A21	19	7	21	13	3	3	12	14·68	16	11·14	11	16	8
A22	14	22	16	15	17	17	8	15·06	18	15·57	20	15	18

Table 9. Ranking pattern obtained by compound parameter approach and average ranking

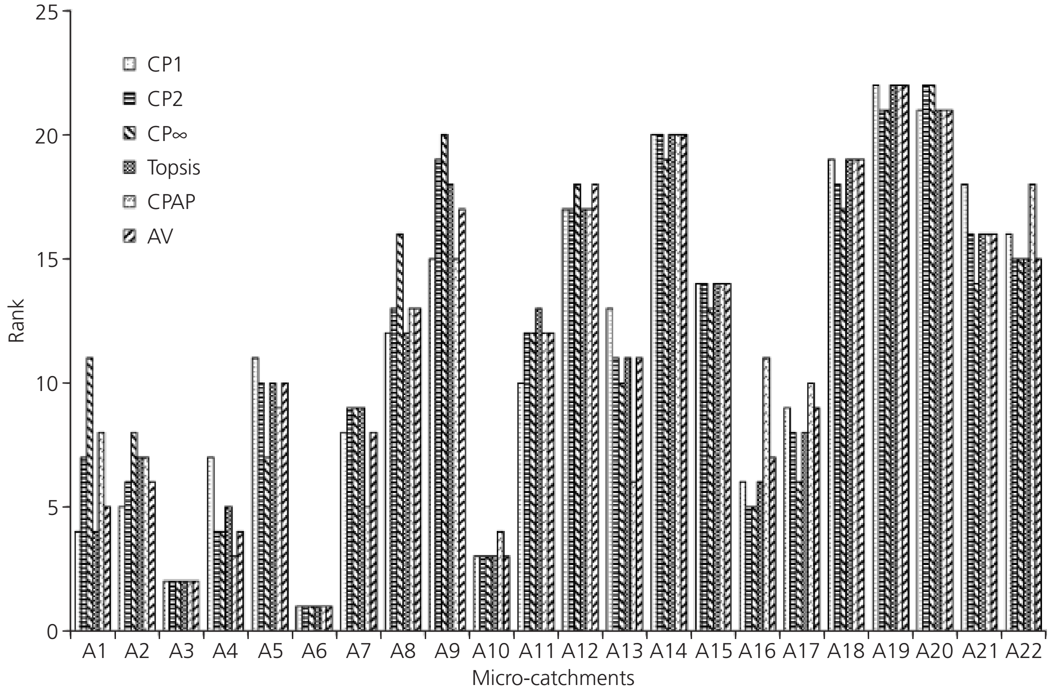

Figure 2. Ranking pattern of micro-catchments by various techniques (varying weights)

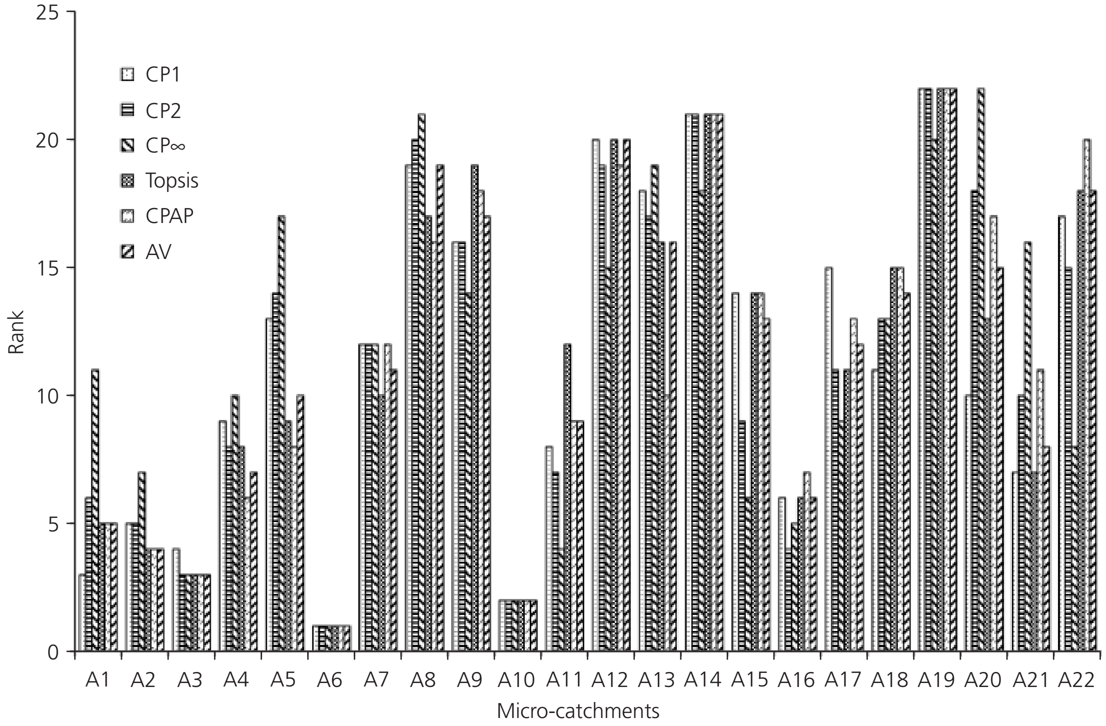

Figure 3. Ranking pattern of micro-catchment by various techniques (equal weights)

indicator to assess the correlation between ranking patterns obtained by various methods.

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