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Identification of Spatial Ranking of Hydrological Vulnerability Using Multi-Criteria Decision Making Techniques: Case Study of Korea

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Abstract Potential flood damage (PFD), potential streamflow depletion (PSD), potential water quality deterioration (PWQD), and watershed evaluation index (WEI) have been developed to spatially quantify the hydrological vulnerability using multi-criteria decision making (MCDM) techniques. All criteria are selected on the basis of a sustainability evaluation concept (pressure-state-response model), and their weights are estimated by an Analytic Hierarchy Process, which is also a type of MCDM technique. The MCDM techniques used for the evaluation are composite programming, compromise programming, ELECTRE II, Regime method, and Evamix method; these techniques can be classified according to data availability and objectives (prefeasibility and feasibility). Furthermore, the WEI is improved to reflect the preferences of the residents with regard to management objectives through weights (of PFD, PSD, and PWQD) obtained from questionaires of residents. Finally, this study derives a procedure to identify the spatial investment prioritization using four indices.

Keywords Hydrological vulnerability · Multi-criteria decision making · Pressure-state-response model · Spatial priority ranking · Sustainability

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1 Introduction

Development of a set of readily measurable indicators which describe the condition and health of watersheds is essential to protection and sustainable use of terrestrial water resources. In recent years, a number of studies have focused on the indicator developments. For example, 'The Freshwater Imperative', a book collectively sponsored by multiple US Federal Agencies, calls for the development of appropriate indicators to track particular environmental changes and their effects on ecological services, human health, aesthetic and recreational activities, and the degree of integration of human, natural, and management sciences in freshwater research and management (Naiman et al. 1995). A central them of the US environmental Monitoring and Assessment Program (EMAP) is similarly focused on the development of ecological indicators to estimate the state and health of the nation's ecological resources on a regional basis (Messer et al. 1991). The US Geological Survey's National Water Quality Assessment Program (NAWQA) places its emphasis on inventory, monitoring, and assessment of water resource conditions. In working with public and private partnerships, the USEPA has developed a set of indicators to measure the water quality of the nation's watersheds (USEPA 1996, 1997). Some researchers have proposed the index of biotic integrity which integrates 12 attributes of fish assemblages to evaluate the ecological quality of a water resource (Karr et al. 1986) and indicators of ecosystem recovery which reflect intrinsic importance, processes, sensitivity, and effects of ecosystems (Kelly and Harwell 1990). These indicators, however, are often based on single purpose such as vegetation, soil, hydrology, or climate frameworks (Bailey 1984; Omernik 1995) and often reflect the partial state of an ecosystem. A set of indices such as an ecological index of integrity which describes the patterns and processes of an ecosystem holistically should be developed to evaluate the state of the ecosystem (Omernik 1995; He et al. 2000).

To incorporate corresponding environmental indices that reflect sustainability-related objectives in the decision making process, the definition and trade-offs among the criteria examined must be clearly established. Sustainability-related objectives cannot be achieved if the projects do not operate according to criteria that ensure sustainability. A significant role in the operational sustainability plays the managerial solutions or alternatives. However, under conditions of scarcity and competing and conflicting uses of water resources, it is required that investment priority be distributed as efficiently as possible (Manoliadis 2001).

This paper presents a methodology to assess the spatial ranking of hydrologic vulnerability using multi-criteria decision making (MCDM) techniques and a sustainability evaluation model. In this study, hydrologic vulnerability implies the potentials of flood damage, streamflow depletion, and water quality deterioration; these parameters are quantified as potential flood damage (PFD), potential streamflow depletion (PSD), and potential water quality deterioration (PWQD), respectively. The watershed evaluation index (WEI) is also developed to quantify the overall hydrologic vulnerability by the numerical integration of PFD, PSD, and PWQD. The use of the proposed indices can provide decision makers with objectively spatial priority for watershed management. In addition, the WEI that reflects the preference of residents for watershed management objectives can provide decision makers with flexibility to obtain stakeholder consensus for water resources planning.

2 Sustainability Evaluation: PSR Model

The 1992 Earth Summit recognized the important role that indicators can play in helping countries make informed decisions concerning sustainable development. This recognition is articulated in Chapter 40 of Agenda 21 which calls on governments at the national level, as well as international, and non-government organizations, to develop and identify indicators of sustainable development (ISDs) that can provide a solid basis for decision making at all levels (UNCSD 2001).

Because sustainability is a function of various economic, environmental, ecological, social and physical goals and objectives, water resources management must inevitably involve multi-objective tradeoffs in multi-disciplinary and multi-participatory decision making process. Therefore, various ways to measure sustainability have been developed. One way is to express relative levels of sustainability as separate or weighted combinations of reliability, resilience, and vulnerability measures; these various criteria contribute to human welfare and vary over time and space.

There are several frameworks around which indicators can be developed and organized for sustainability evaluation. There is no unique framework that generates sets of indicators for every purpose. A framework may also change over time as scientific understanding of environmental problems increases and as societal values evolve. In the context of the work of the Group on the State of the Environment, the Pressure-State-Response (PSR) framework has been used. The PSR model considers that human activities exert pressures in the environment and affect its quality and the quantity of natural resources (state); society responds to these changes through environmental, economic and sectoral policies and through changes in awareness and behavior (societal response). The PSR model has the advantage of highlighting these links, helping both decision makers and the public recognize environmental and other issues as interconnected (OECD 1993, 1998).

3 Multi-Criteria Decision Making Techniques

3.1 Overview

Environmental decisions are often complex and multifaceted and involve many different stakeholders with different priorities or objectives—presenting exactly the type of problem that behavioral decision research has shown that humans are poorly equipped to solve unaided. Most people, when confronted with such problems, will attempt to use intuitive or heuristic approaches to simplify the complexity until the problem seems more manageable. In the process, important information may be lost, opposing points of view may be discarded, and elements of uncertainty may be ignored. In short, there are many reasons to expect that, on their own, individuals (either lay or expert) will often experience difficulty making informed, thoughtful choices in a complex decision-making environment involving value trade offs and uncertainty (McDaniels et al. 1999).

The MCDM process generally follows the sequence of (1) identifying DMs (final decision makers), actors (people involved in the decision analysis process), and stakeholders (anyone involved in the decision analysis process); (2) selecting criteria; (3) defining alternatives; (4) choosing an MCDM technique(s); (5) weighting the criteria; (6) assessing the performance of alternatives against the criteria; (7) transforming the criteria performance values to commensurable units, if required; (8) applying the selected MCDM technique(s); (9) performing sensitivity analysis; and (10) making the final decision. Weighting the criteria and assessing the performance of alternatives against the criteria are two of the most important and difficult aspects of applying the MCDM methodology and are potential sources of considerable uncertainty (Roy and Vincke 1981; Larichev and Moshkovich 1995). This study transforms above procedure and performs in Section 5.

Evaluation methods for MCDM must be changed as to the following conditions (Janssen 1992).

- The set of alternatives: Discrete vs Continuous problem
- The measurement scale of the attributes: Quantitative vs Qualitative
- The decision rule: Priorities, trade-offs or prices
- The value of function: Standardization vs Valuation
- The weights: Unknown vs Known (Cardinal, Ordinal)
- The ranking: Complete vs Incomplete

Composite programming, compromise programming, ELECTRE II, Evamix method, and Regime method are selected in this study to consider measurement scales, uncertainty of weights, and ranking types in a discrete and priority problem using standardized data.

3.2 Composite Programming

Composite programming (CP), which is a multi-level/multi-objective programming method, was introduced as an empirical technique to resolve a geological exploration problem by Bardossy and Bogardi (1983). A general multi-objective problem can be transformed to a single objective problem. This transformation is done via a step-by-step regrouping of a set of objectives into a single objective.

CP employs a double-weighting mechanism. One set of weights are indicators which articulate the decision-maker's preferences regarding the relative importance of each indicator. The other set are balancing factors given to groups in which any numbers of indicators are involved. Unlike weights, balancing factors are associated with groups rather than with each indicator. While the choice of weights emphasizes the relative importance of the indicators to each other, selecting the balancing factors identifies how larger deviations in groups of indicators may affect the process. The purpose of high balancing factors is to give more emphasis to the indicators which have large negative values (Goicoechea et al. 1982).

Once the relevant indicators, associated boundary values (ideal and worst values), actual values and weights are determined, the first step is to normalize the basic values (transforming them into the range of $0 \sim 1$). This is undertaken to make all indicators comparable to each other, thereby avoiding differences in units. Given the ideal value ($f_{i,j}^{\text{ideal}}$), and the worst value ($f_{i,j}^{\text{worst}}$), the normalized value of an actual indicator value ($f_{i,j}(a)$) of alternative a can be calculated. The next step is to calculate second-level composite distances for each second-level group of basic indicators using the following equation:

$$L_j(a) = \left(\sum_{i=1}^{N_j} w_{ij} \left(\frac{f_{i,j}^{\text{ideal}} - f_{i,j}(a)}{f_{i,j}^{\text{ideal}} - f_{i,j}^{\text{worst}}} \right)^{b_j} \right)^{1/b_j} \tag{1}$$

where i is the sequential number given to a basic indicator, j the sequential number of a certain group of basic indicators, $L_j(a)$ the distance from the ideal point in second-level group j, N_j the number of basic indicators in a second-level group j, w_{ij} the weights expressing the relative importance of the N_j basic indicators in group j, the sum of weights in any group being equal to one, b_j the balancing factor, which is equal or greater than 1, among indicators within the group j. The consecutive computations of higher-level composite indices are made in the same manner until a final composite distance for a system is reached. $L_j(a)$ will be values of PFD, PSD, and PWQD. The additional information can be obtained by Hartmann et al. (1987).

CP uses indicators from different categories to calculate a composite distance, which identifies the distance of the actual system from the ideal state. Hence, schemes with small composite distances are closer to the ideal state than those with large composite distances (Yurdusev and O'Connel 2005).

3.3 Compromise Programming

In the compromise programming (Zeleny 1973) the alternatives are ranked according to the distance that each alternative is removed from a hypothetically ideal situation. Environmental policy is often concerned with removing threats to the environment rather than maximizing the overall results of alternatives. This is a useful decision rule for environmental problems.

Assuming that alternatives cover all extremes of the solution space, the ideal point can be found by selecting the single objective maximum for each criterion. This is similar to the concept of pay-off matrix as used in relation to mathematical programming. It is also possible to define the ideal point by the set of policy goals held by the decision maker, if this set is known.

The ideal point is defined as the best score on each criterion within this set of criteria. Various distance measures can be applied to establish the distance between the ideal point and each alternative. A convenient and flexible distance metric is the weighted L_a metric. The next equation shows the ideal point method in the J-dimensional case using this metric in its general form.

$$D_{(a)} = \left[\sum_{i=1}^{n} w_i^p \left| \frac{f_i^* - f_i(a)}{f_i^* - f_{i,w}} \right|^p \right]^{1/p} \tag{2}$$

Where the α_i is the weights, f_i^* and $f_{i,w}$ are the optimal and worst value of the ith criterion, and $f_i(a)$ is the result of implementing alternative a with respect to the ith criterion (Goicoechea et al. 1982).

The scaling coefficient p makes it possible to include a relationship between relative size of the effect and weight into the decision rule. If there is a linear relationship, such as the balancing of benefits over costs, p must be 1; if there is a decreasing marginal utility, p must be higher than 1. The value of p depends on the policy objectives. If, as is often the case with air and pollution, only the highest value is relevant, p must be infinite; the metric is known as the weighted Tchebycheff metric.

3.4 Electre II

Variants of ELECTRE (Elimination and Choice Translating Reality) have been successfully used in water resources literature (Tecle et al. 1988; Hobbs et al. 1992; Roy et al. 1992; Raju and Duckstein 2004). ELECTRE II is a variant of ELECTRE family that produces a ranking of alternatives rather than indicating the most preferred. It outranks based on alternatives that are preferred with respect to most of the criteria and that do not drastically fail with respect to any one or more criteria. The first attribute is expressed by the "concordance" index and the second by the "discordance" index. Alternative A outranks alternative B if both concordance and discordance indices are satisfied (Belton and Stewart 2003). The concordance index $C(A, B)$ measures the strength of support in the information given for the hypothesis that A is at least as good as B. The discordance index $D(A, B)$ measures the strength of evidence against this hypothesis. The concordance index is calculated as

$$C(A, B) = \frac{w^{+} + w^{=}}{w^{+} + w^{=} + w^{-}} \tag{3}$$

where w^{+} is the sum of the weights of all criteria where A is better than B; w^{-} is the opposite case, i.e., the sum of the weights of the criteria where B is better than A; and $w^{=}$ is the indifferent cases. A discordance index can be calculated as follows:

$$D(A, B) = \max \ (v_{iB} - v_{iA}) \tag{4}$$

where v_{iB} is the value function of the impact of alternative B with respect to criterion (i) and v_{iA} is the value function of the impact of alternative A to outrank B, $C(A, B)$ has to be greater than $D(A, B)$, and both of $C(A, B)$ and $D(A, B)$ should be higher than a present threshold value p and lower than a preset threshold value q, respectively. Moreover, w^{+} has to be greater than w^{-}.

3.5 Regime Method

The regime method can be viewed as an ordinal generalization of pairwise comparison methods such as concordance analysis (Hinloopen and Nijkamp 1990). The starting point of the regime method is the concordance index $c_{ii'}$ as defined in the ELECTRE method. The focus of this method is on the sign of $c_{ii'} - c_{i'i}$ for each pair of alternatives. If this sign is positive, alternative i is preferred to i'; and the reverse holds if the sign is negative.

The ordinal weights are interpreted as unknown quantitative weights. A set **S** is defined containing all sets of quantitative weights that confirm to the qualitative priority information. In some cases the sign will be the same for the whole set **S** and the alternatives can be ranked accordingly. In other cases the sign of the pairwise comparison cannot be determined unambiguously: for parts of the set **S** the sign of $c_{ii'} - c_{i'i}$ is positive and for other parts it is negative. The distribution of the weights within **S** is assumed to be uniform and therefore the relative sizes of the subsets of **S** can be interpreted as the probability that alternative i is preferred to alternative i'. Probabilities are aggregated to produce an overall ranking of the alternatives. The relative sizes of the subsets can also be estimated using a random generator. This is recommended if the problem contains seven or more criteria since the number of sunsets increases exponentially with the number of criteria (Nijkamp et al. 1990).

3.6 Evamix Method

The Evamix method (Voogd 1982; Nijkamp et al. 1990) is designed to deal with an effects table containing both ordinal and quantitative criteria. The set of criteria in the effects table is divided into a set of ordinal criteria O and a set of quantitative criteria Q. For both sets dominance criteria are calculated:

$$\alpha_{ii'} = \left[\sum_{j \in O} \left\{ w_j \times f\left(x_{ji} - x_{ji'}\right) \right\}^p \right]^{1/p}$$

$$\beta_{ii'} = \left[\sum_{j \in Q} \left\{ w_j \times \left(\hat{x}_{ji} - \hat{x}_{ji'}\right) \right\}^p \right]^{1/p}$$

$$\text{and} \quad f\left(x_{ji} - x_{ji'}\right) = \begin{array}{rlcll} +1 & \text{if} & x_{ji} & > & x_{ji'} \\ 0 & \text{if} & x_{ji} & = & x_{ji'} \\ -1 & \text{if} & x_{ji} & < & x_{ji'} \end{array} \tag{5}$$

The scaling factor p must be a positive integer. The method requires quantitative weights but can be used in combination with any if the methods dealing with ordinal priority information. A total dominance score is found by combining the indices α_{ij} and β_{ij} calculated separately for the quantitative and qualitative scores. To be able to combine α_{ij} and β_{ij} both indices need to be standardized. Voogd (1983) offers various procedures for this standardization. The most straightforward standardization divides qualitative indices by the absolute value of their sum and does the same with quantitative indices. The total dominance score is calculated as the weighted sum of the qualitative and quantitative dominance scores.

3.7 Analytic Hierarchy Process (AHP)

AHP is a mathematical tool that enables the explicit ranking of tangible and intangible factors against each other for the purpose of resolving conflict or setting priorities. It combines qualitative and quantitative approaches and has the following benefits (Saaty 1980):

1. It helps dissect the problem and structure it into a rational decision hierarchy;
2. It gives an insight about the right data that needs to be collected for the alternatives at hand by the pairwise comparisons concluded under each criterion or subcriterion;
3. It prioritizes alternatives according to the preweighted criteria or makes a decision out of different scenarios; and
4. It examines the validity of the comparisons made between alternatives by testing these comparisons with consistency measures.

The AHP is a stable process, which uses basic steps that can be summarized as follows (Saaty 1980):

1. Define the problem and structure the hierarchy using criteria and possible solutions;
2. Construct a pair-wise comparison matrix of alternatives for each criterion or subcriterion;
3. Calculate priorities; and
4. Determine consistencies.

To define the problem, assessors have to make sure that they understand what it is. They also need to know what alternatives are available to solve the problem. Using these alternatives and the predetermined criteria, the hierarchy can be built. Each criterion in this level is decomposed into subcriteria at the next level and so on. The alternatives lay at the bottom of the hierarchy. Key to the entire AHP methodology us the determination of the respective weights of criteria and subcriteria. One common method of determining weights is through a process of comparison.

3.8 Correlation Analysis

To facilitate interpretation of the results, significance analysis can be used to identify the relative contribution that each input parameter has determining the total value of an alternative. In this study, Spearman rank correlation coefficient is used to determine the association of measure between ranks obtained by different MCDM techniques (Gibbons 1971; Kottegoda and Rosso 1997).

$$R = 1 - \frac{6 \sum_{a=1}^{A} D_a^2}{A\left(A^2 - 1\right)} \tag{6}$$

Where a is index of alternatives (=1, 2, ..., A), A is total number of alternatives, and difference between ranks (U_a–V_a). $R = -1$ represents perfect disagreement between the ranks. The value of R always lies between −1 and +1, where a value of −1 or +1 indicates perfect association between the parameters, the plus sign occurring for identical rankings and the minus sign occurring for reverse rankings. When R is close to zero, it means no association between the rankings of the alternatives.

4 Study Watershed

The Anyangcheon watershed (AY) was selected in this study. The Anyangcheon (stream) is the first tributary of the Han River in Korea. The study stream has a length of 32.38 km. The watershed is bounded by the latitudes 37°18′ N and 37°33′ N and the longitudes 126°47′ E and 127°04′ E.

The average annual precipitation from 1972 to 2001 is reported as 1,325.2 mm; 69.9% of the precipitation occurs during the monsoon months from June to September, and the rest (30.1%) occurs from October to May. However, it has been reported that the average annual precipitation changed during the next five years (2002–2006).

The average annual precipitation and occupancy of monsoon months increased up to 1,468.4 mm and 73.8%, respectively. That is, since the intensity of summer season become higher and the amount of rainfall in the remaining months decreased (391.5 to 385.4 mm), water resources management has become increasingly difficult.

On the basis of the digital elevation model (DEM), stream network, and storm sewers, the study watershed was divided into 12 subwatersheds (OJ, WG, DJ, SB, HU, SA, SB1, SS, SH, MG, and DR). Four subwatersheds with large areas and their tributaries were divided into smaller subwatersheds: HU (GH, CGS), SS (SM), MG (GH1, GS, YG, OR), and DR (BC, DB). The watershed area, in which approximately 387.6 million people reside, is 287.15 km^2 (population density: 13,527 persons per km^2). Primary land cover types within the watershed (as of 2000) comprise 43.03% of urban area, 39.79% of forest area, and 12.95% of agricultural area.

5 Application

5.1 Decision Making Procedure

Generally, the MCDM procedure involves the use of a decision matrix. The decision matrix is used to describe an MCDM problem. In an MCDM problem, if there are M alternative options and each must be assessed on N criteria, then the decision matrix for the problem has M rows and N columns. Each element is either a single number or a single grade, representing the performance of alternative a on criterion j. The general decision procedure using the decision making matrix is given as follows.

1. Brainstorm the evaluation criteria appropriate to the situation (Section 5.2)
2. Discuss and refine the list of criteria (Section 5.2)
3. Assign a relative weight to each criterion (using AHP) (Section 5.3)
4. Evaluate each alternative against the criteria (Section 5.4)
5. Rank all alternatives using MCDM techniques (Sections 5.5, 5.6, 5.7, 5.8)

5.2 Selection of Evaluation Criteria

Based on the concept of the pressure-state-response model, all criteria (indicators) to quantify PFD, PSD, and PWQD are carefully determined by some experts, who are researchers and local governmental officials, since this process requires discussion and refinement, as mentioned in Section 5.1. The structure of the selected criteria is shown in Table 1. The WEI is the numerical integration of PFD, PSD, and PWQD.

5.3 Assignment of Relative Weights Using AHP

All the weights of the criteria and sustainability components (pressure, state, and response) of PFD, PSD, and PWQD are established using an Analytic Hierarchy

Table 1 Indicator structure and all weights of sustainability component and indicators using AHP (Lee and Chung 2007)

Name of index		Sustainability component	Weight	Name of indicator	Weight
WEI	PFD (21/30)[a]	Pressure (19/30)[b]	0.372	Property value	0.208
				Population density	0.350
				Infrastructure	0.275
				Natural and cultural resources	0.166
		State (22/30)[b]	0.293	Rainfall intensity	0.282
				Urban area ratio	0.256
				Watershed slope	0.221
				Amount of annual flood damage	0.241
		Response (23/30)[b]	0.335	Stability of levee inundation	0.392
				Pumping station capacity	0.268
				Reservoir capacity	0.341
	PSD (22/30)[a]	Pressure	0.371	Population density	0.800
				Population	0.200
		State (24/30)[b]	0.375	Streamflow seepage/diversion	0.219
				Urban area ratio	0.373
				Groundwater withdrawal	0.274
				Watershed slope	0.134
		Response (20/30)[b]	0.254	Reuse of treated wastewater	0.270
				Reservoir capacity	0.342
				Use of groundwater collected by subway stations	0.196
				Diversion from other watershed	0.192
	PWQD (24/30)[a]	Pressure	0.302	Population	1.000
		State (24/30)[b]	0.388	BOD loads	0.073
				COD loads	0.073
				SS loads	0.072
				TN & TP loads	0.072
				Intrusion of wastewater	0.346
				Population density	0.185
				Ratio of covered length	0.179
		Response	0.310	Streamflow treatment facility	1.000
				Street sweeping	–

[a] Number of available data/number of total data (sustainability component)

[b] Number of available data/number of total data (indicators)

Process. This study used the results of Lee and Chung (2007). A survey was conducted on 30 local governmental officials and researchers in the field of river management. The results of the weighting values are shown in Table 1. The number of data available to satisfy the condition, consistency ratio $CR < 0.15$[1] is shown in parentheses.

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[1] The common upper limit is $CR < 0.10$. But the criterion was changed in this study since there were many values from 0.1 to 0.15.

5.4 Evaluation of Each Alternative Against the Criteria

There are 30 types of data for the calculation of PFD, PSD, and PWQD. They can be obtained by literature review, site survey, and computer simulation as follows.

- Literature review: population density, property value, infrastructure, natural and cultural resources, rainfall intensity, urban area ratio, slope of watershed, amount of flood damage, number of reservoirs, number of pumping stations, groundwater withdrawal, inter-basin transfer, reuse of treated wastewater, use of groundwater collected by subway stations, length of covered stream, streamflow treatment facility, and river and street sweeping
- Site survey: streamflow seepage and untreated wastewater intrusion
- Computer simulation: stability of levee overflow (HEC-RAS) and loads of BOD, COD, TSS, TN, and TP (PLOAD; Edwards and Miller 2001)

5.5 Identification of Spatial Vulnerability Using Various MCDM Techniques

5.5.1 Composite Programming

The values of PFD, PSD, PWQD, and WEI are calculated using composite programming as shown in Tables 2 and 3. Table 3 shows the WEIs of generally feasible cases of weights of three management objectives and balancing factor.

Hartmann et al. (1987) have proposed that all the alternatives can be classified into three groups (“Sound”, “Acceptable”, and “Poor”) from the values obtained by composite programming. Therefore, this study classified the alternatives into five groups (“A”–“E”) for the specific grouping as follows. Grades are also shown in Tables 2 and 3.

A (∼0.3) Very sound
B (0.3 ∼ 0.4) Quite sound
C (0.4 ∼ 0.5) Moderate
D (0.5 ∼ 0.6) Quite poor
E (0.6∼) Very poor

From the average values of PFD, PSD, and PWQD in Table 2, it is inferred that the study watershed has a considerably poor condition (grade “D”). In particular, the potentials of streamflow depletion and water quality deterioration are very high. WG, OJ, DJ, SB, SA, SB1, MG, GH, and YG are of grade “D” and SH, OR, DR, BC, and DB are of grade “E” according to the WEIs in Table 3. They need some alternatives to rehabilitate the hydrological cycle.

To find the relations between PFD, PSD, and PWQD, correlation coefficients are calculated as follows:

Correlation (PFD, PSD) = 0.495
Correlation (PFD, PWQD) = 0.344
Correlation (PSD, PWQD) = 0.909

Since PSD is closely related to PWQD but not to PFD, management to improve the hydrological condition should consider both the prevention of streamflow depletion and enhancement of water quality.

Table 2 Indices and grades of PFD, PSD, and PWQD using composite programming

Name of sub-watershed	PFD				PSD				PWQD			
	$b=1$	$b=2$	Average	Grade	$b=1$	$b=2$	Average	Grade	$b=1$	$b=2$	Average	Grade
WG	0.380	0.563	0.471	C	0.49	0.68	0.58	D	0.35	0.56	0.45	C
OJ	0.435	0.580	0.508	D	0.47	0.61	0.54	D	0.37	0.57	0.47	C
DJ	0.517	0.671	0.594	D	0.51	0.62	0.56	D	0.57	0.68	0.62	E
SB	0.519	0.659	0.589	D	0.46	0.58	0.52	D	0.57	0.68	0.62	E
HU	0.365	0.502	0.433	C	0.24	0.33	0.28	A	0.15	0.21	0.18	A
CGS	0.464	0.646	0.555	D	0.38	0.60	0.49	C	0.31	0.56	0.43	C
GH	0.315	0.507	0.411	C	0.35	0.53	0.44	C	0.36	0.56	0.46	C
SS	0.398	0.534	0.466	C	0.34	0.54	0.44	C	0.37	0.56	0.46	C
SM	0.395	0.531	0.463	C	0.41	0.61	0.51	D	0.33	0.56	0.44	C
SA	0.596	0.706	0.651	E	0.47	0.63	0.55	D	0.36	0.56	0.46	C
SB1	0.562	0.677	0.619	E	0.45	0.61	0.53	D	0.34	0.56	0.45	C
SH	0.521	0.661	0.591	D	0.69	0.78	0.73	E	0.65	0.76	0.70	E
MG	0.345	0.395	0.370	B	0.54	0.62	0.58	D	0.58	0.68	0.63	E
GH1	0.548	0.679	0.613	E	0.39	0.59	0.49	C	0.32	0.56	0.44	C
GS	0.164	0.341	0.253	A	0.35	0.53	0.44	C	0.40	0.61	0.50	D
OR	0.393	0.540	0.467	C	0.65	0.73	0.69	E	0.69	0.77	0.73	E
YG	0.517	0.577	0.547	D	0.47	0.57	0.52	D	0.50	0.64	0.57	D
DR	0.559	0.638	0.599	D	0.79	0.82	0.80	E	0.84	0.88	0.86	E
BC	0.544	0.670	0.607	E	0.66	0.73	0.70	E	0.71	0.77	0.74	E
DB	0.592	0.731	0.662	E	0.79	0.87	0.83	E	0.76	0.83	0.79	E
Average	0.46	0.59	0.52	D	0.49	0.63	0.56	D	0.48	0.63	0.55	D

Table 3 WEIs and grades of various weights using composite programming

Name of sub-watershed	Case 1 b=1	Case 2 b=2	Case 3 b=1	Case 4 b=2	Case 5 b=1	Case 6 b=2	Case 7 b=1	Case 8 b=2	Average	Grade
PFD	0.333	0.333	0.500	0.500	0.250	0.250	0.250	0.250		
PSD	0.333	0.333	0.250	0.250	0.500	0.500	0.250	0.250		
PWQD	0.333	0.333	0.250	0.250	0.250	0.250	0.500	0.500		
WG	0.404	0.602	0.399	0.593	0.426	0.622	0.390	0.593	0.504	D
OJ	0.425	0.586	0.428	0.585	0.438	0.593	0.411	0.582	0.506	D
DJ	0.529	0.655	0.527	0.660	0.524	0.646	0.539	0.662	0.593	D
SB	0.515	0.638	0.516	0.644	0.500	0.623	0.529	0.648	0.576	D
HU	0.251	0.368	0.280	0.406	0.247	0.359	0.227	0.336	0.309	B
CGS	0.383	0.603	0.404	0.614	0.382	0.603	0.365	0.592	0.493	C
GH	0.340	0.533	0.334	0.527	0.342	0.533	0.345	0.541	0.437	C
SS	0.366	0.546	0.375	0.543	0.359	0.545	0.366	0.551	0.457	C
SM	0.377	0.565	0.382	0.557	0.385	0.576	0.365	0.564	0.471	C
SA	0.475	0.635	0.505	0.653	0.473	0.634	0.448	0.618	0.555	D
SB1	0.449	0.615	0.478	0.632	0.449	0.613	0.423	0.602	0.533	D
SH	0.619	0.734	0.595	0.716	0.636	0.746	0.627	0.739	0.677	E
MG	0.487	0.576	0.452	0.537	0.500	0.587	0.511	0.603	0.532	D
GH1	0.416	0.611	0.449	0.629	0.409	0.607	0.391	0.599	0.514	D
GS	0.304	0.505	0.269	0.470	0.316	0.512	0.328	0.532	0.404	C
OR	0.576	0.687	0.531	0.654	0.594	0.698	0.604	0.710	0.632	E
YG	0.496	0.598	0.502	0.593	0.490	0.592	0.498	0.609	0.547	D
DR	0.729	0.783	0.687	0.750	0.745	0.792	0.757	0.807	0.756	E
BC	0.637	0.726	0.614	0.713	0.643	0.728	0.655	0.739	0.682	E
DB	0.714	0.810	0.684	0.791	0.734	0.825	0.727	0.814	0.762	E

5.5.2 Other MCDM Techniques

The rankings of vulnerability on flood damage, streamflow depletion possibility, water quality deterioration, and overall watershed condition are identified using compromise programming, ELECTRE II, Regime method, and Evamix method. All WEI rankings obtained by four MCDM techniques are shown in Table 4. It can be generally observed that most rankings are similar except for ELECTRE II, which is a type of outranking method. In case of the investments priority problem, WEI can be used since it reflect overall quantified values of all subwatersheds on problems.

5.6 Ranking and Grading of Spatial Vulnerability

The rankings of PFD, PSD, PWQD, and WEI are summarized in Table 5. It means seven-ranking-averaged values (two cases of composite programming, two cases of compromise programming, ELECTRE II, regime, and evamix methods). It means the overall ranking of all subwatersheds on the basis of hydrologic vulnerability. Grading is also presented in Tables 4 and 5 according to the following standards: "E" (ranks 1 ∼ 4), "D" (ranks 5 ∼ 8), "C" (ranks 9 ∼ 12), "B" (ranks 13 ∼ 16), and "A" (ranks 17 ∼ 20). WEI uses all indicators of PFD, PSD and PWQD shown in the structure of Table 1. This grouping criterion is different from that of composite programming since ELECTRE II derives only rankings and Regime and EVAMIX methods derived different ordered values of all subwatersheds.

Table 4 WEI rankings obtained by various MCDM techniques

Name of sub-watershed	Compromise			ELECTRE II	Regime	Evamix
	$p = 1$	$p = 2$	$p = 10$			
WG	14	14	13	14	18	13
OJ	12	15	14	5	15	11
DJ	6	6	7	9	6	6
SB	7	7	11	9	7	7
HU	20	20	20	20	9	20
CGS	15	13	12	20	20	15
GH	18	17	15	20	13	18
SS	17	18	18	16	14	15
SM	16	16	16	14	16	15
SA	10	8	9	2	10	9
SB1	11	10	10	5	12	11
SH	4	3	2	14	4	4
MG	9	11	6	1	11	9
GH1	13	9	8	16	19	13
GS	19	19	19	20	17	19
OR	5	5	4	10	5	5
YG	8	12	17	11	8	7
DR	1	1	1	9	2	1
BC	3	4	5	6	3	3
DB	2	2	3	3	1	2

Table 5 Summary of all sub-watersheds obtained by different MCDM techniques

Name of sub-watershed	PFD		PSD		PWQD		WEI	
	Rank	Grade	Rank	Grade	Rank	Grade	Rank	Grade
WG	16	B	8	D	16	B	14	B
OJ	12	C	11	C	10	C	12	C
DJ	8	D	6	D	8	D	6	D
SB	9	C	10	C	7	D	7	D
HU	19	A	20	A	20	A	19	A
CGS	10	C	16	B	19	A	15	B
GH	18	A	17	A	14	B	18	A
SS	14	B	19	A	13	B	17	A
SM	13	B	14	B	17	A	16	B
SA	2	E	9	C	13	B	8	D
SB1	3	E	13	B	16	B	10	C
SH	6	D	3	E	5	D	4	E
MG	17	A	8	D	6	D	9	C
GH1	4	E	15	B	19	A	13	B
GS	20	A	18	A	11	C	20	A
OR	15	B	5	D	4	E	5	D
YG	11	C	12	C	9	C	11	C
DR	7	D	2	E	1	E	2	E
BC	5	D	4	E	3	E	3	E
DB	1	E	1	E	2	E	1	E

General management strategies according to their grades can be considered as follows:

E Intensive and integrated structural management plan to rehabilitate the distorted hydrologic cycle
D Various structural management options for specific targets
C Several structural management options making an effect on the partial of watershed.
B nonstructural management plan
A efforts to maintain the status

From these results, all the subwatersheds can be categorized into eight parts as shown in Table 6. It shows not only the problem characteristics but also the management objectives of all the subwatersheds. If a sub-watershed has a special

Table 6 Classification of sub-watersheds

Flood damage	Instreamflow	Water quality	Name of sub-watershed
Good	Poor	Poor	MG, OR
Good	Good	Poor	None
Good	Poor	Good	WG
Good	Good	Good	HU, GH, SS, SM, GS
Poor	Poor	Poor	DJ, SH, DR, BC, DB, SB
Poor	Good	Poor	None
Poor	Poor	Good	OJ, YG, SA
Poor	Good	Good	SB1, GH1, CGS

Table 7 Spearman rank correlation coefficient between ranking patterns obtained by different MCDM techniques

Index	Method	Composite compromise ($b = 1; p = 1$)	Composite ($b = 2$)	Compromise ($p = 2$)	Compromise ($p = 10$)	ELECTRE II	Regime	Evamix
WEI	Composite compromise (b = 1; p = 1)	1	0.920	0.956	0.874	0.641	0.811	0.993
	Composite (b = 2)		1	0.976	0.895	0.489	0.689	0.909
	Compromise (p = 2)			1	0.940	0.544	0.737	0.939
	Compromise (p = 10)				1	0.525	0.626	0.850
	ELECTRE II					1	0.448	0.658
	Regime						1	0.802
	Evamix							1
PFD	Composite compromise (b = 1; p = 1)	1	0.931	0.934	0.800	0.151	0.762	0.976
	Composite (b = 2)		1	0.988	0.917	0.032	0.632	0.913
	Compromise (p = 2)			1	0.940	0.028	0.647	0.917
	Compromise (p = 10)				1	−0.175	0.497	0.755
	ELECTRE II					1	−0.083	0.265
	Regime						1	0.751
	Evamix							1
PSD	Composite compromise (b = 1; p = 1)	1	0.923	0.958	0.780	0.793	0.726	0.980
	Composite (b = 2)		1	0.877	0.723	0.790	0.600	0.903
	Compromise (p = 2)			1	0.887	0.680	0.744	0.947
	Compromise (p = 10)				1	0.446	0.639	0.781
	ELECTRE II					1	0.416	0.789
	Regime						1	0.688
	Evamix							1
PWQD	Composite compromise (b = 1; p = 1)	1	0.991	0.985	0.962	0.906	0.750	0.923
	Composite (b = 2)		1	0.983	0.959	0.876	0.739	0.911
	Compromise (p = 2)			1	0.981	0.862	0.698	0.898
	Compromise (p = 10)				1	0.823	0.674	0.902
	ELECTRE II					1	0.783	0.881
	Regime						1	0.758
	Evamix							1

problem, some effective alternatives can be proposed and implemented through the excessive discussion between decision makers and stakeholders.

5.7 Correlation Analysis

Spearman rank correlation coefficients of WEI, PFD, PSD, and PWQD are calculated, as shown in Table 7, from seven rankings of five MCDM techniques. Most values are over 0.7, except for ELECTRE II. In particular, the coefficients of composite programming, compromise programming, and Evamix method have high values. The coefficients of ELECTRE II are lower than those of others since it calculates incomplete ranking on the basis of outranking. Overall, since the results are closely related, any method can be applied to the available data characteristics (quantitative/qualitative), weights uncertainties (ordinal/cardinal), and ranking objectives (complete/incomplete).

5.8 Estimation of WEI Considering the Preferences of Residents on Management Objectives

Since the WEI is the numerical integration of PFD, PSD, and PWQD, it can reflect the residents' demand for watershed management objectives through the weights of PFD, PSD, and PWQD. If the demand can be quantified and introduced into the weights, the WEI can also be the management prioritization index. However, since every subwatershed has different values, this study divided into six regions by classification of Table 7 and location as follows.

Region 1: WG, OJ
Region 2: DJ, SB
Region 3: HU (GH, CGS)
Region 4: SS (SM), SA, SB1
Region 5: MG (GH1, OR, YG, OR)
Region 6: SH, DR (BC, DB)

Therefore, the survey for AHP was conducted on the residents of the six groups, and the values are shown in Table 8. The number of data is 321. Residents in region 1, 2, 3, and 5 gave high weights on water quality enhancement while residents in Region 4 and 6 thought prevention of streamflow depletion and flood damage mitigation were the most important, respectively. Overall the eager for clean streams is too high.

Table 8 Number of data and weighting values of three objectives

Region	Number of total data	Number of available data	Weighting values		
			Flood damage mitigation	Prevention of stream-flow depletion	Water quality Enhancement
I	78	53	0.224	0.297	0.479
II	57	31	0.159	0.228	0.613
III	48	32	0.225	0.192	0.584
IV	48	36	0.225	0.403	0.373
V	41	27	0.169	0.198	0.633
VI	49	24	0.397	0.247	0.357
Average	53.3	35.8	0.233	0.261	0.506

Table 9 Comparison of two WEIs in case of composite programming ($b = 1$) and various MCDM results

Name of sub-watersheds	Equal weighted WEIs		WEIs reflecting stake-holders' preferences		Various MCDM techniques
	Index	Rank	Index	Rank	Rank
WG	0.396	13	0.404	14	14
OJ	0.414	12	0.425	12	12
DJ	0.544	6	0.529	6	6
SB	0.536	7	0.515	7	7
HU	0.217	20	0.251	20	19
CGS	0.358	17	0.383	15	15
GH	0.348	19	0.340	18	18
SS	0.362	16	0.366	17	17
SM	0.376	14	0.377	16	16
SA	0.458	10	0.475	10	8
SB1	0.434	11	0.449	11	10
SH	0.609	5	0.619	4	4
MG	0.533	8	0.487	9	9
GH1	0.369	15	0.416	13	13
GS	0.349	18	0.304	19	20
OR	0.630	4	0.576	5	5
YG	0.498	9	0.496	8	11
DR	0.717	1	0.729	1	2
BC	0.632	3	0.637	3	3
DB	0.703	2	0.714	2	1

This study developed the WEI which can be calculated by linearly combining the results of the composite programming ($b = 1$), as shown in Table 2 and the weights of Table 8. The equation for the WEI of a-th sub-watershed is as follows:

$$\text{WEI}\,(a) = \alpha_1 \text{PFD}\,(a) + \alpha_2 \text{PSD}\ (a) + \alpha_3 \text{PWQD}\ (a) \tag{7}$$

where α_1, α_2 and α_3 ($\alpha_1 + \alpha_2 + \alpha_3 = 1$) are the relative importances of PFD, PSD and PWQD. The results including two cases, equal-weighted WEI and average ranking by various MCDM techniques are shown in Table 9. While the rankings were not significantly different, small differences may be important in special situations such as cases with budget limitations, because even small differences can determine the performance.

6 Conclusion

The indicators of sustainable development can allow better communication and access to information by bridging the gap between the producer and the user of information, i.e., between the information available through scientific resources and the need for information for decision making. Indicators can provide crucial guidance for decision making in various ways. They can translate physical and social science knowledge into manageable units of information that can facilitate the decision making process (UNCSD 2001).

This study proposed four indices to identify the spatial ranking of hydrological vulnerability using MCDM techniques and to apply it to the Korean urban watershed. The indices of hydrological vulnerability for sustainable development are PFD, PSD, PWQD, and WEI. The WEI shows the overall present condition quantitatively. Based on the sustainability evaluation concept, PSR model, all criteria are selected by some experts, and their values are assigned using AHP. Each index is calculated using five MCDM techniques (composite programming, compromise programming, ELECTRE II, Region method, and Evamix method). Furthermore, the WEI is improved to consider the preferences of the residents on management objectives, which are flood damage mitigation, prevention of streamflow depletion, and enhancement of water quality using weights (of PFD, PSD, and PWQD) obtained from a survey of residents. It may be a type of collaborative planning and management. Finally, these four indices can identify the spatial investment prioritization.

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Appendix: Information of Indicators

All indicators of PFD, PSD and PWQD are explained as follows. WEI is the integration of PFD, PSD and PWQD which is shown in Eq. 7.

A.1 Potential Flood Damage (PFD)

Pressure

- Property value: This is the average land value per area which can be obtained from national annual report.
- Population density: Population can be obtained from the website (www.nso.or.kr) of KNSO (Korea National Statistical Office), but it should be calculated according to each subwatershed. Therefore, the data by administrative district must be transformed into those by sub-watershed. Population density is the population per unit area.
- Infrastructure: This usually includes general civil structures, for example, military service, hospital, power plant, road, rail road, airport, and so on. In this study it was total roads and rail road area per unit area.
- National and cultural resources: This means the number of national treasures and cultural properties per unit area.

State

- Rainfall intensity: This means the fifty-year-frequency rainfall intensity.
- Urban area ratio: This can be obtained from GIS software, ARCVIEW.
- Watershed slope: This can be obtained from GIS software, ARCVIEW.
- Amount of flood damage: This can be usually obtained from the national flood damage reports. It is the monetary amount of flood damage per unit area.

Response

- Stability of levee inundation: This is the ratio of improved bank to total stream length for flood damage protection.
- Pumping station: This is the total pumping capacity per unit area.
- Reservoir capacity: This can be obtained from the design or annual operation report. This is the total reservoir capacity per unit area.

A.2 Potential Streamflow Depletion (PSD)

Pressure

- Population density: This is the same value of PFD.
- Population: This is the same value of PFD.

State

- Streamflow seepage/diversion: This can be investigated by many field trips since it is not open at usual.
- Urban area ratio: This is the same value of PFD.
- Groundwater withdrawal: This can be obtained from the national annual reports. In this study we got this data from 'Groundwater Survey' (KOWACO 2007). Its unit is mm which can be obtained by total used amount of groundwater per unit area.
- Watershed slope: This can be obtained from GIS software, ARCVIEW.

Response

- Reuse of treated wastewater: This can be obtained from the design or annual operation report of waste water treatment plant. Its unit is mm and can be calculated as total daily amount per unit area.
- Reservoir capacity: This is the same value of PFD.
- Use of groundwater collected by subway stations: This can be obtained from the design or annual operation report. Its unit is 'mm' and can be calculated as total daily capacity per unit area.
- Diversion from other watershed: This can be obtained from the design or annual operation report. Its unit is 'mm' and can be calculated as total daily diverted amount per unit area.

A.3 Potential Water Quality Deterioration (PWQD)

Pressure

- Population: This is the same value of PFD.

State

- BOD, COD, SS, TN and TP loads: These can be obtained by simple calculation as follows:

$$U_j(a) = \sum_{k=1}^{p} u_{j,k} A_k(a) \tag{8}$$

  where j is the pollutant type, k is the landuse type, p is the number of land use types, a is the name of sub-watershed, $u_{j,k}$ is the pollutant j's unit load of landuse k and $A_k(a)$ is the total area of landuse, k of the subwatershed, a.
- Intrusion of wastewater: This can be investigated by many field trips since it's not open at usual.
- Population density: This is the same value of PFD.
- Ratio of covered length: This can be obtained as the value which is covered length for impervious area divided by total length of the stream.

Response

- Streamflow treatment facility: This can be obtained from the design or annual operation report. Its unit is 'mm' and can be calculated as daily average treated amount divided by the subwatershed area.
- Street sweeping: This is the total number of street sweeping by relevant admistrations in a year. But it was not used in this study for the data limitation.

References

Bailey RG (1984) Testing an ecosystem regionalization. J Environ Manag 19:239–248

Bardossy A, Bogardi I (1983) Network design for the spatial estimation of environmental variables. Appl Math Comput 12:339–369. doi:10.1016/0096-3003(83)90046-2

Belton V, Stewart TJ (2003) Multiple criteria decision analysis: an integrated approach. Springer, New York

Edwards C, Miller M (2001) PLOAD Version 3.0 User's Manual. USEPA, Washington DC

Gibbons JD (1971) Nonparametric statistical inference. McGraw-Hill, New York

Goicoechea A, Hansen DR, Duckstein L (1982) Multiobjective decision analysis with engineering and business application. John Wiley and Sons, New York

Hartmann L, Torno C, Bogardi I, Higler L (1987) Methodological guidelines for the integrated environmental evaluation of water resources development. Unep/Unesco Project FP/5201-85-01, Paris

He C, Malcolm SB, Dahlberg KA, Fu B (2000) A conceptual framework for integrating hydrological and biological indicators into watershed management. Landsc Urban Plan 49:25–34. doi:10.1016/S0169-2046(00)00047-5

Hinloopen E, Nijkamp P (1990) Qualitative multiple criteria choice analysis, the dominant regime method. Qual Quant 24:37–56. doi:10.1007/BF00221383

Hobbs BF, Chankong V, Hamadeh W, Stakhiv EZ (1992) Does choice of multicriteria method matter? An experiment in water resources planning. Water Resour Res 28:1767–1779. doi:10.1029/92WR00712

Janssen R (1992) Multiobjective decision support for environmental management. Kluwer Academic Publisher, Dordrecht

Karr JR, Fausch KD, Angermeier PL, Yant PR, Schiosser IJ (1986) Assessing biological integrity in running waters: a method and its rationale. Natural History Survey Special Publication 5

Kelly JR, Harwell MA (1990) Indicators of ecosystem recovery. Environ Manage 14(5):527–545. doi:10.1007/BF02394708

Kottegoda NT, Rosso R (1997) Statistics, probability, and reliability for civil and environmental engineers. McGraw-Hill, Singapore

KOWACO (Korea Water Resources Corporation) (2007). Groundwater survey. Ministry of Construction and Transportation of Korea, KOWACO, Daejeon (in Korean)

Larichev OI, Moshkovich HM (1995) ZAPROS-LM: a method and system for ordering multiattribute alternatives. Eur J Oper Res 82:503–521. doi:10.1016/0377-2217(93)E0143-L

Lee KS, Chung ES (2007) Development of integrated watershed management schemes for an intensively urbanized region in Korea. J Hydro-Environ Res 1(2):95–109

Manoliadis OG (2001) Environmental indices in irrigation management. Environ Manage 28(4):497–504. doi:10.1007/s002670010239

McDaniels TL, Gregory RS, Fields D (1999) Democratizing risk management: successful public involvement in local water management decisions. Risk Anal 19:497–510

Messer JJ, Linthurst RA, Overton WS (1991) An EPA program for monitoring edological status and trends. Environ Monit Assess 17:67–78. doi:10.1007/BF00402462

Naiman RJ, Magnuson JJ, McKnight DM, Stanford JA (eds) (1995) The freshwater imperative: a research agenda. Island Press, Washington DC

Nijkamp P, Rietveld P, Voogd H (1990) Multicriteria evaluation in physical planning. North-Holland, Amsterdam

OECD (1993) OECD core set of indicators for environmental performance reviews. OECD Environment Monographs 83. OECD, Paris

OECD (1998) Towards sustainable development: environmental indicators. OECD, Paris

Omernik JM (1995) Ecoregions: a framework for managing ecosystems. George Wright Forum 12(1):35–50

Raju KS, Duckstein L (2004) Integrated application of cluster and multicriterion analysis for ranking water resources planning strategies: a case study in Spain. J Hydroinformatics 6:295–307

Roy B, Vincke P (1981) Multicriteria analysis: survey and new directions. Eur J Oper Res 8(3):207–218. doi:10.1016/0377-2217(81)90168-5

Roy B, Slowinski R, Treichel W (1992) Multicriteria programming of water supply systems for rural areas. Water Resour Bull 28:129–140

Saaty TL (1980) The analytic hierarchy process. McGraw-Hill, New York

Tecle A, Fogel M, Duckstein L (1988) Mulitcriterion selection of wastewater management alternatives. J Water Resour Plan Manage 114:383–398

UNCSD (United Nations Commission on Sustainable Development) (2001) Indicators of sustainable development: framework and methodologies commission on sustainable development. Ninth Session, 16–27 April 2001, Background Paper No. 3, New York, UN

US Environmental Protection Agency (1996) Environmental indicators of water quality in the United States. EPA 841-R-96-002

US Environmental Protection Agency (1997) The Index of Watershed Indicators. EPA 841-R-97-010

Voogd H (1982) Multicriteria evaluation with mixed qualitative and quantitative data. Environ Plann B 9:221–236. doi:10.1068/b090221

Voogd H (1983) Multicriteria evaluation for urban and regional planning. Pion, London

Yurdusev MA, O’Connel PE (2005) Environmentally-sensitive water resources planning: 1. Methodology. Water Resour Manage 19:375–397. doi:10.1007/s11269-005-7999-x

Zeleny M (1973) Compromising programming. In: Starr MK, Zeleny M (eds) Multiple criteria decision making. University South Carolina Press, Columbia