Integrated Watershed Management
Using Multicriteria Decision Making Techniques

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Abstract

The objective of this study was to develop an alternative evaluation index (AEI) in order to determine the priorities of a range of alternatives using both the hydrological simulation program in FORTRAN (HSPF) and multicriteria decision-making (MCDM) techniques. All evaluation criteria were selected using the Driver–Pressure–State–Impact-Response (DPSIR) model, a sustainability evaluation concept. The Analytic Hierarchy Process was used to estimate the weights of the criteria and the effects of water quantity and quality were quantified by HSPF simulation. The use of the proposed procedure could provide decision makers with sustainable watershed planning, consequently reducing the time and cost of the stakeholder's consensus.

Keywords Alternative evaluation index, HSPF, Driver-Pressure-State-Impact-

Response model, Multi-criteria decision making techniques

1. **Introduction**

In recent years, technical tools for modeling water resources problems have improved significantly, and multicriteria decision making (MCDM) procedures are widely considered to be very useful in resolving conflicts related to water management. The usefulness of these procedures depends on the logical structure of valuation procedures and on the common language developed for defining and discussing complex water problems. These procedures are also a useful tool for communication between those who have to make the decisions and those who are affected by them. Finally, MCDM easily includes the effect of uncertainties that often characterizes water management problems in the decision-making process (Jakeman et al., 2005).

There have been many researches to prioritize the alternatives just using continuous simulation models, but it is not easy to find out the researches of decision making using hydrologic simulation model and MCDM technique together. Therefore, this paper documents the development of a methodology to assess the prioritization of alternatives using a continuous water quantity/quality simulation model as well as multicriteria decision making techniques. All criteria for alternative performance were selected based on the framework of the DPSIR (Driver–Pressures–State–Impact–Response) model, while their weights were estimated using the Analytic Hierarchy Process (AHP).

2. Theoretical backgrounds

2.1 Description of the HSPF model

HSPF is a deterministic, lumped-parameter continuous time model that has evolved out of the Stanford Watershed Model, the USEPA Agricultural Runoff Management (ARM) model, and NPS model. It can also used as a distributed parameter model as it reproduces spatial variability by dividing the basin in hydrologically homogenous land segments and simulating runoff for each land segment independently. A detailed description of the model is given by Bicknell et al. (2001).

2.2 Sustainability evaluation concept: DPSIR model

DPSIR framework was originally developed by the European Environment Agency (1999) for environmental reporting purposes, as result of environmental monitoring, on different environmental assessment tools like environmental impact assessment, and structures the description of the environmental problems, by formalizing the relationships between various sectors of human activity and the environment as causal chains of links.

The environmental management process under the DPSIR framework, may thus be described as a feedback loop controlling a cycle consisting of five stages (Economic and Social Commission for Asia and Pacific, 2004).

- **Driving forces** are the underlying causes, which lead to environmental pressures. Examples are the human demands for agricultural land, energy, industry, transport and housing
- These driving forces lead to **Pressures** on the environment, for example the exploitation of resources (land, water, minerals, fuels, etc.) and the emission of pollution.
- The pressures in turn affect the **State** of the environment. This refers to the quality of the various environmental media (air, soil, water, etc.) and their consequent ability to support the demands placed on them (for example, supporting human and non-

human life, supplying resources, etc.).

- Changes in the state may have an **Impact** on human health, ecosystems, biodiversity, amenity value, financial value, etc. Impact may be expressed in terms of the level of environmental harm.
- The **Responses** demonstrate the efforts by society (e.g. politicians, decision makers) to solve the problems identified by the assessed impacts, e.g. policy measures, and planning actions.

3. The study area

The Anyangcheon watershed (AY) was selected in this study. 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.

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 areas.

4. Results

4.1 Decision procedure

Generally, a MCDM procedure is related to the decision matrix, whereby a decision matrix is used to describe a MCDM problem. In a MCDM problem, if there are M alternative options and each need to be assessed based on N criteria, then the decision matrix for the problem has M rows and N columns. Each element is either a single numeral value or a single grade, representing the performance of alternative a on criterion j. The general decision procedure using the decision matrix is as follows:

(1) Brainstorm the evaluation criteria appropriate to the situation

(2) Discuss and refine the list of criteria

(3) Assign a relative weight to each criterion (using AHP)

(4) Create feasible alternatives

(4) Evaluate each alternative against the criteria

(5) Rank all alternatives using MCDM techniques

4.2 Selection of evaluation criteria

In many cases, budget and resources are generally limited and thus all feasible alternatives are seldom accepted simultaneously. Managers should therefore find a set of alternatives that maximizes the desired objective (i.e. maintenance of the minimum instreamflow and water quality enhancement). However, ranking feasible alternatives might be preferred to finding an optimal solution, particularly when the constraints are uncertain. This would also allow decision makers to be able to execute a water resources project according to the rankings of alternatives, depending on available budget and resources.

On the basis of the concept of the Driver-Pressure-State-Impact-Response model, all criteria (indicators) to quantify AEI are determined with care by experts such as researchers and local governmental officials, since this process requires discussion and refinement, as discussed in the above section. The structure of the selected criteria is shown in Fig. 1.

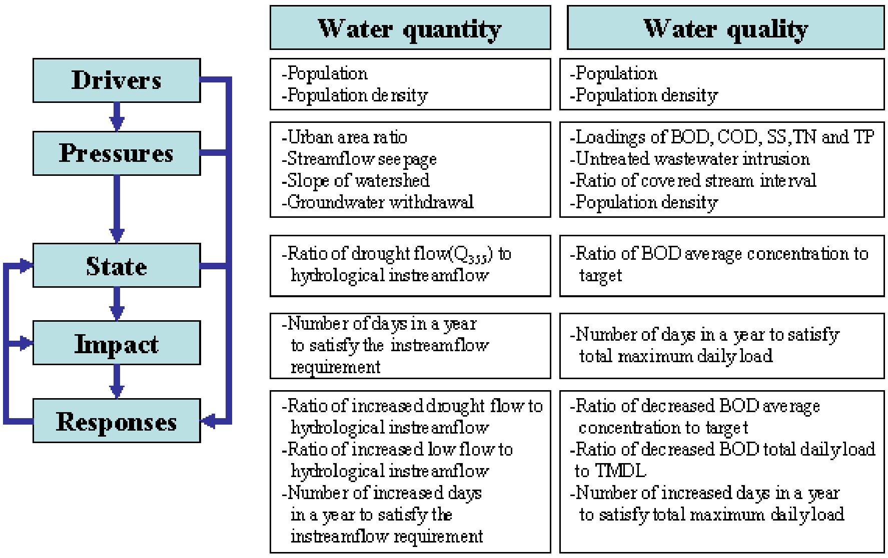

Fig. 1. DPSIR framework of this study

The evaluation equation is able to consider the sustainability DPSIR model as follows:

$$f_j(a_i) = bDR_{j,i} + c\ PR_{j,i} + d\ ST_{j,i} + eIM_{j,i} + f\ RE_{j,i}, \qquad j = 1, 2 \qquad (1)$$

where, j is the effectiveness, DR PR, ST, IM and RE are the driving force, pressure, state, impact and response, respectively, and b, c, d, e and f are the weighting factors ($b + c + d + e + f = 1$). It is the role of the manager to select the indicators for the driver, pressure, state, impact and response.

In this study,

$$DR_{1,i} = b_{1,1}s_{PD,n} + b_{1,2}s_{P,n} \tag{8}$$

$$PR_{1,i} = c_{1,1}s_{SS,n} + c_{1,2}s_{UR,n} + c_{1,3}s_{GE,n} + c_{1,4}s_{SW,n} \tag{9}$$

$$ST_{1,i} = 1 - \frac{t_1(a_1)/d(a_i)}{\max\limits_{i}\ t_1(a_i)/d(a_i)} \tag{10}$$

$$IM_{1,i} = 1 - \frac{n_1(a_i)}{\max\limits_{i}\ n_1(a_i)} \tag{11}$$

$$RE_{1,i} = 1/3 \times \frac{\Delta d\ (a_i)/t_1(a_i)}{\max\limits_{i}\ \Delta d\ (a_i)/t_1(a_i)} + 1/3 \times \frac{\Delta l\ (a_i)/t_1(a_i)}{\max\limits_{i}\ \Delta l\ (a_i)/t_1(a_i)} + 1/3 \times \frac{n_1(a_i)}{\max\limits_{i}\ \Delta n_1(a_i)} \tag{12}$$

$$DR_{2,i} = b_{2,1}s_{PD,n} + b_{2,2}s_{P,n} \tag{13}$$

$$PR_{2,i} = c_{2,1}s_{LB,n} + c_{2,2}s_{LC,n} + c_{2,3}s_{LS,n} + c_{2,4}s_{LPN,n} + c_{2,5}s_{WI,n} + c_{2,6}s_{PD,n} + c_{2,7}s_{CSN,n} \tag{14}$$

$$ST_{2,i} = 1 - \frac{q_1(a_1)/t_2(a_i)}{\max\limits_{i}\ q_1(a_i)/t_2(a_i)} \tag{15}$$

$$IM_{2,i} = 1 - \frac{n_2(a_i)}{\max\limits_{i}\ n_2(a_i)} \tag{16}$$

$$RE_{1,i} = 1/4 \times \frac{\Delta q_1(a_i)/t_2(a_i)}{\max\limits_{i}\ \Delta q_1(a_i)/t_2(a_i)} + 1/4 \times \frac{\Delta q_2(a_i)/t_3(a_i)}{\max\limits_{i}\ \Delta q_2(a_i)/t_3(a_i)} + 1/4 \times \frac{\Delta n_2(a_i)}{\max\limits_{i}\ \Delta n_2(a_i)} + 1/4 \times \frac{\Delta n_3(a_i)}{\max\limits_{i}\ \Delta n_3(a_i)} \tag{17}$$

where, $d(a_i)$, and $l(a_i)$ are the 355th flow and the 275th flow, respectively, of the flow duration curve of the watershed, of which the alternative a_i will be applied and $q_1(a_i)$ and $q_2(a_i)$ are the average BOD concentration and the total daily load, respectively. $t_1(a_i)$, $t_2(a_i)$, and $t_3(a_i)$ are the instreamflow, the target BOD concentration and the BOD total daily maximum load (TMDL), respectively. $n_1(a_i)$, $n_2(a_i)$, and $n_3(a_i)$ are the increased number of satisfying days for the instreamflow requirement, the target BOD concentration, and BOD TMDL of the watershed, of which the alternative a_i will be applied. Δ is the changed value due to the alternative a_i.

While this equation is based on the concept of driving force-pressure-state-impact-response, various formats are now being tested in ongoing research to find the most appropriate index.

4.3 Assigning of relative weights using AHP

All the weights of the criteria and sustainability components (driver, pressure, state, impact and response) were established using the Analytic Hierarchy Process. A survey was conducted on 30 local governmental officials and researchers working in the field of river management.

4.4 Creating feasible alternatives

Before creating feasible alternatives, it is necessary to determine the present condition of the hydrological cycle. Therefore, the hydrologic cycle of the Anyangcheon watershed was simulated using HSPF. This results provide the sufficient information to propose all necessary alternatives.

All possible alternatives were proposed by local governmental officials, residents and experts. However, because there are too many possible alternatives to be analyzed in detail, some feasible alternatives were screened according to three basic criteria, those of technical, economic, and environmental feasibility. The results from the alternatives are shown in Fig. 2.

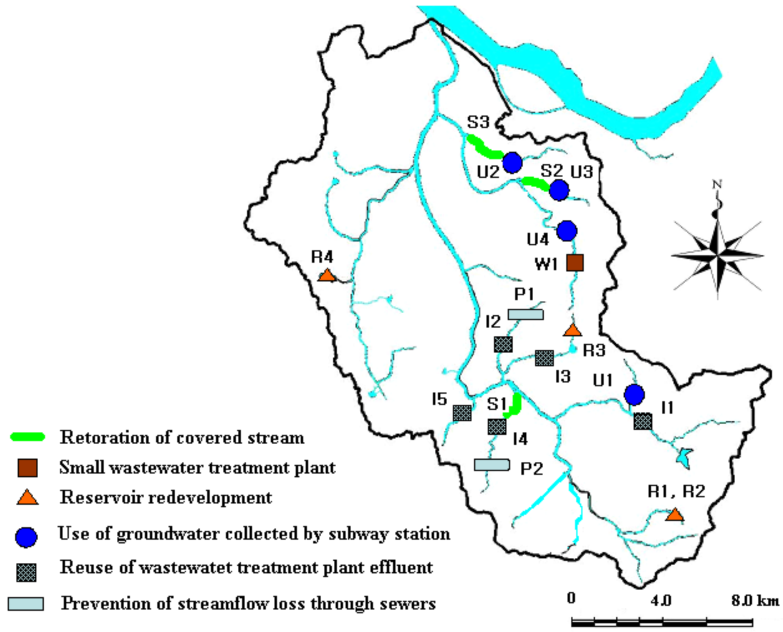

Fig. 2. Feasible alternatives

4.5 Evaluating each alternative using the HSPF model

The continuous water quantity and quality simulation model, the HSPF, was applied for an analysis of alternatives effectiveness. The instreamflow requirements and target concentrations were obtained from Lee et al. (2007). The instreamflow, which is shown by monthly values, was calculated by comparing the hydrological drought flow (Q_{355} of the flow duration curve) with the monthly ecological flow, while the target quality is that stipulated by the local government.

The decision matrix for the water quantity and quality are formulated. The values of pressures and states measured against criteria were obtained from the national report and websites and the states, impacts and responses from the HSPF simulation. Each alternative is systemized into the HSPF and is individually simulated.

4.6 Identifying a ranking for alternatives using MCDM techniques

A summary of the ranking for the alternatives is shown in Table 1. The final rankings are calculated by averaging all the ranks provided by the five methods. The restoration of a covered stream is typically the most efficient way to rehabilitate the distorted hydrologic cycle, while reusing of wastewater treatment plant (WWTP) effluent only if the instreamflow is extremely poor. While the latter is effective in increasing water quantity during a dry period, this method is also more harmful to the quality of the water. The construction of small wastewater treatment plants is a somewhat positive alternative, while the use of groundwater collected by subway stations is ranked within the middle of the possible alternatives. Though reservoir redevelopment is not ranked as a positive alternative, it can be feasible due to the low cost.

Table 1. Summary of AEI using different MCDM techniques

Name of alternative	Composite programming		ELECTRE II	Regime	EVAMIX	Average	Rank
	b = 1	b = 2					
R1	14	15	13	13	14	13.8	15
R2	11	12	13	10	11	11.4	11
R3	17	16	19	18	16	10.2	10
R4	10	10	10	11	10	4.4	4
R group	13.0	13.3	13.8	13.0	12.8	13.2	IV
S1	4	5	2	7	4	4.4	4
S2	6	6	2	8	4	5.2	6
P2+S3	9	7	9	9	8	8.4	9
S4	3	3	6	3	1	3.2	3
S5	2	2	6	2	1	2.6	2
S group	4.8	4.6	5.0	5.8	3.6	4.8	I
I1	18	18	19	16	18	17.8	19
P1+I2	16	17	19	17	16	17.0	16
I3	15	14	15	19	15	15.6	15
P2+S3+I4	13	11	13	15	13	13.0	13
I5	12	13	14	12	12	12.6	12
I group	14.8	14.6	16.0	15.8	14.8	15.2	V
U1	19	19	19	14	18	17.8	19
U2	8	9	9	6	8	8.0	8
S4+U3	5	4	6	4	4	4.6	5
S5+U4	1	1	6	1	1	2.0	1
U group	8.3	8.3	10.0	6.3	7.8	8.1	III
W1	7	8	9	5	7	7.2	7
W group	7	8	9	5	7	7.2	II

6. Conclusion

This study developed an indicator (AEI) to prioritize the alternatives using a continuous water quantity/quality simulation model as well as multicriteria decision-making techniques. All criteria for alternative performances were selected based on the framework of the DPSIR (Driver–Pressures–State–Impact–Response) model, while their weights were estimated using the Analytic Hierarchy Process.

The proposed procedure can be used to provide decision makers with sustainable watershed planning, thus reducing the time and cost for the stakeholder’s consensus.

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