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Integrated Use of a Continuous Simulation Model and Multi-Attribute Decision-Making for Ranking Urban Watershed Management Alternatives

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Abstract The objective of this paper is to introduce a continuous simulation-based screening procedure for ranking urban watershed management alternatives using multi-attribute decision making (MADM). The procedure integrates continuous urban runoff simulation results from the United States Environmental Protection Agency's Storm Water Management Model (SWMM) with the use of an alternative evaluation index (AEI) and MADM techniques, following the driver-pressure-state-impact-response (DPSIR) approach. The analytic hierarchy process estimates the weights of the criteria, and SWMM results are used to quantify the effects of the management alternatives on water quantity and quality metrics. In addition, the tendency of AEI to reflect resident preferences toward management objectives is incorporated to include stakeholder participation in the decision-making process. This systematic decision support process is demonstrated for a Korean urban watershed. According to the AEI, seven alternatives were divided into three groups: poor (0∼0.3), acceptable (0.3∼0.6), and good (0.6∼1). The use of multiple MADM

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techniques provided a consistency check. The demonstration illustrates the ability of the continuous simulation-based MADM approach to provide decision makers with a ranking of suitable urban watershed management alternatives which incorporate stakeholder feedback.

Keywords Alternative evaluation index · Decision support system · Urban watershed management · DPSIR

1 Introduction

Urbanization alters the hydrologic cycle by introducing impervious surfaces (Schueler 1994), compacting pervious surfaces (Pitt et al. 2008), replacing indigenous vegetation with irrigated ornamental vegetation (Boyer and Burian 2002), withdrawing water for urban uses, and discharging treated wastewater collected from municipal and industrial users (Heaney et al. 2000). Pollutant loading increases from a myriad of new potential point and nonpoint sources, including urban storm water runoff, combined-sewer overflows (CSOs), sanitary-sewer overflows, industrial discharges, and atmospheric deposition (Novotny 2003). These alterations to the hydrologic cycle and pollutant loading are manifested in changes to stream flow quantity and floods (Hollis 1975), water quality, in-stream aquatic and riparian habitats (Klein 1979), and in-stream and near-stream ecological integrity (Alberti et al. 2007).

The urbanization-induced hydrologic and pollutant loading modifications are various and complex, and the relative importance of the range of impacts is difficult to quantify and rank. Consequently, the use of single-objective decision-making approaches to guide urban watershed management planning and design is not appropriate. There is a need for integrated watershed management (IWM) or integrated water resources management (IWRM) approaches (WSM 2004; Lee and Chung 2007) and the tools necessary to implement these decision-making frameworks. IWM or IWRM encourages planning and management activities to consider a broad variety of sectors, such as the environment, energy, industry, agriculture, and tourism. IWM and IWRM are by nature complex and subject to conflict because they require the involvement of numerous decision makers operating at different levels and a large number of stakeholders with differing preferences and value judgments (Davis 2007; Lahdelma et al. 2000). There is a need to develop methodologies and tools capable of supporting IWM concepts by integrating science and research to support policy development and implementation (ICSU 2002).

Decision making in urban environmental management can be complex and seemingly intractable, principally because of the inherent trade-offs between sociopolitical, environmental, ecological, and economic factors. The selection of appropriate remedial and abatement strategies for contaminated sites, land use planning, and regulatory processes often involves multiple additional criteria, such as spatial vulnerability, distribution of costs and benefits, environmental impacts for different populations, safety, ecological risks, and human values. Some of these criteria cannot be easily condensed into a monetary value, partly because environmental concerns often involve ethical and moral principles that may not be related to any economic use or value. Furthermore, even if it were possible to aggregate multiple criteria ranking into a common unit, this approach would not always be desirable because the ability to track conflicting stakeholder preferences may be lost in the process. Consequently, the process of selecting from several different alternatives often involves the generation of trade-offs that fail to satisfy one or more stakeholder groups. To address these challenges (which are often present in urban watershed management), the considerable recent progress in multi-attribute decision making (MADM) analysis (Kiker et al. 2005) must play a leading role. The usefulness of the procedures, however, depends on the logical structure of valuation procedures and on the common language developed for defining and discussing complex water problems.

The increasing complexity of water management problems has undoubtedly been one motivation for the development of methods that allow multiple impacts to be explicitly considered in decision analysis (Goicoechea et al. 1976; Trombino et al. 2007; Guinarães and Magrini 2008; Opricovic 2009; Fattahi and Fayyaz 2010). These methods have been recently developed to link multi-attribute decision problems and hydrological simulation models in decision support applications (Giupponi et al. 2004; Fassio et al. 2005). Although prioritization of decision alternatives has also been accomplished through application of continuous simulation models, including the Soil and Water Assessment Tool (SWAT; Jayakrishnan et al. 2005; Tripathi and Panda 2005; Lee et al. 2008; Sulis et al. 2009), the United States Environmental Protection Agency's (USEPA) Storm Water Management Model (SWMM; Jang et al. 2006), and the Hydrologic Simulation Program-Fortran (HSPF; Lee and Chung 2007; Mishra et al. 2007; Choi and Deal 2008; Chung and Lee 2009a, b), the integration of continuous simulation tools and MADM to address urban watershed management has not been explored in depth. This paper addresses this need by presenting a continuous simulation-based screening procedure implementing alternative evaluation index (AEI) and MADM techniques to prioritize urban watershed management alternatives. The criteria for alternative performance are selected based on the driver-pressure-state-impact-response (DPSIR) framework (EEP 1999), while the criteria weights are estimated using the analytic hierarchy process (AHP). In addition, AEIs that reflect residents' preferences for management objectives are identified to induce the stakeholders to participate in the decision-making process. The integrated continuous simulation-MADM approach is demonstrated for a case study watershed in Korea.

2 Methodology

The approach illustrated in Fig. 1 consists of four steps: (1) develop with local government officials, technical experts, and stakeholders a set of feasible alternatives for solving the urban watershed management problem(s), (2) analyze feasible alternatives using the SWMM continuous urban hydrologic model, (3) quantify DPSIR indicators using literature reviews, expert input, GIS analyses, monitoring data, and SWMM results, and (4) calculate AEI and rank all alternatives using MADM techniques (DEFINITE). The sub-sections below provide brief background information about SWMM, DPSIR, AEI, and DEFINITE before the framework case study is presented.

2.1 SWMM

The USEPA SWMM (Rossman 2009) is a comprehensive mathematical model used for simulation of urban runoff quantity and quality in storm and combined sewer

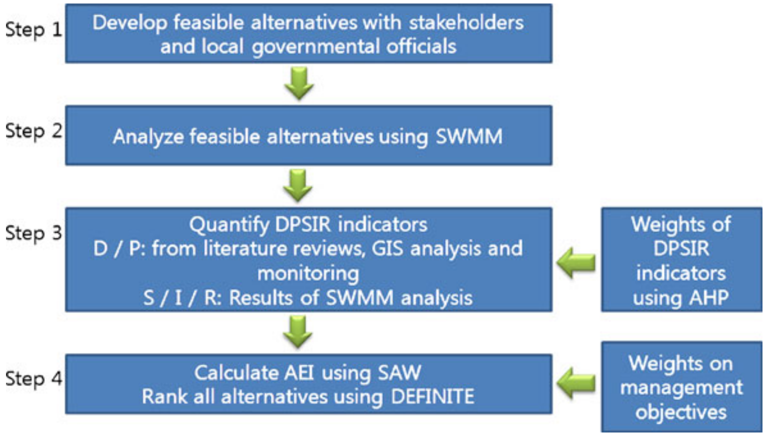

Fig. 1 Flow chart of the continuous simulation—MADM decision support framework

systems and natural waterways. It incorporates dynamic rainfall–runoff computations for both single-event and continuous simulations of runoff quantity (Huber and Dickinson 1998). Precipitation is applied to defined subcatchments, infiltration excess is determined using Horton's or Green and Ampt's models, the time of concentration is computed based on kinematic wave theory, and runoff is generated using the nonlinear reservoir algorithm. Surface runoff is computed in SWMM considering land use type and topography and accounting for antecedent moisture conditions, infiltration losses in pervious areas, surface detention, overland flow, channel/pipe flow and constituents carried by runoff into inlets. Important input parameters include catchment slope, pervious and impervious depression storages, channel and conduit layouts, geometries and properties, the Manning roughness coefficients for both overland and channel flows, and rainfall intensity. Flows are routed using the dynamic wave solution of the Saint-Venant equations through pipes, channels, and other drainage system elements. Runoff quality is simulated using one of several options, including accumulation/wash-off, rating curve, or constant concentration. SWMM is capable of both single-event and continuous simulations to provide the flow hydrographs and pollutographs needed to compute the SIR components of the DPSIR criteria for use in the decision support framework (see Fig. 1).

2.2 DPSIR Approach

DPSIR stands for drivers-pressures-state-impacts-response: the components of an analytical framework that link the socioeconomic factors (drivers) forcing anthropogenic activities (pressures), the resulting environmental conditions (states, e.g., concentrations of pollutants, disturbance of hydrological regime), the environmental consequences resulting from these conditions (impacts, e.g., eutrophication, fish deaths, water unsuitable for drinking) and, finally, the measures taken to improve the environmental state (response). The DPSIR framework was originally developed by the European Environment Agency (1999) for reporting environmental monitoring data according to different environmental assessment tools (e.g., environmental impact assessment). DPSIR provides structure to the environmental problems by formalizing the relationships among various sectors of human activity and the environment as causal chains. Problem-specific criteria and weights are defined for the DPSIR framework and are quantified using simulation results and expert input. The weights and criteria are then integrated (e.g., by simple additive weighting) to provide input to the AEI step of the process.

2.3 AEI

AEI was developed by Chung and Lee (2009a, b) to prioritize alternatives for IWM using hydrological simulation and MADM techniques. AEI is a linear combination of evaluation values for water quantity and quality:

$$f(a_i) = \alpha_r\, f_r(a_i) + \alpha_s\, f_s(a_i), \tag{1}$$

where $f_r(a_i)$, and $f_s(a_i)$ are evaluation values of water quantity and quality of the watershed, for which the alternative a_i is applicable, respectively, and α_r and α_s $(\alpha_r + \alpha_s = 1)$ represent the relative importances of water quantity and quality, respectively. Evaluation values were determined based on the DPSIR framework as follows:

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

where j is the decision factor (r: water quantity, s: water quality); DR, PR, ST, IM and RE the values of driving force, pressure, state, impact and response components, respectively; and b, c, d, e, and f are the weighting factors on driving force, pressure, state, impact and response $(b + c + d + e + f = 1)$. It is the role of the decision makers to select the indicators for the driver, pressure, state, impact, and response. The criteria and weights from the DPSIR are input to the AEI index to produce a ranking of alternatives.

2.4 DEFINITE

DEFINITE (decisions on a finite set of alternatives; Janssen and van Herwijnen 1992) is a decision support software package that has been developed to improve the quality of environmental decision making. DEFINITE is a comprehensive tool kit of methods that can be used for a wide variety of problems. The program contains a number of methods for supporting problem definition, as well as graphical tools to support representation. DEFINITE includes five different multi-attribute methods, as well as cost-benefit and cost-effectiveness analysis tools. Related procedures, such as weight assessment, standardization, discounting, and a large variety of methods for sensitivity analysis, are also available. In this study, a new version of DEFINITE (Janssen et al. 2000) is used. DEFINITE provides a software package to analyze a range of ranking MADM methods to integrate into the AEI approach to check consistency and to provide a qualitative comparison to decision makers.

3 Case Study Demonstration

The integrated continuous simulation-MADM approach described above is tested through application to the Mokgamcheon watershed (Fig. 2). The Mokgamcheon River is a second order tributary of the Han River in Korea. The study stream has a length of 13.5 km. The watershed, bounded by latitudes 37°23′ and 37°29′ N and longitudes 126°48′ and 126°52′ E, is 56 km^2 and contains approximately 473,000 people (population density = 8,437 persons/km^2). The primary land cover types (as of 2000) are 31% urban, 35.5% forest, and 18.5% agriculture. The average annual precipitation from 1972 to 2001 was 1,325 mm, with 70% of the precipitation falling during the monsoon months of June to September. However, recent precipitation observations from 2002 to 2006 have significantly increased the average annual precipitation to 1,468 mm, with 74% falling during the monsoon season. The increase in precipitation concentrated during the monsoon season has exacerbated existing urban watershed management problems.

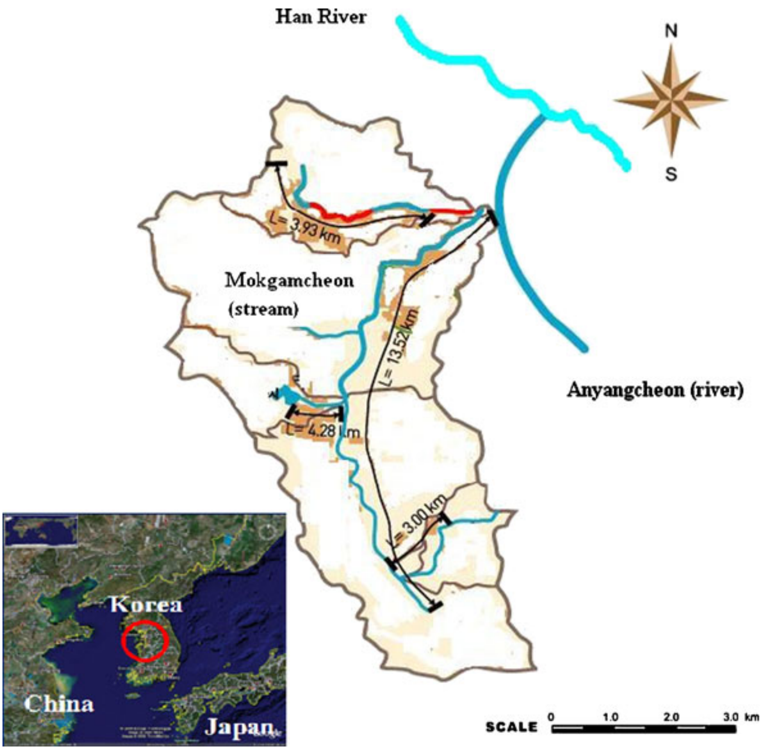

Fig. 2 Vicinity map of the Mokgamcheon watershed in Korea

3.1 SWMM Model Formulation

SWMM is used to simulate the runoff response of the Mokgamcheon watershed. A 1:25,000 digital elevation model (DEM) and land use map (2000) from the National Geographic Information Institute (NGII) of the Korean Ministry of Land and Ocean (MLO) provides watershed topography to determine drainage area delineation and surface slopes used in SWMM. Storm and combined sewer infrastructure data (e.g., pipe characteristics) obtained from the MLO are used to represent the drainage network characteristics and are combined with the watershed topography to delineate sub-watershed boundaries. The land use types are used to assign watershed surface parameters, including the percentage directly connected to the impervious area (DCIA), Manning's roughness for pervious and impervious surfaces, and depression storage. Infiltration is simulated using the Green-Amp equation because it has the advantage over the Horton equation of using physically-based parameters that can be determined a priori (Huber and Dickinson 1998). Soils data from the National Institution of Agricultural Science (NIAS) of Technology from the Rural Development Administration are used to parameterize the Green-Ampt parameters (capillary suction head at the wetting front, initial moisture deficit, saturated hydraulic conductivity). Daily historic data (1974–2007) of precipitation, temperature, average wind speed, average humidity, and average solar radiation were obtained from the Suwon and Seoul stations of the Korea Meteorological Administration (KMA), both of which are located in the watershed boundary. Over 100 observations of stream-flow quantity and quality that had been irregularly measured at the outlet of the study watershed (2006~2007) were obtained from Lee (2008). The wastewater quantity and quality data and the unit load of household emission were obtained from the Korean Ministry of Environment.

The SWMM model was subjected to a sensitivity analysis to identify parameters to be used in the calibration step. Sensitivity analyses of watershed and conduit roughness values, depression storage, infiltration parameters, and the accumulation/wash-off parameters were conducted to determine their importances for influencing the total volume of runoff and peak flow, total load and peak concentration of biochemical oxygen demand (BOD), and suspended solids (SS) in the Mokgamcheon watershed. All parameters were found to sufficiently influence the test output parameters to be included in the calibration. PERVN (pervious area Manning's roughness), ROUGH (Manning's roughness of conduit) and HYDCON (saturated hydraulic conductivity), IMPN (impervious area Manning's roughness), IDS (impervious area depression storage, mm), and PDS (pervious area depression storage, mm) were selected as hydrologic parameters. QFACT (1) (limit for buildup, kg/ha), QFACT (2) (power of exponent for buildup), QFACT (3) (coefficient for buildup, ka/ha/day), WASHPO (wash-off power, /mm) and RCOEF (wash-off coefficient) were chosen as water quality parameters. FC (field capacity), TH1 (initial upper zone moisture), HCO (hydraulic conductivity vs. moisture content curve-fitting parameter), PCO (average slope of tension vs. soil-fitting parameter), CET (maximum evapotranspiration rate assigned to the upper zone), and DP (coefficient for unquantified losses) were considered as groundwater parameters.

The SWMM model was calibrated manually using trial-and-error until the simulation results satisfactorily matched the observations (Refsgaard 1997; Santhi et al.

2001; Albek et al. 2003). The objective function for calibration is the model efficiency (Nash and Sutcliffe 1970):

$$\max \quad R^2 = \frac{F_0^2 - F^2}{F_0^2} \tag{3}$$

$$F_0^2 = \sum_{i=1}^{n} \left(M_{ob} - Q_{ob,i}\right)^2, \tag{4}$$

$$F^2 = \sum_{i=1}^{n} \left(Q_{sim,i} - Q_{ob,i}\right)^2, \tag{5}$$

where n is the number of values; i is the order of the days; $Q_{ob,i}$ is the observed value for the ith day; M_{ob} is the average of the observed values for all n-th days; $Q_{sim,i}$ is the simulated value for the ith day; F_0^2 represents the initial variation in the observed values; and F^2 is the index of disagreement between the observed and the simulated values. The model becomes more efficient as R^2 approaches 1. Summarized results of the calibration and validation of the water quantity and quality are shown in Table 1.

For the case study, the calibrated SWMM model is used to simulate the runoff quantity and quality responses to urban watershed management alternatives (described below) over a 35-year time period using meteorological data from 1974 to 2007 on a daily time step.

3.2 Feasible Alternatives

In many cases, budgets and resources are generally limited, and thus all feasible alternatives are seldom accepted for further analysis. Managers should therefore determine a set of alternatives that maximizes the desired objective (e.g., maintenance of the average low flow, water quality enhancement). However, ranking feasible alternatives might be preferred to identifying an optimal solution, particularly when the constraints are uncertain. Ranking also facilitates the analysis of options according to additional factors, including costs related to budget and resources.

For this study, local government officials, residents (stakeholders), and technical experts provide a set of possible urban watershed management alternatives. However, because there are too many alternatives to be analyzed in detail for this demonstration, the alternatives were screened according to three criteria: technical, economic, and environmental feasibilities. Ten feasible options remained after the screening (Table 2), and these were reorganized into seven feasible combinations

Table 1 SWMM calibration and verification results

Category		Number of data	Model efficiency	RMSE	RMAE
Flowrate	Calibration[a]	26	0.919	1.318 cms	0.139
	Verification	22	0.648	0.607 cms	0.303
BOD	Calibration	25	0.678	3.957 mg/L	0.150
	Verification	21	0.635	3.913 mg/L	0.156
SS	Calibration	20	0.735	34.652 mg/L	0.189
	Verification	14	0.861	4.661 mg/L	0.103

RMSE root mean square error, *RMAE* root mean absolute error
[a]Calibration period: 1/31/2007∼9/1/2007; verification period: 6/9/2006∼12/22/2006

of alternatives: I1 + O1, O3, L3 + O2, I2 + S2, O2 + L1, O2 + L1 + L2, O2 + L1 + L2 + S1, shown in Fig. 3. Alternatives such as interceptor, local WWTP (Waste Water Treatment Plant), and combined sewer separation aim to improve the water quality, and the objective of reservoir modifications is to supply sufficient in-stream flow. L1 and L2 were proposed in different locations of the MG sub-watershed (shown in Fig. 3).

3.3 DPSIR Criteria, Weights, and Values

According to the DPSIR framework, all criteria (indicators) used to quantify the AEI were determined via consultation with local researchers, technical experts, and government officials (Fig. 4).

Based on Fig. 4, the additive weighting equations on water quantity are as follows:

$$DR_{1,i} = b_{1,1}s_{PD,n} + b_{1,2}s_{P,n}, \tag{6}$$

where $s_{PD,n}$ is the population obtained from the Korean National Statistical Office (www.nso.or.kr KNSO), sub-divided for each sub-watershed, and $S_{P,n}$ is the population density calculated as population per unit area.

$$PR_{1,i} = c_{1,1}s_{UR,n} + c_{1,2}s_{SS,n} + c_{1,3}s_{GE,n} + c_{1,4}s_{SW,n}, \tag{7}$$

where $s_{UR,n}$ is the urban area ratio obtained from GIS analysis of land use, $s_{SS,n}$ is the stream-flow seepage/diversion estimated during site visits, and $s_{GE,n}$ is the annual groundwater withdrawal quantity obtained from the national “Groundwater Survey” (KOWACO 2007) document, and $s_{SW,n}$ is the average watershed slope obtained from GIS analysis of topography.

$$ST_{1,i} = 1 - \frac{t_1(a_i)/d(a_i)}{\max\limits_i \ t_1(a_i)/d(a_i)}, \tag{8}$$

where $t_1(a_i)$ is the drought flow (Q355 of flow duration curve), and $d(a_i)$ is the average low flow (Lee et al. 2008). Q355 is determined via the SWMM simulation,

Table 2 Descriptions of feasible alternatives

Alternatives	Sub-watershed	Description	Name
Interceptor	OR	Installation of interceptor	I1
	YG		I2
Local WWTP	MG	Construction of small WWTP in upstream regions	L1
	GS	BOD = 1.8 mg/L*	L2
		TN = 8.275 mg/L*	
		TP = 0.762 mg/L*	L3
		SS = 1.5 mg/L*	
Combined sewer separation	MG	Replacing combined sewer with separated sewer	S1
	YG		S2
Reservoir modifications	OR	Rehabilitation of reservoir Proper operation (release 0.05 cm)	O1
	GS	Construction of sluice gate Proper operation (release 0.05 cm)	O2
	GH	Rehabilitation of reservoir Proper operation (release 0.055 cm)	O3

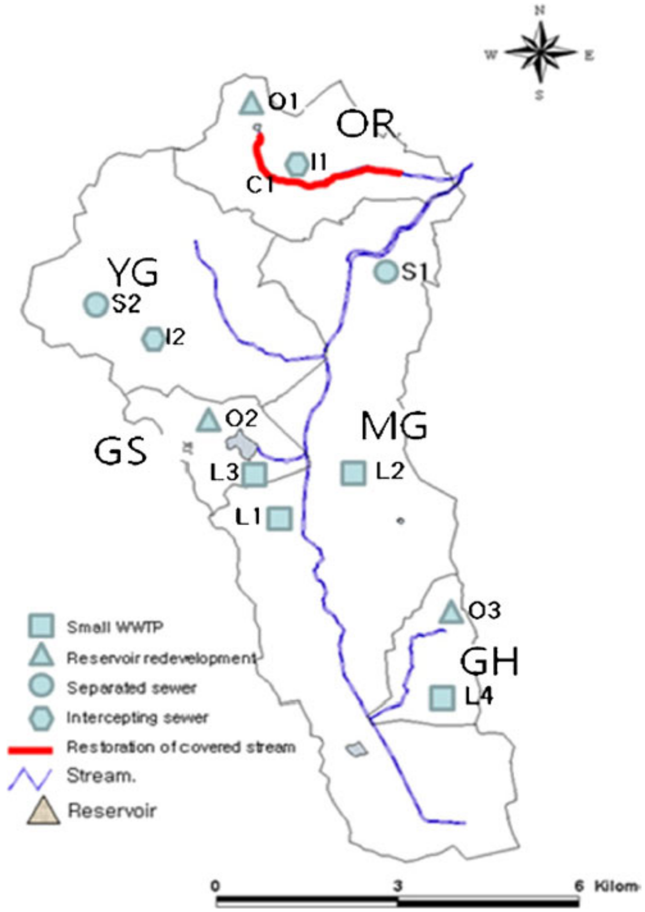

Fig. 3 Map of all feasible alternatives

and the average low flow is determined using regional regression (see Lee et al. 2008 for a description of methods).

$$IM_{1,i} = 1 - \frac{n_1(a_i)}{\max\limits_i \; n_1(a_i)}, \tag{9}$$

where $n_1(a_i)$ is the number of days in a year satisfying the average low flow requirement. It can be computed based on post-processing SWMM results and the average low flow estimate according to the regional regression equation (Lee et al. 2008)

$$RE_{1,i} = 1/3 \times \frac{\Delta d(a_i)/t_1(a_i)}{\max\limits_i \; \Delta d(a_i)/t_1(a_i)} + 1/3 \times \frac{\Delta l(a_i)/t_1(a_i)}{\max\limits_i \; \Delta l(a_i)/t_1(a_i)} + 1/3 \times \frac{\Delta n_1(a_i)}{\max\limits_i \; \Delta n_1(a_i)} \tag{10}$$

where $\Delta d(a_i)/t_1(a_i)$ is the ratio of increased Q355 to average low flow computed using SWMM simulation results and estimated average low flow, $\Delta l(a_i)/t_1(a_i)$ is the

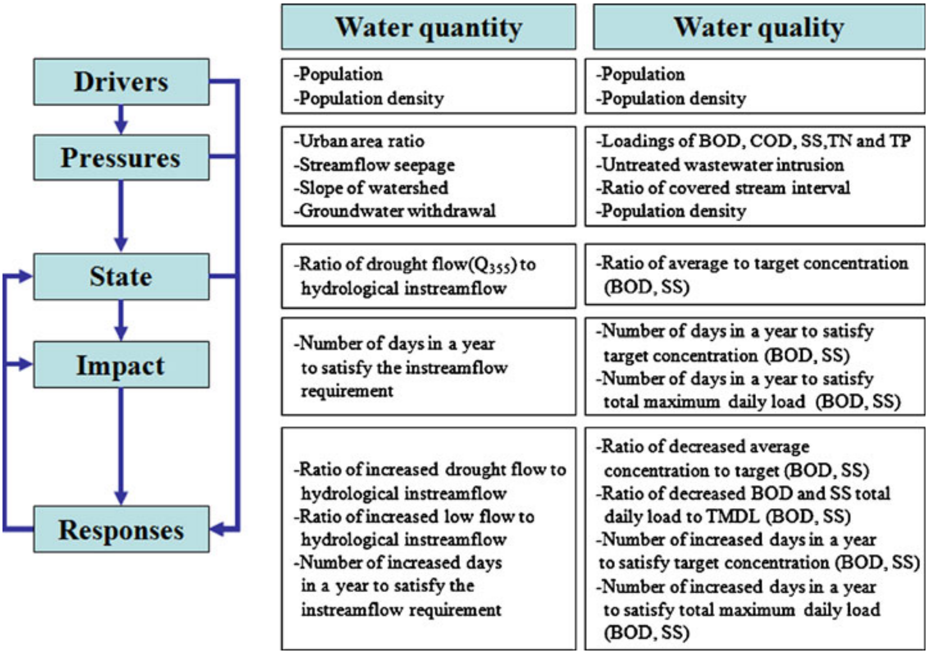

Fig. 4 Structure of selected DPSIR criteria

ratio of increased Q275 to average low flow computed using SWMM simulation results and estimated average low flow, and $\Delta n_1(a_i)$ is the number of days in a year that satisfy the average low flow requirements based on the SWMM simulation results.

Based on Fig. 4, the additive weighting equations on water quantity are as follows:

$$DR_{2,i} = b_{2,1}s_{PD,n} + b_{2,2}s_{P,n} \tag{11}$$

$$PR_{2,i} = c_{2,1}s_{LB,n} + c_{2,2}s_{LC,n} + c_{2,3}s_{LS,n} + c_{2,4}s_{LPN,n} + c_{2,5}s_{WI,n} + c_{2,6}s_{PD,n} + c_{2,7}s_{CSN,n}, \tag{12}$$

where $s_{WI,n}$ is the intrusion of wastewater determined by site visits, $s_{CSN,n}$ is the ratio of covered length (calculated as the length of stream covered by impervious area divided by the total stream length), and $s_{LB,n,}$, $s_{LC,n}$, s_{LS} and s_{LPN} are the BOD, COD, SS, and TN&TP loads calculated using Eq. 13:

$$U_j(a) = \sum_{k=1}^{p} u_{j,k} A_k(a), \tag{13}$$

where j is the pollutant type, k is the land use type, p is the number of land use types, a is the sub-watershed, $u_{j,k}$ is the pollutant j's unit load of land use k, and $A_k(a)$ is the total area of land use k of the sub-watershed, a.

$$ST_{2,i} = 1 - \left(\alpha \times \frac{qc_{BOD}(a_1)/t_{BOD}(a_i)}{\max\limits_i \; qc_{BOD}(a_i)/t_{BOD}(a_i)} + \beta \times \frac{qc_{SS}(a_1)/t_{SS}(a_i)}{\max\limits_i \; qc_{SS}(a_i)/t_{SS}(a_i)} \right) \tag{14}$$

where $qc_{BOD}(a_1)/t_{BOD}(a_i)$ and $qc_{SS}(a_1)/t_{SS}(a_i)$ are the ratios of average to target concentrations (BOD and SS). The average concentration is determined using SWMM, and the target concentration is determined by the local government.

$$IM_{2,i} = 1 - \left(\alpha \times \frac{nc_{BOD}(a_i)}{\max\limits_i \; nc_{BOD}(a_i)} + \beta \times \frac{nc_{SS}(a_i)}{\max\limits_i \; nc_{SS}(a_i)} \right), \tag{15}$$

where $nc_{BOD}(a_i)$ and $nc_{SS}(a_i)$ are the numbers of days in a year that satisfy the total maximum daily loads (TMDL) of BOD and SS that were determined from SWMM simulation results.

$$\begin{aligned} RE_{2,i} = \alpha \times 1/4 \times & \left(\frac{\Delta qc_{BOD}(a_i)/tc_{BOD}(a_i)}{\max\limits_i \; \Delta qc_{BOD}(a_i)/tc_{BOD}(a_i)} + \frac{\Delta ql_{BOD}(a_i)/tl_{BOD}(a_i)}{\max\limits_i \; \Delta ql_{BOD}(a_i)/tl_{BOD}(a_i)} \right. \\ & \left. + \frac{\Delta nc_{BOD}(a_i)}{\max\limits_i \; \Delta nc_{BOD}(a_i)} + \frac{\Delta nl_{BOD}(a_i)}{\max\limits_i \; \Delta nl_{BOD}(a_i)} \right) \\ + \beta \times 1/4 \times & \left(\frac{\Delta qc_{SS}(a_i)/tc_{SS}(a_i)}{\max\limits_i \; \Delta qc_{SS}(a_i)/tc_{SS}(a_i)} + \frac{\Delta ql_{SS}(a_i)/tl_{SS}(a_i)}{\max\limits_i \; \Delta ql_{SS}(a_i)/tl_{SS}(a_i)} \right. \\ & \left. + \frac{\Delta nc_{SS}(a_i)}{\max\limits_i \; \Delta nc_{SS}(a_i)} + \frac{\Delta nl_{SS}(a_i)}{\max\limits_i \; \Delta nl_{SS}(a_i)} \right) \end{aligned} \tag{16}$$

where $\Delta qc_{BOD}(a_i)/tc_{BOD}(a_i)$ and $\Delta qc_{SS}(a_i)/tc_{SS}(a_i)$ are the ratios of decreased average concentration targets (BOD and SS) determined from SWMM simulation results, and $\Delta ql_{BOD}(a_i)/tl_{BOD}(a_i)$ and $\Delta ql_{SS}(a_i)/tl_{SS}(a_i)$ are the ratios of decreased total daily load to TMDL (BOD and SS) determined from SWMM simulation results, Δnc_{BOD} and Δnc_{SS} are the numbers of days in a year that satisfy the target concentration determined from SWMM simulation results, and Δnl_{BOD} and Δnl_{SS} are the numbers of days in a year that satisfy the TMDL determined from SWMM simulation results. Δ changes in value with alternative a_i, and α and $\beta(\alpha + \beta = 1)$ are the weights of BOD and SS. In this study, they are assumed to be equal ($\alpha = \beta = 1/2$) and to be the residents' demands on watershed management (water quantity and quality).

In the absence of direct quantitative estimates for the criteria and sustainability components (DPSIR), values were assigned in consultation with local government officials and researchers working in the field of river and water resources management. Quantification was based on the pairwise comparison test (Saaty 1980) using a normalized judgment scale ranging from 0 (lowest score) to 1 (highest score) such that the sum of an indicator's values across all options is 1. All the weights were established using the AHP. A survey was conducted of 30 local governmental officials and researchers working in the field of river and water resources management.

Values of drivers and pressures were obtained via field surveys, statistics derived from field observations, and GIS analyses. Values of states, impacts, and responses were obtained through SWMM simulation for the set of alternatives being tested.

4 Results

4.1 SWMM Simulations

Seven alternatives were analyzed using the calibrated SWMM model. The results are shown in Tables 3 and 4. Table 3 shows both the changes in Q355 and Q275 with respect to water quantity and the changes in average concentration and total daily load of BOD and SS as a result of the implementation of the alternatives. Table 4 shows the changes in the number of days for which the average low flow requirements, target concentrations, and TMDLs are satisfied due to the alternatives. "Zero" in this table means that the in-stream flow had never been satisfied.

4.2 AEI Calculation

The decision matrix for the water quantity and quality can be formulated using simulated values and Eqs. 6, 7, 8, 9, 10, 11, 12, 13, 15 and 16. The results of the simple additive weighting (SAW) approach for computing the AEI are shown in Table 5. Hartmann et al. (1987) proposed that all alternatives could be classified into three groups: sound, acceptable, and poor. Following this logic, according to the AEI values, all alternatives are divided into three groups: poor (P, 0∼0.3), acceptable (A, 0.3∼0.6), and good (G, 0.6∼1). Using this system, all of the alternatives for this present study are classified as follows: G (I1 + O1), A(O3, L3 + O2, I2 + S2, O2 + L1, O2 + L1 + L2, O2 + L1 + L2 + S1), P(I2 + S2). Alternatives for MG and OR (I1 + O1, L3 + O2, O2 + L1) sub-watersheds show better effectiveness compared to those for YG. Also, all O-included alternatives considering both water quantity and quality impacts are efficient.

AEI can reflect the desires of residents with regard to watershed management objectives. This can be achieved by calculating the pairwise comparison of prevention of stream flow depletion and water quality enhancement. If the demand can be quantified and introduced into the weights, the AEIs can also be used as a management prioritization index (Chung and Lee 2009a, b). In a survey of 300 residents, the weights for prevention of stream flow depletion and water quality enhancement were 0.238 and 0.762, respectively. The AEIs were recalculated by linearly combining the results of SAW and resident preferences, as shown in Table 5. 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 alter overall performance.

To assure consistency, the alternatives are ranked using multiple MADM techniques (SAW, Electre II, Regime, and Evamix) and DEFINITE. ELECTRE II is useful for outranking method, Evamix method for mixed measurement scale and cardinal weights, and Regime method for mixed measurement scale and ordinal weights. Their detailed descriptions and applications are explained in Hobbs et al.

Table 3 Comparisons of simulation results with and without alternatives

Name of subwatershed	Alternatives	Water quantity (cms)			Water quality					
		Low flow (Q_{275})	Drought flow (Q_{355})	Efficiency	BOD Concentration (mg/L)	BOD TDL (kg/day)	BOD Efficiency	SS Concentration (mg/L)	SS TDL (kg/day)	SS Efficiency
OR	Without alternatives	0.001	0.001	–	90.380	2386.7	–	65.98	2,124.8	–
	I1 + O1	0.051	0.020	69.00	5.520	113.6	1.89	47.94	1,270.4	0.676
GH	Without alternatives	0.002	0.001	–	22.930	28.6	–	73.64	346.1	–
	O3	0.006	0.063	64.08	4.260	36.1	0.55	36.94	353.1	0.478
GS	Without alternatives	0.010	0.001	–	13.200	31.5	–	60.39	374.4	–
	L3 + O2	0.051	0.051	75.69	3.100	38.1	0.56	27.88	379.4	0.525
YG	Without alternatives	0.314	0.280	–	9.390	278.5	–	37.40	603.8	–
	I2 + S2	0.314	0.280	0.00	1.670	60.0	1.61	31.90	506.1	0.308
MG	Without alternatives	0.239	0.166	–	23.552	1272.1	–	80.95	5,302.4	–
	O2 + L1	0.424	0.296	1.56	12.469	1082.3	0.62	62.97	5,205.3	0.240
	O2 + L1 + L2	0.424	0.296	1.56	10.298	950.0	0.82	63.46	5,227.7	0.230
	O2 + L1 + L2 + S1	0.442	0.199	1.05	9.826	794.8	0.96	66.27	5,179.7	0.204

Table 4 Numbers of days for which the water quantity and quality targets are satisfied

Name	Category	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Sum
OR	Without alternatives	0	0	0	0	0	0	0	0	0	0	0	0	0
	I1 + O1	2	0	0	1	3	4	8	0	0	16	2	2	38
GH	Without alternatives	1	0	0	0	2	2	6	0	0	0	0	1	12
	O3	31	28	31	0	2	4	7	0	0	0	30	31	164
GS	Without alternatives	1	0	0	0	2	4	8	0	0	1	0	2	18
	L3 + O2	1	0	0	30	31	4	10	0	0	1	1	2	80
YG	Without alternatives	31	28	31	0	2	3	7	0	0	1	30	31	164
	I2 + S2	31	28	31	0	2	3	7	0	0	1	30	31	164
MG	Without alternatives	0	0	0	0	0	0	0	5	0	0	30	31	66
	O2 + L1	0	27	31	0	31	30	31	31	0	16	30	31	258
	O2 + L1 + L2	0	27	31	0	31	30	31	30	0	17	30	31	258
	O2 + L1 + L2 + S1	0	9	31	0	31	30	31	31	0	6	30	31	230

Table 5 AEIs, ranks, and grades according to the simple additive weighing method

Name of alternative	Water quantity	Water quality	Equal weights			Residents' weights		
			AEI	Rank	Grade	AEI	Rank	Grade
I1 + O1	0.70	0.73	0.72	1	G	0.73	1	G
O3	0.66	0.35	0.50	5	A	0.42	5	A
L3 + O2	0.59	0.31	0.45	6	A	0.38	6	A
I2 + S2	0.14	0.40	0.27	7	P	0.34	7	A
O2 + L1	0.63	0.46	0.55	2	A	0.50	2	A
O2 + L1 + L2	0.63	0.44	0.54	3	A	0.49	3	A
O2 + L1 + L2 + S1	0.60	0.44	0.52	4	A	0.48	4	A

(1992), Roy et al. (1992), Tecle et al. (1988), Raju and Duckstein (2004) (ELECTRE II), Voogd (1982), Hinloopen and Nijkamp (1990); Nijkamp et al. (1990); Janssen and van Herwijnen (1992) (Regime method, Evamix method) and Chung and Lee (2009a, b).

The results using equal weight on water quantity and quality are shown in Table 6. Values obtained from SAW, Regime and Evamix methods are the relative evaluation result. Therefore, the higher the value is, the better the effectiveness of the corresponding alternative becomes. But values obtained from ELECTRE II means the outranking. So, alternatives showing “1” outrank the others (showing “2” and “3”). The rankings of SAW and Evamix methods are fairly consistent and same as the AEI rankings. Electre II results do not integrate the multiple attribute assessment into a single ranking, but the results are consistent in that the higher ranked alternatives) from the other MADM techniques (I1 + O1, O2 + L1, O2 + L1 + L2, O2 + L1 + L2 + S1) do not rank low for any of the attributes. SAW, Evamix, and Regime rankings have been found to be similar in past studies (Chung and Lee 2009a, b); however, this study shows different rankings, possibly because Regime method quantify information on the relative certainty of the results within the limits of the qualitative information. Figure 5 shows the DEFINITE's scatter diagram of f_r and f_s (left section) and the resident rankings (right section) using weights (water quantity/quality = 0.24:0.76). We can determine the change in alternative ranking depending on the weights of water quantity and quality. Although the MADM techniques do show differences, they can be combined to provide relative rankings of the alternatives while accounting for the uncertainty in the process.

Table 6 Results of SAW, Electre II, Regime and Evamix methods

Name of alternative	SAW	Electre II	Regime method	Evamix method
I1 + O1	0.72	1	0.50	0.24
O3	0.50	3	0.17	0.00
L3 + O2	0.45	3	0.33	−0.07
I2 + S2	0.27	3	0.50	−0.25
O2 + L1	0.55	2	0.67	0.04
O2 + L1 + L2	0.54	2	0.83	0.03
O2 + L1 + L2 + S1	0.52	2	0.50	0.01

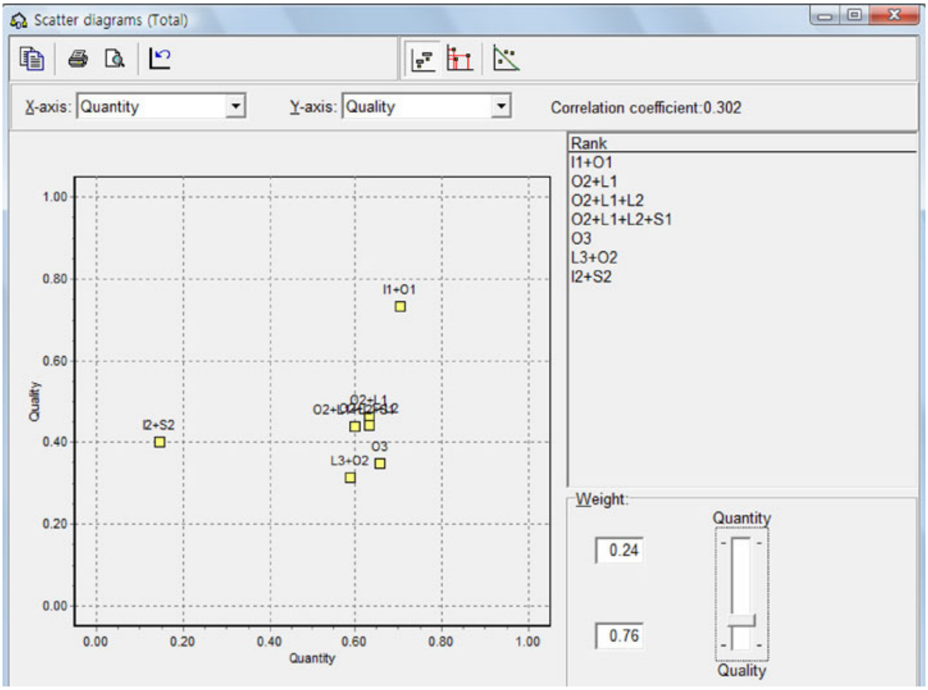

Fig. 5 Screen shots of DEFINITE results: Scatter diagram to weights on water quantity and quality

5 Conclusions

This paper introduced a continuous simulation-based screening procedure for ranking urban watershed management alternatives using MADM. The procedure integrated the SWMM continuous urban runoff simulation model using the AEI and multiple MADM techniques, following the DPSIR framework. The analytic hierarchy process estimated the weights of the criteria, and SWMM results quantified the effects of the management alternatives on water quantity and quality metrics. This decision support process was demonstrated for the Mokgamcheon watershed in Korea, an area with multiple urban watershed management problems that have been exacerbated by recent increases in rainfall frequency and intensity. Key findings from this study are the usefulness of using DPSIR to quantitatively represent sustainability criteria into a coordinated index and the value of the AEI framework for incorporating preferences of residents toward management objectives as a way to include stakeholder participation in the decision-making process. Furthermore, the MADM approach combining AEI with other MADM techniques through the use of DEFINITE provides a robust decision support approach analogous to using ensembles of models to capture uncertainties in the input data, weights, and process and to assure consistency. The demonstration illustrated the value of the approach, but refinement and validation of the methods must continue such that they can eventually be incorporated into policy making.

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