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An index-based robust decision making framework for watershed management in a changing climate

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HIGHLIGHTS

- An index-based robust decision making framework was developed for watershed management
- It used two indices based on sustainable development and stakeholder participation
- Robust strategies were selected using multicriteria decision making under complete uncertainty

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ABSTRACT

This study developed an index-based robust decision making framework for watershed management dealing with water quantity and quality issues in a changing climate. It consists of two parts of management alternative development and analysis. The first part for alternative development consists of six steps: 1) to understand the watershed components and process using HSPF model, 2) to identify the spatial vulnerability ranking using two indices: potential streamflow depletion (PSD) and potential water quality deterioration (PWQD), 3) to quantify the residents' preferences on water management demands and calculate the watershed evaluation index which is the weighted combinations of PSD and PWQD, 4) to set the quantitative targets for water quantity and quality, 5) to develop a list of feasible alternatives and 6) to eliminate the unacceptable alternatives. The second part for alternative analysis has three steps: 7) to analyze all selected alternatives with a hydrologic simulation model considering various climate change scenarios, 8) to quantify the alternative evaluation index including social and hydrologic criteria with utilizing multi-criteria decision analysis methods and 9) to prioritize all options based on a minimax regret strategy for robust decision. This framework considers the uncertainty inherent in climate models and climate change scenarios with utilizing the minimax regret strategy, a decision making strategy under deep uncertainty and thus this procedure derives the robust prioritization based on the multiple utilities of alternatives from various scenarios. In this study, the proposed procedure was applied to the Korean urban watershed, which has suffered from streamflow depletion and water quality deterioration. Our application shows that the framework provides a useful watershed management tool for incorporating quantitative and qualitative information into the evaluation of various policies with regard to water resource planning and management.

1. Introduction

Now it is clear that some degree of climate change is inevitable. Therefore, research over the past several decades has extensively investigated the potential impacts of climate change on regional hydrology and consequent implications for water resource management systems. Despite these efforts, there is no consensus in the literature on appropriate strategies to cope with non-stationary climate, or on even the criteria by which to determine the relative merit of alternative adaptation policies (Lempert and Schlesinger, 2000). Therefore, a systematic framework for watershed management has become necessary for the robust decision making in a changing climate environment.

In the past, adaptations to either climate variability or change have mostly been responsive, mainly driven by record-breaking extreme weather events. As awareness about the potential impacts of human-induced climate change has grown (at different levels throughout countries and sectors), so has the desire to plan (in advance) for the impacts of climate change so that the negative hazards can be mitigated and the benefits enhanced (Scheraga and Grambsch, 1998). However, climate change adaptation planning has been hindered by the unavailability and unreliability of climate forecasts or predictions (Dessai et al., 2005). Therefore, scenarios, which are plausible and internally consistent images of the future, are widely used for adaptation planning. This traditional framework rests on the assumption that we can predict

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the future with certainty. Despite the usefulness of climate scenarios such as the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES), there remains a significant gap between current scenario practice and its potential contributions (Parson et al., 2006). Two of the most important, unresolved methodological challenges involve the means to choose several scenarios to summarize what is often a very wide range of uncertainties and how to include probabilistic information with such scenarios.

Given such uncertainty of future, it is crucial to seek for robust policy approaches. In particular, it is of growing interest in environmental index utilizing various indicators. The Organization for Economic Co-operation and Development(OECD) (1993) defined environmental index as attributes of land units that are policy relevant, analytically sound, and measurable. The index-based strategic planning in the highly uncertain situation is very effective and is used frequently (Giri et al., 2012). It has some benefits of: 1) providing a structured approach for focusing on strategies, objectives, and performance indicators, 2) improving foresight and anticipation, ability to detect change, enables rapid change of course corrections in the case of status indicators, 3) assisting in prioritizing the allocation of program resources and 4) informing debate within the country on policy choices available at any given time, facilitating the involvement of civil society in the planning process Economic and Social Commission for Asia the Pacific(ESCAP) (2004).

Several studies in the past have developed the index-based assessment tools for water resources management. Chung and Lee (2009b) developed three indices to quantify the vulnerabilities such as potential flood damage (PFD), potential streamflow depletion (PSD) and potential water quality deterioration (PWQD) and the composite index of the previous three, watershed evaluation index (WEI) using the pressure-state-response (PSR) framework. Those indices were improved by Jun et al. (2011). They considered the impact of climate change and also used one of the popular multi-criteria decision analysis (MCDA) methods, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS; Hwang and Yoon, 1981). Furthermore, Chung and Lee (2009a) developed the alternative evaluation index (AEI) for the prioritization of some water resources projects using driving force-pressure-state-impact-response (DPSIR) framework and various MCDA methods. Recently, Kim and Chung (2012) improved the AEI to include the changes in effectiveness of alternatives under climate change.

Previous index-based assessments for water management, however, could be improved in several ways. First, they did not consider the uncertainty of index development as well as the uncertainty of the climate change scenarios. Second, the index-based assessment was applied for a certain part of water management limitedly and it was not integrated into a comprehensive tool for water management. In this study, we therefore aimed to develop a comprehensive and robust tool for an index-based water management under uncertain future climate change as to better practice an integrated water management (IWM). Here the IWM can be defined as watershed management to integrate water quantity and quality, and natural (environmental impact) and human (social impact) systems simultaneously and even consider costing and legal, institutional and administrative concerns (Heathcote, 1998). Specifically, we developed a nine-step index-based robust decision making framework for watershed management with considering complete uncertain climate change scenarios. This study integrates the previously developed indices for watershed management with employing various MCDA methods for quantifying the indices and considers the uncertainty of index development and climate change scenarios.

2. Methodology

2.1. Procedure of index-based watershed management framework

This study developed a systematic, nine-step process to organize an integrated approach to watershed planning and management as shown in Fig. 1. This procedure can be divided into two parts of management alternative development and analysis. While the first six steps for alterative development combined our past studies (Lee and Chung, 2007; Chung and Lee, 2009a,b; Chung et al., 2011a,b), the last three of nine steps for alternative analysis were newly developed to include the impact of climate change.

The first part of Steps 1 to 6 develops all feasible alternatives with simple assessments. Step 1 is to understand the watershed components and processes. It includes water quantity/quality monitoring and simulation as well as the estimation of annual pollutant loads from unit loads of all land uses. Step 2 is to identify and rank the problems for sub-watersheds. It quantifies the watershed vulnerability, which consists of potential streamflow depletion (PSD) and potential water quality deterioration (PWQD). All indicators are constructed based on the sustainability concept of Pressure-State-Response (PSR; OECD, 1993) framework. All weights are determined with conducting a survey. PSDs and PWQDs of all sub-watersheds are calculated by using Weighted Sum Method (WSM), the most conventional MCDA method. In Step 3, the residents' preferences with regard to management objectives, which are the prevention of streamflow depletion and water quality enhancement, are quantified. The watershed evaluation index (WEI) that represents the comprehensive watershed vulnerability, can be calculated using PSD, PWQD, and the residents' preferences. In Step 4, the specific goals and quantitative objectives are set according to the results from Steps 2 and 3. The objectives are set to minimally maintain the environmental flow requirement (EFR) and maintain the total maximum daily load (TMDL). Step 5 is to investigate general and creative alternatives and develop a list of suitable options, and Step 6 is to eliminate the infeasible alternatives according to technical, economical, and environmental criteria.

The part two of Steps 7 to 9 assesses all management options in details. Step 7 analyzes the effectiveness of all feasible strategies using a continuous rainfall runoff simulation model under climate change scenarios. The criteria for water quantity are derived from the changed Q_{275} and Q_{355} (drought and low flows) and the changed number of days to satisfy the EFR due to the alternatives. The criteria for water quality are proposed as the change in average BOD concentration and the total daily loads, as well as the number of days needed to satisfy the target water quality. Step 8 involves the calculation of alternative evaluation index (AEI) using MCDA approaches of WSM and TOPSIS. The indicators of AEI are constructed based on the sustainability concept of the Drivers-Pressure-State-Impact-Response (DPSIR; Smeets and Weterings, 1999). As shown in the arrows beside the procedure of Fig. 1, the output of step 2, 3, 4, 6 and 7 are used to calculate all AEIs. That is, values of PSD and PWQD in step 2, weights from residents in step 3, EFRs and TMDLs in step 4, selected alternatives in step 6 and their hydrologic effectiveness in step 7 were combined in step 8. Step 9 is to select the best management options based on a minmax regret strategy for the robust alternative prioritization.

2.2. Indicators of sustainable development (ISDs)

ISDs provide a tool for guiding sustainability policies including monitoring of measures and their results, and communication to the public at large (Spangenberg et al., 2002). ISDs should provide hard quantitative data to ensure a sound basis for both environmental and economic policy in the future. In addition, sustainable development planning must be based on environmental and biophysical baseline indices that effectively define comparative development potential and environmental constraints (Schultink, 2000). Therefore, ISDs can be used to improve multi-objective environmental decision making under conditions of unknown variability (Levy et al., 2000).

Monitoring indicators can be grouped in two categories. One measures changes in the status of a system or sub-system over which an organization or several organizations have responsibility, e.g., a watershed. Indicators used in this type of monitoring are