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Short communication

Modeling climate change uncertainties in water resources management models

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ABSTRACT

The impact of climate change on hydrologic design and management of hydrosystems could be one of the important challenges faced by future practicing hydrologists and water resources managers. Many water resources managers currently rely on the historical hydrological data and adaptive real-time operations without consideration of the impact of climate change on major inputs influencing the behavior of hydrologic systems and the operating rules. Issues such as risk, reliability and robustness of water resources systems under different climate change scenarios were addressed in the past. However, water resources management with the decision maker's preferences attached to climate change has never been dealt with. This short paper discusses issues related to impacts of climate change on water resources management and application of a soft-computing approach, fuzzy set theory, for climate-sensitive management of hydrosystems. A real-life case study example is presented to illustrate the applicability of a soft-computing approach for handling the decision maker's preferences in accepting or rejecting the magnitude and direction of climate change.

1. Introduction

The impact of climate change and climate variability on several hydrologic regimes throughout the world and on water resources management is discussed in several works (Dam, 1999; Frederick, 2002; IPCC, 2007; Brekke et al., 2009) published till date. Main conclusions, however inconclusive they are at times, derived from these works indicate that predicted changes will influence the hydrologic cycle in one form or the other. General consensus from these studies is that feed back mechanisms within climate are not properly understood to make accurate predictions of impacts of climate change on hydrologic regimes. Predictions discussed in the intergovernmental panel on climate change (IPCC, 2007) reports indicate that earth may experience a rise of 1–3.5 °C in global surface temperature and changes in spatial and temporal patterns of precipitation. Potential impacts of climate change on runoff mechanisms are also documented in several works (IPCC, 1992, 1995, 2001, 2007) that suggest future climate change will involve greater extremes of weather, including more high intensity rainfall events or decreased streamflow conditions. Insufficient hydrologic record lengths, natural variability blended with anthropogenic induced changes, inconclusive results from climate change studies, and the effect of future climatic changes on the hydrologic design and water resources management, are all major issues to be addressed by all future practicing hydrologists and water resources managers.

Despite considerable efforts that have been undertaken in research and modeling climate change, the results are still highly uncertain, for a number of reasons, ranging from shortcomings and capabilities of general circulation models (GCMs) to the different coupling methods used at different levels of scales in integration of GCMs and hydrologic models. However, researchers suggest that water resources managers may continue to rely on scientists' 'best estimates' of future climate change for any long-term planning and will have to await the anticipated improvements in models and methodologies to obtain better estimates (Leavesley, 1999). A level of uncertainty and distrust associated with the conclusions related to climate change from many of these works prevail among practicing hydrologists and water resources managers. Substantial uncertainty remains in trends of hydrological variables because of large regional differences, gaps in spatial coverage and temporal limitations of data (Huntington, 2006). Stainforth et al. (2007) discussed uncertainty in the models, model forcing, and initial conditions. Studies by Murphy et al. (2004), Tebaldi and Knutti (2007) and Dettinger (2005) have attempted to derive future climate probability distributions from climate projections to characterize uncertainty associated with climate change information. Increasing amount of literature and studies related to climate change is getting slow attention and there is cautious reluctance in accepting the possible climate change scenarios. Many earlier studies focusing on impacts of climate change (e.g. Bogardi and

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Kundzewicz, 2002; Thomas and Bates, 2002; Shreshtha, 2002) discuss criteria for understanding risk, reliability and robustness of water resource systems considering future climate change scenarios, and fall short of discussing the consequences of preferences or beliefs of resource managers attached to climate change that influence water resources management.

Leiserowitz (2006) indicates that risk perceptions associated to climate change are strongly influenced by experiential factors, including affect, imagery, and values, and demonstrate responses to climate change are influenced by both psychological and socio-cultural factors. While the water resources management agencies and decision makers acknowledge the limitations of the climate change models, their perceptions towards the accuracy of results from these models are generally translated to preferences to predicted future changes to the main hydrological inputs. To address hydrological uncertainties associated with stochastic hydrological inputs a general-purpose scenario-modeling framework to solve water system optimization problems was presented recently by Pallottino et al. (2005). The main objective of this short communication is to discuss issues related to the influence of climate change on water resources management. A soft-computing approach, fuzzy set theory (Zadeh, 1965), for handling the preferences attached by the decision makers to magnitude and direction of climate change in water resources management models is discussed. A case study of a multi-purpose reservoir operation is used to address above issues within an optimization framework.

2. Fuzzy set-based reservoir operation model

A fuzzy linear programming (FLP) formulation is proposed for solving a reservoir operation problem and also to address the preferences attached to the direction and magnitude of climate change by the reservoir managers or decision makers. No specific GCM-based scenario directly linked to the case study area is used but an overall reduction in streamflows is considered following the conclusions of a climate change study (Mulholland and Sale, 2002) conducted for southeastern part of the U.S. To demonstrate the utility of FLP model in the current context, a short-term operation model is developed for Green Reservoir, Kentucky, U.S.A. The primary objective of the reservoir is flood control in the Green River basin as well as in the downstream areas of the Ohio River. Secondary objectives include recreation and low flow augmentation. An optimization model formulation is developed and solved to fulfill these objectives.

The original FLP formulation (Teegavarapu and Simonovic, 1999) that uses piecewise linearized non-linear loss (penalty) function defined for storage and release is modified for this purpose. The penalty or loss function, and the penalty values (monetary points) used in this study and within the optimization formulation are shown in Fig. 1. Higher penalty values are assigned for storage once the value of storage in any time interval is above the maximum storage (i.e., 892.02×10^6 m^3) or below the ideal target value (i.e., 200.99×10^6 m^3). Considering the recreational benefits and flood protection objectives, the reservoir level was maintained high in the summer (reducing releases) and lowered in winter (increasing releases). The penalty values provided in Fig. 1 are for winter months. Ideal target storage values are emphasized through penalty values to accommodate late winter flows into the reservoir due to spring runoff. The inflow scheme for the time periods for which optimal operation rules are required is known. The objective is to minimize the sum of under-achievements or over-achievements (reflected in penalty values) in meeting the storage and release target requirements over a specific time horizon with time interval of one day. Constraints are defined for release and storage zones using upper and lower bounds of these variables along with the best possible target values. Fuzzy constraints are developed for inflows and the problem formulation (original) is solved first, then revised and re-solved twice (intermediate and final) to handle the preferences. The penalty values for storage and release zones, and details of the case study can be obtained from earlier work by Can and Houck (1984). Due to space limitations associated with this short communication, complete presentation of fuzzy mathematical programming formulations is avoided.

3. Fuzzy membership functions

Membership functions are generally defined on fuzzy sets to describe the degrees of truth on a scale [0–1] for a physical quantity or a linguistic variable. The scale is used to characterize the uncertainty or vagueness associated with the definition of the variable as perceived by humans. Fuzzy membership functions (Zadeh, 1965; Zimmermann, 1987) are used to model the preferences of the decision maker's or reservoir managers preferences attached to possible variations in hydrologic inputs due to climate change. Membership functions for such preferences are shown in the Fig. 2 for streamflow range [β°, β] and objective function values [θ°, θ]. Functions in the Fig. 2 indicate higher preference to lower original objective function value (overall penalty value) θ, and similar preference to low value of streamflows, β°. The nature of the function suggests the decision maker is more certain about the future reduction in inflow values and therefore increasing preference is attached. The linear membership functions adopted in the current study are used to illustrate the applicability of fuzzy sets in uncertain decision making environment. Although they are conceptually simple and comprehensible, non-linear membership functions can be derived using actual surveys (Fontane et al., 1997). Derivation of non-linear membership functions along with their appropriateness to different management problems are discussed by Cox (1999). Practical methods to derive membership functions are discussed in an earlier work by Teegavarapu and Simonovic (1999). Teegavarapu and Elshorbagy (2005) discussed the development and use of membership functions for hydrologic model evaluation. Excellent review of development of fuzzy membership function and aggregation operators was provided by Despic and Simonovic (2000). In general, sigmoidal or "s" shaped functions are more appropriate to define smooth transitions in the degree of importance (Zimmermann, 1987).

The use of FLP in developing the compromise operating policies is illustrated by using an experiment in which a 15% decrease in the daily streamflow values is considered for the operation period. The exact value of percentage decrease in streamflow values is not derived from any specific GCM-based simulation. An arbitrary value of 15% is fixed based on general agreement related to reduction of runoff in southeastern part of the U.S. (Mulholland and Sale, 2002) considering a special case of doubled CO_2 alone. The assumption regarding the reduction of inflows is appropriate as the case study area is located in southeastern part of the U.S. Three formulations, original, intermediate and final are required for solution of FLP model. The original formulation is solved for normal conditions (constraints and objective function) and the intermediate formulation is solved for increased/decreased values of variables (e.g. inflows). The final formulation is the fuzzy optimization model that considers the membership functions for variables and the objective function. The final formulation provides the compromise solution based on fuzzy constraints relevant to decrease in inflow values with an objective of maximizing the overall membership value. More details of these three formulations are available else where (Teegavarapu and Simonovic, 1999).

The final formulation provides the compromise solution based on fuzzy constraints relevant to preferences attached to inflow decrease. The solution of the FLP formulation yields three objective

Storage zone (10^6 m^3)	Penalty Points/(10^6 m^3)	Release zone (10^6 m^3)	Penalty Points/(10^6 m^3)
190.00	5000	1.50	10
200.99	1	2.50	0.1
200.99	Target	2.5	Target
220.00	50	7.00	150
893.58	800	9.79	900
1507.09	15000	14.67	2000

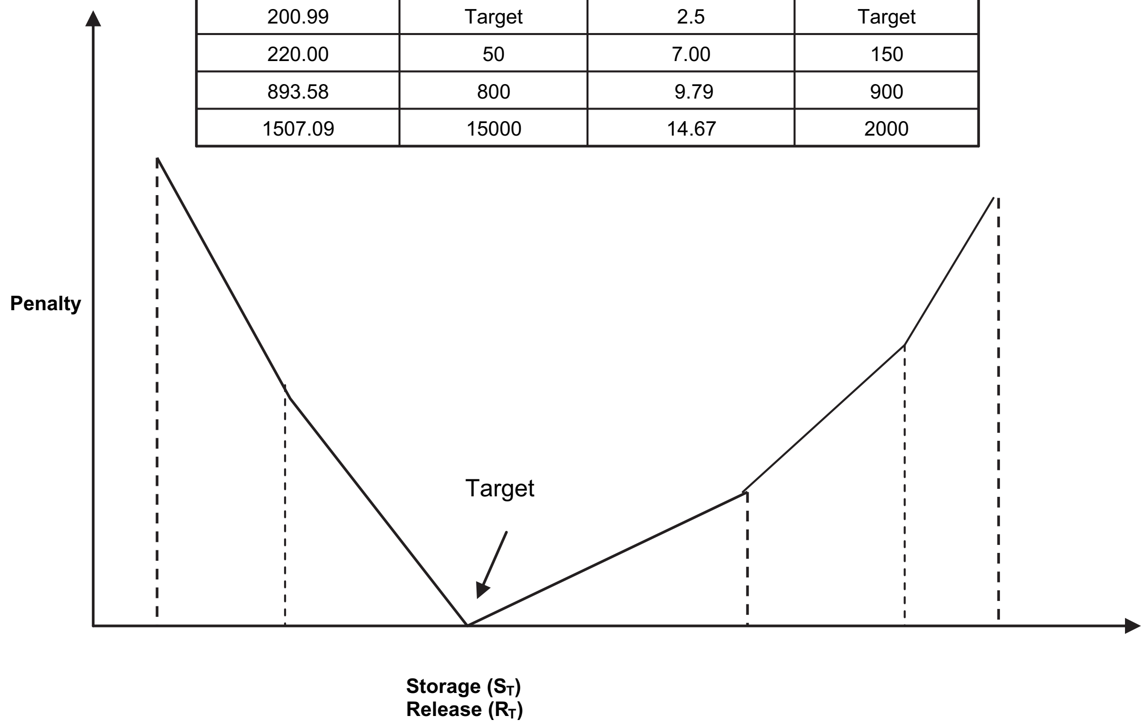

Fig. 1. Linearlized penalty function for storage or release and associated penalty values.

function values, 108.56 (θ°), 122.19 (θ) and 113.86 points/10^6 m^3, and corresponding operating rules. A decrease in the inflow values increases the penalty function (objective) value as less water is available for release and to meet storage and release targets. This is reflected in the higher value of objective function from the intermediate formulation when the inflow values are decreased. In the final formulation the objective function value obtained is in between that of the initial and intermediate formulations suggesting that a compromise is achieved based on the conflicting nature of membership functions. The release and storage variations based on three different formulations are shown in the Fig. 3a and b, respectively. It is evident from these figures that release values are reduced to achieve the storage target as the penalty values for under achieving and over achieving storage target are higher than those associated with release target.

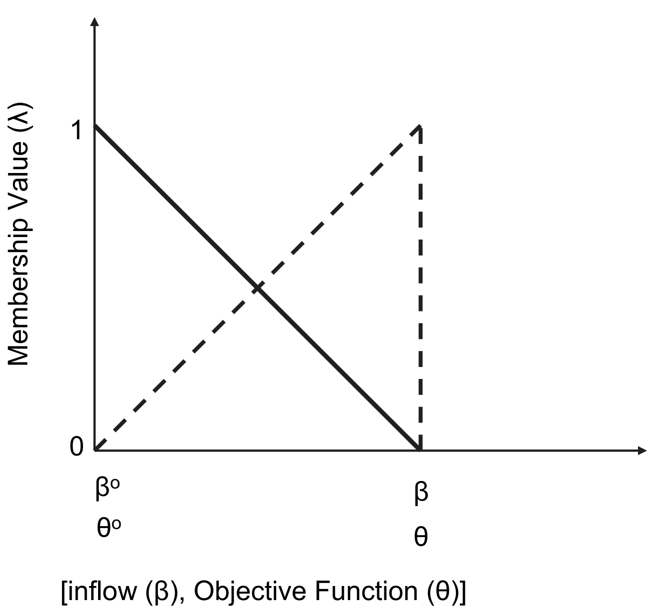

Fig. 2. Membership functions for flow range [β°, β] and objective function [θ°, θ].

The final membership function value (the level of satisfaction) obtained from the final formulation is 0.63, with a maximum possible value being equal to 1. The final membership value reflects a compromise based on conflicting behavior of the objective function value which is being minimized and the membership function for inflow variable with higher preference attached to lower than original values. The membership function for inflow variables increases the penalty value. Any value of final membership function value between 0 and 1 does not necessarily indicate that the final results relevant to storages and releases will lie between the results from intermediate and original formulations. It is important to note that improved solutions (objective function values) are not always possible using fuzzy optimization formulations. The solutions obtained are appropriate for stipulations imposed on constraints and are sensitive to decision maker's preferences defined via membership functions.

It can be concluded from the variations observed in storage and release from original values that the reservoir operating rules are sensitive to decision maker's preferences attached with the magnitude and direction of climate change. Sensitivity analysis of operation rules for a variety of conditions is not equivalent to what is achieved by the fuzzy optimization model discussed in this paper.

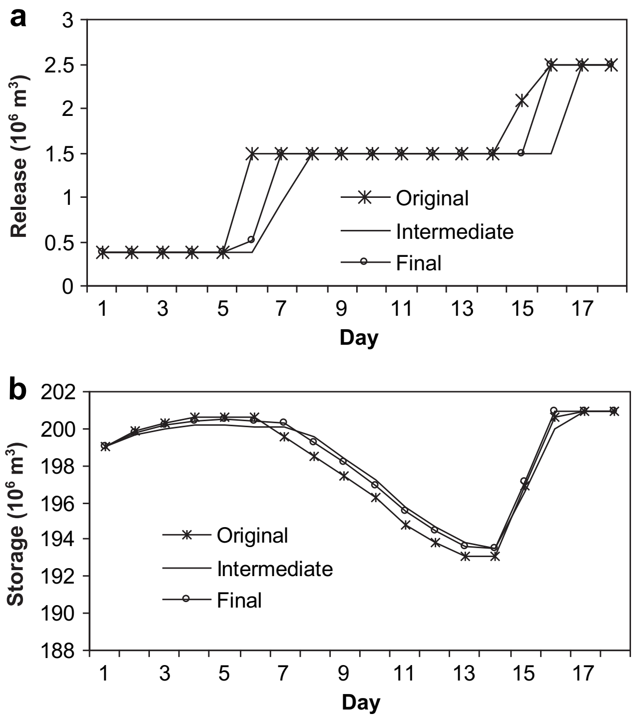

Fig. 3. Release and storage changes considering the decreased inflow scenario for three different formulations: original, intermediate (tolerances added to constraints) and final (fuzzy constraints).

A major limitation of traditional sensitivity analysis approach is the inability to handle the preferences. Conflicting nature of the fuzzy constraints dealing with inflow values or zones, and the objective (monetary units), is captured in this fuzzy optimization framework.

4. Climate sensitive management of water resources systems

A number of recommendations can be made to handle the issues related to climate change in management models. General consensus among modelers and water resources management personnel is needed to agree on and to utilize the results from several climate change studies/investigations that use a wide variety of methodologies and a range of assumptions, regarding the magnitude and direction of the change. Conceptually acceptable practical approaches (Teegavarapu and Simonovic, 2002) should be devised to model the decision maker/resource manager's preferences in accepting the magnitude and direction of climate change within the framework of management models.

Compromise operating policies and water resource management models that are climate-sensitive should be devised based on long-term effects of climate change on major hydrologic processes that influence the quantity and frequency of major inputs to the hydrosystems. Sustainable operation of hydrosystems based on short-term and long-term policies must be derived. The long-term policies can be easily derived based on operations of the systems using new hydrologic inputs derived based on climate change scenarios. Through the case study example discussed in this paper and the recommendations provided, the author intends to motivate the water resources community and practising hydrologists to look into soft-computing modeling approaches such as fuzzy set theory for handling the human perceptions associated with future climate change in operational models. Sensitivity analyses based on different climate change scenarios can only inform the risks associated with operation of water resource systems. However, operating rules that are derived based on preferences of water resources managers are more indicative of how the future changes are perceived by the managers.

5. Conclusions

This short paper highlights several issues related to climate change and its impact on water resource management and addresses a few by providing methodologies that can help to deal with climate change in water resources management models. Climate-sensitive compromise operating policies for hydrosystems are derived by considering predicted magnitude and direction of climate change along with the decision maker's/resource manager's preferences attached to those changes in a fuzzy mathematical programming framework. Few recommendations are made in regard to development of sustainable operating policies generated by a compromise between short-term and long-term operating policies. Fuzzy operational model proposed, developed and explained in this paper would help the decision makers to explicitly include their degree of belief or acceptance associated with climate change predictions and processes.

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