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Spatial probabilistic multi-criteria decision making for assessment of flood management alternatives

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SUMMARY

Flood management alternatives are often evaluated on the basis of flood parameters such as depth and velocity. As these parameters are uncertain, so is the evaluation of the alternatives. It is thus important to incorporate the uncertainty of flood parameters into the decision making frameworks. *This research develops a spatial probabilistic multi-criteria decision making (SPMCDM) framework to demonstrate the impact of the design rainfall uncertainty on evaluation of flood management alternatives.* The framework employs a probabilistic rainfall–runoff transformation model, a two-dimensional flood model and a spatial MCDM technique. Thereby, the uncertainty of decision making can be determined alongside the best alternative. A probability-based map is produced to show the discrete probability distribution function (PDF) of selecting each competing alternative. Overall the best at each grid cell is the alternative with the mode parameter of this PDF. This framework is demonstrated on the Swannanoa River watershed in North Carolina, USA and its results are compared to those of deterministic approach. While the deterministic framework fails to provide the uncertainty of selecting an alternative, the SPMCDM framework showed that in overall, selection of flood management alternatives in the watershed is "moderately uncertain". Moreover, three comparison metrics, *F* fit measure, κ statistic, and Spearman rank correlation coefficient (ρ), are computed to compare the results of these two approaches. An *F* fit measure of 62.6%, κ statistic of 15.4–45.0%, and spatial mean ρ value of 0.48, imply a significant difference in decision making by incorporating the design rainfall uncertainty through the presented SPMCDM framework. The SPMCDM framework can help decision makers to understand the uncertainty in selection of flood management alternatives.

1. Introduction

Flood management is complex and multifaceted, affected by different factors, involving various stakeholders, competing alternatives and different tradeoffs (Levy et al., 2007; Hall and Solomatine, 2008; Schröter et al., 2014). Under these circumstances, multi-criteria decision making (MCDM) can assist flood management by providing a systematic framework to deal with such complex problems. Several MCDM techniques with different capacities can be identified based on the literature. There has been a vast application of various MCDM techniques in different categories of flood management such as flood risk mapping (Sinha et al., 2008; Meyer et al., 2009; Y.R. Chen et al., 2011; Zou et al., 2012), flood hazard zoning (Fernandez and Lutz, 2010; Kourgialas and Karatzas, 2012; Stefanidis and Stathis, 2013; Radmehr and Araghinejad, 2014; Papaioannou et al., 2015; Rahmati et al., 2015), flood risk assessment (Lee et al., 2015; Malekian and Azarnivand, 2015), flood vulnerability analysis (Radmehr and Araghinejad, 2015), site selection of flood mitigation measures (Ahmadisharaf et al., 2015b), prioritization of flood mitigation strategies (Willette and Sharda, 1991; Bana E Costa et al., 2004; Levy, 2005; Chitsaz and Banihabib, 2015) and integrated assessment of long-term flood management scenarios (Brouwer and van Ek, 2004). Main reason of applying MCDM for flood management is the inherent complexity and multidisciplinarity, and the capability of MCDM techniques to structure such a multifaceted problem into a simple quantifiable format.

Flood management should be considered a spatial problem because flood intensities and characteristics vary with geographic location (Foudi et al., 2015). There has been a growing interest in coupling GIS with MCDM techniques due to the capabilities of GIS in handling wide range of criteria data from different sources (Chen et al., 2010). Conventional flood management decision making does not account for the spatial variability of the evaluation criteria (Qi et al., 2013). Consequently, the selected alternative might

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not be necessarily the best option for all locations within the region (Tkach and Simonovic, 1997). In other words, while some areas may benefit from implementing an alternative, that measure might aggravate the flood status in other locations. Using spatial MCDM (SMCDM) is more desirable as it enables decision makers (DMs) to account for the spatial variability of flood characteristics, namely, depth, velocity and duration. Considering the needs for spatial dimension of flood management problems, this study uses Spatial Compromise Programming (SCP) (Tkach and Simonovic, 1997), to evaluate a pool of flood management alternatives on a cell-by-cell basis.

Evaluation of flood management alternatives relies on flood parameters. The flood parameters are produced by integrating hydrologic and hydraulic models. Both these models are associated with uncertainty, which causes the prioritization of alternatives be highly risky if the model parameters are not fixed. In hydrologic modeling, uncertainty in prediction of hydrograph arises from calibration\validation data, model structure and parameters as well as input variables (Krzysztofowicz and Kelly, 2000; Krzysztofowicz and Herr, 2001; McMillan et al., 2010). One of the primary inputs in the hydrologic models is rainfall. The rainfall dataset is obtained directly from measurement or by statistically analyzing the rainfall records. The latter is the commonly used approach to determine a design storm, in which rainfall depth is assigned a return period by fitting a suitable probability distribution function (PDF). As the inferred design storm through this statistical procedure is subject to uncertainty, so are the generated hydrographs. These hydrographs feed to hydraulic models, which causes the uncertainty to be propagated through these models. As a result, the produced flood parameters are associated with uncertainty (Kalyanapu et al., 2012). In addition to this source of uncertainty, uncertainty in hydraulic modeling might come from model structure and parameters, observed data, digital elevation model (DEM), land use and soil data as well as choice of performance measures (Pappenberger et al., 2006; Smemoe et al., 2007; Merwade et al., 2008; Aronica et al., 2012; Bhuyian et al., 2015). Probabilistic methods can be used to incorporate this uncertainty into both hydrologic and hydraulic models (Di Baldassarre et al., 2010). One concern about using probabilistic approach is the high computational time needed by hydraulic models (in particular, multi-dimensional models) to perform the routing problem for multiple hydrographs. However, recent advances in computational capabilities of flood models with tremendous speedup (e.g., Flood2D-GPU by Kalyanapu et al. (2011)) can assist modelers in efficiently using probabilistic-based analyses. Due to these advances, decision making needs to be improved by incorporating probabilistic frameworks.

The uncertainty in a MCDM may stem from selection of the criteria as well as criteria weights and values (Hyde et al., 2003, 2004; Ascough et al., 2008; Chen et al., 2010; Ahmadisharaf et al., 2015a). Most of the studies in the area of flood management have incorporated the uncertainty of criteria weights through sensitivity analysis (B.S. Kang et al., 2013) and considered the uncertainty of performance values by using fuzzy methods (Lee et al., 2013; Kim and Chung, 2014; Kim et al., 2015). However, probabilistic approach using all plausible performance values has not received any attention yet. Rational decision making requires that the uncertainty of hydrologic predictions being quantified in terms of PDFs, which is the most perfect uncertainty description method (Tung, 2011), subject to the available information and knowledge (Krzysztofowicz, 1999). Probabilistic hydrologic predictions are more favorable as they are scientifically more reliable, enabling rational decision making (Krzysztofowicz, 2001). Edjossan-Sossou et al. (2014) stated that it is critical to adequately analyze uncertainty and examine its influences to improve the decision making. Madani and Lund (2011) recommended use of more rigorous approaches to inform the DM about the impacts of the uncertainty on prioritizing the alternatives. Mosadeghi et al. (2013) highlighted the need for integrating simulation algorithms such as Monte Carlo (MC) method into SMCDM in order to analyze the influences of uncertainty. Pappenberger et al. (2013) and Ronco et al. (2014) emphasized that the uncertainties attributed to predicted flood risks must be clearly communicated to the DMs. Nevertheless, the DMs are often poorly served with information about the impacts of uncertainty on flood management decisions (Pappenberger and Beven, 2006; Rosner et al., 2014).

Therefore, the objective of this paper is to develop a spatial probabilistic MCDM (SPMCDM) framework to prioritize the flood management alternatives considering the impact of the design rainfall depth uncertainty. The unique aspect of this study is to present uncertainty level to the decisions on prioritization of flood management alternatives by using the developed SPMCDM framework. This framework is illustrated on the Swannanoa River watershed in North Carolina, USA. The remaining of this paper is organized as follows: Section 2 describes the methodology that is used to develop the SPMCDM framework; Section 3 introduces the case study to demonstrate the developed framework; Section 4 discusses the case study results, including analysis of the impacts of design rainfall uncertainty on decision making by comparison of deterministic and probabilistic frameworks; and Section 5 provides a summary of the framework development and the study implications.

2. Methodology

The developed SPMCDM framework contains three modules as shown in Fig. 1: (1) Probabilistic hydrologic modeling; (2) Hydraulic modeling; and (3) SMCDM. In the first module, a probabilistic hydrologic model is employed to simulate rainfall–runoff transformation process. In the second module, a flood model named Flood2D-GPU is applied to model subsequent flood. In the third module, SCP is used to prioritize multiple flood management alternatives.

2.1. Probabilistic hydrologic modeling module

A probabilistic continuous semi-distributed conceptual hydrologic model is developed in GoldSim® environment. GoldSim® is a dynamic simulation software with applications ranging from water resources management to financial predictions, and provides a versatile user-friendly graphical user interface (GUI) for probabilistic modeling. The model takes rainfall time series in tandem with the characteristics of river cross sections and subwatersheds as input variables and generates the flow hydrograph at subwatersheds' outlets and different locations of the river. It accounts for the spatial variability of rainfall, topography, soil characteristics and land use by dividing the study watershed into multiple subwatersheds. The Snyder's method (Snyder, 1938), Soil Conservation Service (SCS) infiltration method (Natural Resources Conservation Service (NRCS), 1986) and Muskingum technique are used to develop the unit hydrograph, to simulate rainfall–runoff transformation process and to perform channel routing, respectively. In addition to reaches and subwatersheds, reservoirs can be also included in the simulations. The model uses level pool routing to route the flow through the reservoirs. Reservoir stage-storage-discharge table and evapotranspiration rate must be entered by the user for reservoir computations. It is to be mentioned that groundwater processes are not taken into account in the model. The deterministic model has been successfully applied in previous studies such as Ahmadisharaf et al. (2015a) for hydrologic modeling and Ahmadisharaf and Kalyanapu (2015) for channel routing.

The probabilistic hydrologic model is developed by extending a deterministic model to probabilistic. For doing so, any desired input can be characterized through a PDF. The probabilistic model