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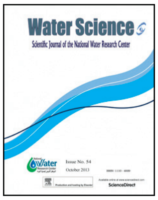

Research Article

Risk-based quantification of the impact of climate change on storm water infrastructure

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Abstract

Storm water detention ponds are usually designed to store-and-release the runoff of extreme rainfall events based on a selected return period, e.g., 100 years. The design storm is typically a recorded historical event or one that is extracted from historical intensity–duration–frequency (IDF) curves. In essence, the selected storm and the resulting design are deterministic. In this research, the inevitable natural weather variability and its impact on the uncertainty of extreme events are simulated and quantified. This study builds on the results of a previous study where a stochastic weather generator, LARS-WG, was used to generate an ensemble of series with a 30-year length of hourly rainfall in the city of Saskatoon, Canada, based on the statistical properties of historical rainfall. Here, the most critical day (24-h rainfall) of each of the series is identified as a possible realization of the design storm. The runoff of each realization of the storm events is routed to a storm water pond in Saskatoon using the XPSWMM model. The critical runoff volume collected in the pond throughout the 24-h duration is also identified. Empirical probability distributions are fitted to the critical values of runoff volumes collected in the pond and compared with the current design storage. Exceedance probabilities and expected flood risk are estimated from the probability distributions for the baseline period (1960–1990), as well as under three projected future (2014–2100) scenarios of climate change (RCP 2.6, 4.5, and 8.5). Along with the magnitude of expected risk, this method provides the probability of the infrastructure's failure due to uncertainty. The proposed risk-based approach presented in this study provides a way for municipalities to quantify the risk associated with their selected design values and for tangible and meaningful interpretation of the risks that projected climate change might pose on storm water infrastructure. The main finding of this study is that the distribution of rain throughout the storm event may play a more important role than the total rainfall depth when water ponding/flooding is the major concern. It is further concluded that risk analysis must be tailored to the type of infrastructure under consideration.

Keywords: Extreme rainfall events; Detention pond; Hydrologic risk; Uncertainty; Climate change

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1. Introduction

The topic of climate change and its potential impacts on our physical environment has been the center of attention for over a decade in water resources literature. The overwhelming attention given to this topic is valid as projected changes in hydrometeorological variables, such as temperature and precipitation, can significantly affect the hydrological cycle and available water resources (Piao et al., 2010; Arnell, 1999), water demand (Doll, 2002; Grouillet et al., 2015), landuse (Wheeler and Braun, 2013; Hanewinkel et al., 2013), risk of extreme events (Coumou and Rahmstorf, 2012; Shahabul Alam and Elshorbagy, 2015; Cai et al., 2014; Monier and Gao, 2015), food security (Gregory et al., 2005; Schmidhuber and Tubiello, 2007), and the viability of water infrastructure. The hydrometeorological research community has made significant strides in the direction of quantifying possible climate change impacts on precipitation (Rudolph et al., 2012; Rana et al., 2014), streamflow (Yang et al., 2014), temperature (Lauri et al., 2012), reservoir operation (Raje and Mujumdar, 2010), flood risks (Veijalainen et al., 2010), and droughts (Jenkins and Warren, 2015).

In many studies, as is often the case in hydrology, surrogates are used to quantify and assess the impacts of climate change. For example, changes in the amount of streamflow is considered to represent water availability (Hassanzadeh et al., 2015). However, the complexity of water resource systems and the interactions among water supply, demand, and policy make the mere changes in streamflow too simplistic as a representation of water shortage. Similarly, progress has been made to estimate the impacts of climate change on the intensity–duration–frequency (IDF) curves and design storms in various regions (Olsson et al., 2012; Rodríguez et al., 2014; Shahabul Alam and Elshorbagy, 2015; Kuo et al., 2014; Srivastav et al., 2014; Hassanzadeh et al., 2014a). However, this alone leaves municipalities with unanswered questions regarding the translation of the estimated change (e.g., 15% increase in extreme rainfall) to the urban storm water management infrastructure and its temporal storage capacity. The manner in which the storm is distributed over time, the runoff routing to detention or retention ponds, and the store-and-release mechanism of the storage facility can absorb or amplify the projected change in the rainfall amount. Until such issues are addressed, it is difficult to convince decision makers of the “real” impacts of climate change on water resource systems and infrastructure.

An example of progress in the direction of quantifying the real impacts of climate change on stakeholders is the use of hydro-economic models to assess the economic impacts of climate change and water shortage on society (Harou et al., 2009; Hassanzadeh et al., 2014b; George et al., 2011; Varela-Ortega et al., 2011). This is achieved through propagating the change of climate on hydrology using a series of models to downscale the climate change effect, predict the effects on streamflow, and use the predicted flows as boundary conditions in hydro-economic water allocation models to estimate the economic effects of shortage on various water users. The outputs of such models are useful for both policy and decision makers, who rely on socioeconomic values for their tradeoff analysis and high level decision making, and utility managers who can assess risks and manage infrastructure assets.

This paper focuses on the effect of storms on small urban watersheds and one of its major storm water infrastructure — detention ponds. The objectives of this paper are to (i) quantify extreme runoff as the variable of interest for storm water ponds, rather than rainfall, along with its uncertainty that stems from natural weather variability; and to (ii) quantify the magnitude of flood risk due to insufficiency of storage capacity, along with the probability of the pond’s failure in meeting its urban flood objectives. The analysis is performed under historical and projected climate change scenarios. The proposed work aims at producing a risk-based framework for evaluating urban water infrastructure and the associated risk of failure.

2. Analysis of the major system of storm water infrastructure

Storm water detention ponds are a popular storm water management practice in many communities (Goff and Gentry, 2006). Their main function is to make the slopes of the outflow hydrographs in the rising and recession segments smoother than those without detention ponds (Chen et al., 2007). Meanwhile, the shape of the peak becomes flatter if a detention pond is installed. Such a function modifies the runoff flowing further downstream through the storm sewer network and receiving rivers. Decades ago, engineers realized that detention ponds designed for a particular return period, e.g., 100-year storm, may have very little effect on the peak flow reduction of even smaller return periods; e.g., 10-year storms (Whippel and Randall, 1983). This was later addressed by considering multiple return periods for the design and analysis of ponds (Akan, 1989). Earlier research placed emphasis on the routing process and the pond’s ability to reduce the outflow peak. The role of storm water ponds in controlling pollution was also considered in

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