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Evaluation of adaptation options to flood risk in a probabilistic framework

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ABSTRACT

Study region: City of Niamey, Niger, West Africa.
Study focus: This paper aims to explore the possibility of implementing a probabilistic framework for flood risk estimation for the city of Niamey, Niger. A probabilistic set of flood maps were generated by forcing a HEC-RAS model with a stochastically generated ensemble of flood peaks representing the river regime at Niamey. Loss curves were derived from expert judgment, and various adaptation options to flood risk were examined by considering two main variables: a) buildings' material; b) dike height (ranged from 180.5 m to 184 m, at a 0.5 m interval) within a scenario-based framework. Floods with return periods of 2- to 1000-yr were considered in estimating total loss, and benefits and costs of different adaptation options were compared.
New hydrological insights for the region: It was found that increasing the height of the dikes would lead to smaller economic losses, while rebuilding with better materials would increase the average annual economic losses, but might decrease the risk of human casualties. Individual and combined impact of decision variables on flood risk were estimated for the city of Niamey. Quantitative tools were developed to help decision-makers and regulators choose the best preventive measures to mitigate flood risk.

1. Introduction

Flood could affect our environment and, in most of vulnerable areas of the world, may cause damages including loss of human life; damage to property and crop; interruption to transportation and utility services; and other damages arisen from economic activity disruption. The number of people who could be affected by flood is reported to be more than all the other natural hazards together (Asian Disaster Reduction Center, 2011); one reason could be the increasing trend of flooding over the last 30 years (Freer et al., 2013). Moreover, floods, which last for several days, endanger affected people to exposure to water-borne and vector-borne diseases, which could lead to death. At some regions along the river bed, sediment deposits could significantly reduce the flood passage capacity of the river, hence increase the amount of the area in the vicinity of the river which could be inundated in case of flooding. Two main categories of flood damages are identified as tangible and intangible damages. Tangible flood damages could be estimated and expressed in monetary value and are further classified as direct (caused by direct contact of floodwater) and indirect types. Both direct and indirect damages are subdivided into primary and secondary damages (Dutta et al., 2003). Intangible damages

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(direct or indirect) cannot be directly assessed or measured in monetary values, mainly due to their subjectivity. Examples of such damages are casualties and health effects. Indirect damages are those caused by disruption to physical and economic linkages such as interruption of traffic flow, and loss of personal income and business profit. To assess these type of damages, a multidisciplinary approach integrating engineering, social science, and economic knowledge should be applied since considering only engineering factors is not sufficient. Therefore, in this study, only direct-tangible losses are being considered.

Risk is defined as the magnitude of a hazard in terms of its frequency and intensity. Accordingly, flood risk analysis, which includes flood hazard mapping, hydraulic structure design, urban drainage system planning, and reservoir management, is a method to quantify flood frequency and its damage. Overall, as the Environmental Agency's Strategy for Flood-Risk Management (Environment Agency, 2003) states, flood risk estimation is to estimate the probability that the safety standard would be exceeded. Flood risk assessments consists of the following main components: a) Flood hazard; b) Exposure; and c) Vulnerability. Flood hazard (i.e. depth, velocity, discharge, and flood frequency), is defined by the probability and magnitude of flooding. Flood hazard assessment estimates the probabilities of different magnitudes of damaging flood conditions, such as the depth and duration of inundation and flow velocity. Different parameters including meteorological, hydrological, hydraulic, and topographic properties of the watershed, channels, and floodplains at upstream and downstream of the location of interest affect the magnitudes for the various probabilities. When flood hazards cause damages to assets, the value of the assets as well as the relationship between the flood hazard and damage to the assets are examined by exposure (i.e. the population and assets located in flood-prone areas) and vulnerability (i.e. the susceptibility of the exposed elements to the hazard) analysis. The results of such analysis may be represented with inundation depth-damage functions for the structures, which predict the damage corresponding to specific water depth.

Increases in loss levels during the recent centuries made the stakeholders and decision-makers to work harder in order to find the scientific approaches to prevent the occurrence of such extreme events and in the areas that the occurrence could not be prevented, to diminish the loss levels as much as possible. The need for flood risk evaluation and assessment is more recognized in flood-prone and vulnerable regions, since the loss level in affected areas is directly proportional to the level of vulnerability and exposure of the area. Growing vulnerability to floods could be related to various economic, social, cultural, political, and environmental drivers. In the case of the current study area, other causal factors of vulnerability could play an important role in diminishing resilience and capacity to cope with and adapt to the extreme events. Some of these factors are lack of any type of early warning system, using low-strength constructional material in the residential areas that are mainly located near the Niger River, and lack of enough disaster recovery and rehabilitation time due to yearly flooding in the region. Through proposing some adaptation options, the main goal of this research is to develop a probabilistic framework in order to evaluate impact of the proposed adaptation options to flood risk in Niamey, the area of interest. It also aims to help decision-makers to contribute to improvements in the ability of Niamey community to better respond in the scenario of any disastrous flooding event.

1.1. Deterministic and probabilistic risk assessment

Risk assessments are being performed using two main approaches: deterministic and probabilistic approaches. Flood risk analysis based on the traditional T-year event (deterministic approach) is used to assess disaster impacts of a given hazard scenario and does not account for the full range of possible floods; therefore provides an incomplete representation of the risk. In deterministic approach, which considers the impact of a single risk scenario, it is not easy to relate the damages of a single flood to the cost of infrastructure for instance. In a probabilistic framework, all possible scenarios, their likelihood and associate impacts are being considered. Probabilistic methods are used to obtain more refined estimates of hazard frequencies and damages; however, probabilistic methods are characterized by inherent uncertainties (because they incorporate the concept of randomness), partly related to the natural randomness of hazards, and partly because of our incomplete understanding and measurement of the hazards, exposure and vulnerability under consideration (OECD, 2012).

Probabilistic Risk Assessment (PRA) has one primary advantage over its deterministic counterpart-it provides the distribution of estimated exposure and risk, which makes it "more realistic" compared to "too conservative" deterministic method. The probabilistic approach has been subject to increasing popularity amongst researchers in recent years as it accommodates for the specification of uncertainty (Apel et al., 2006, 2008; Purvis et al., 2008; Di Baldassarre et al., 2009b, 2010; Neal et al., 2013; Dyck and Willems, 2013; Ganguli and Reddy, 2013; Dale et al., 2014; Jalayer et al., 2014; Shortridge et al., 2017; Tang et al., 2018). In addition to describing uncertainty in the model inputs, probabilistic modelling also provides information on the uncertainty in the model output. Despite the better results of risk assessment using probabilistic approach, complex and specific mathematical calculations in this approach make it more challenging to use. Deterministic modelling, in contrast, whilst ignoring uncertainty, has the pragmatic advantage of simplicity in analysis and results.

Historical losses can explain the past; however, they do not necessarily provide a good guide to the future since most disasters that could happen have not happened yet (UNISDR, 2013). PRA resolves this problem posed by the limits of historical data, through simulating future disasters, which are likely to occur based on scientific evidence (UNISDR, 2015). Therefore, probabilistic flood risk assessment is the subject of various recent projects and has been considered by many others. As an example, Dyck and Willems (2013) developed a probabilistic flood risk assessment methodology to estimate the recurrence rate of flood losses to geographically distributed properties in the large areas where limited information is available. They presented the results of the application of their methodology to river flood loss from residential buildings in Belgium. While considering all the major sources of uncertainty that introduce variation on the flood losses, the methodology simplifies the necessary calculations considerably and estimates the model parameters either directly from general topographic information and historical observations, or on the basis of simulated model results. In another study, Apel et al. (2006), developed complex spatially distributed models representing the relevant meteorological,