Science of the Total Environment 538 (2015) 445–457

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Flood risk and adaptation strategies under climate change and urban expansion: A probabilistic analysis using global data

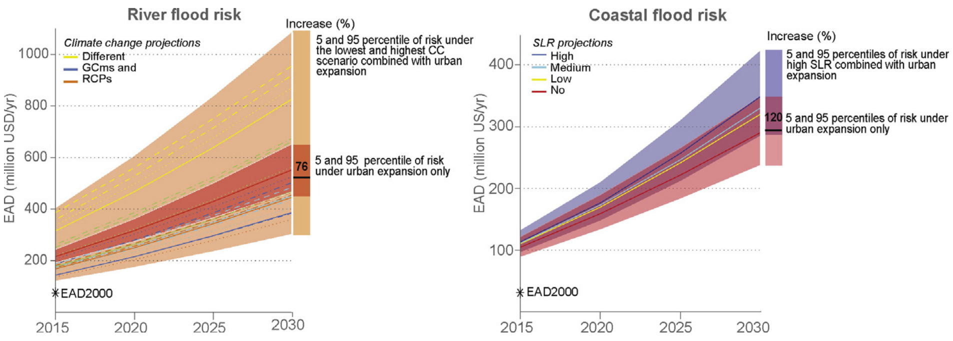
Sanne Muis [a,*], Burak Güneralp [b], Brenden Jongman [a], Jeroen C.J.H. Aerts [a], Philip J. Ward [a]

[a] *Institute for Environmental Studies (IVM), VU University Amsterdam, The Netherlands*
[b] *Department of Geography, Texas A&M University, College Station, USA*

HIGHLIGHTS

- We develop a probabilistic method to assess future flood risk on a country-scale.
- Urban expansion will drive large increases in flood risk in Indonesia.
- Climate change amplifies coastal risk by 19–37%, its impact on river risk is uncertain.
- Adaptation is effective and increasingly urgent, regardless of climate uncertainties.
- Global data is used successfully for a probabilistic risk analysis, including adaptation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 May 2015
Received in revised form 12 August 2015
Accepted 12 August 2015
Available online xxxx

Editor: D. Barcelo

Keywords:
Flood risk
Adaptation
Global modeling
Urbanization
Climate change impacts
Indonesia

ABSTRACT

An accurate understanding of flood risk and its drivers is crucial for effective risk management. Detailed risk projections, including uncertainties, are however rarely available, particularly in developing countries. This paper presents a method that integrates recent advances in global-scale modeling of flood hazard and land change, which enables the probabilistic analysis of future trends in national-scale flood risk. We demonstrate its application to Indonesia. We develop 1000 spatially-explicit projections of urban expansion from 2000 to 2030 that account for uncertainty associated with population and economic growth projections, as well as uncertainty in where urban land change may occur. The projections show that the urban extent increases by 215%–357% (5th and 95th percentiles). Urban expansion is particularly rapid on Java, which accounts for 79% of the national increase. From 2000 to 2030, increases in exposure will elevate flood risk by, on average, 76% and 120% for river and coastal floods. While sea level rise will further increase the exposure-induced trend by 19%–37%, the response of river floods to climate change is highly uncertain. However, as urban expansion is the main driver of future risk, the implementation of adaptation measures is increasingly urgent, regardless of the wide uncertainty in climate projections. Using probabilistic urban projections, we show that spatial planning can be a very effective adaptation strategy. Our study emphasizes that global data can be used successfully for probabilistic risk assessment in data-scarce countries.

---

* Corresponding author at: Institute for Environmental Studies — Instituut voor Milieuvraagstukken (IVM), VU University Amsterdam, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands.
E-mail address: sanne.muis@vu.nl (S. Muis).

http://dx.doi.org/10.1016/j.scitotenv.2015.08.068
0048-9697/© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Over the past decades, urban areas around the world have expanded rapidly (Seto et al., 2011; Angel et al., 2011). According to the latest global projections, the urban population will increase from 2.8 billion in 2000 to 5 billion in 2030 (UN, 2013); and urban land cover will triple from 2000 to 2030 (Seto et al., 2012). Nearly half of the urban expansion is projected to take place in Asia, where some of the world's highest concentrations of people and assets are located in low-lying areas and are highly prone to flooding from rivers and coastal surge (Hallegatte et al., 2013; Jongman et al., 2012; Nicholls and Cazenave, 2010). Major floods can be a key threat to these cities and can cause catastrophic losses with large impacts on national economies.

Global flood risk has been increasing during the last few decades (Bouwer et al., 2007). Hereby, flood risk is defined as the combination of hazard (i.e. the frequency and intensity of floods), 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) (IPCC, 2012; UNISDR, 2011). Several studies show that increasing exposure is the main driver of increasing risk (e.g. Bouwer, 2011; Visser et al., 2014); although recent studies show that reductions in vulnerability in the past decades may have reduced the overall risk, which could mask potential signals of climate change (Jongman et al., 2015; Mechler and Bouwer, 2014). Over the coming decades, flood risk is expected to continue increasing due to socio-economic development and climate change (Visser et al., 2014; IPCC, 2012; UNISDR, 2011). By 2030, 40% (195,000 km^2) of the global urban land is projected to be located in high-frequency flood zones, compared to 30% in 2000 (Güneralp et al., 2015). According to IPCC (2013), global sea levels are likely to rise between 0.26 m and 0.82 m by 2100 relative to 1986–2005, resulting in more severe coastal floods. Studies of global-scale river flood risk project large climate-induced increases over the coming century (Arnell and Lloyd-Hughes, 2014; Hirabayashi et al., 2013).

Increasing global losses demand effective and efficient risk-reducing strategies (Aerts et al., 2014; Brown et al., 2014), whose implementation should be based on an accurate understanding of the drivers of risk (e.g. Jha et al., 2012; Jongman et al., 2014a; Mechler and Bouwer, 2014). This means it is of key importance to integrate both climate and anthropogenic drivers (Kim and Chung, 2014). Future risk projections are characterized by high uncertainty, which is most frequently addressed by using different scenarios. While a scenario-based approach is useful to explore the potential impact of climate change, unlike a probabilistic approach, they provide any quantitative information on the uncertainty to assess the relative risk of particular adaptation actions. In response to the debate on the need for probabilistic climate change scenarios (Pittock et al., 2001; Schneider, 2001, 2002), various studies have focused on quantifying the probabilities of (the impacts of) climate change (e.g. Ward et al., 2013a; Webster et al., 2012; Purvis et al., 2008; New et al., 2007). The uncertainties related to projected socio-economic development have received less attention in the flood risk community, and the few studies that integrate future climate and socio-economic projections are based on discrete scenarios (e.g. Hinkel et al., 2014; Hallegatte et al., 2013; Penning-Rowsell et al., 2013; te Linde et al., 2011).

Probabilistic estimates of current and future risk that include the dynamics of hazard, exposure, and vulnerability are therefore rare (e.g. Aerts et al., 2014). This is especially true for developing countries, where the data needed to conduct such analyses are scarce. With the increasing availability of hydrological datasets with continental to global-coverage and new generations of flood models, several models for assessing flood hazard at the global-scale have been developed in recent years (e.g. Hinkel et al., 2014; Hirabayashi et al., 2013; Winsemius et al., 2013). Although there are constraints due to the relatively low spatial resolution of the data, particularly related to the global elevation datasets available, a major benefit of this development is that it enables large-scale analysis of floods, even in countries where data are scarce. In addition, the increasing availability of land-use and land-cover data at continental- to global-scales (Klein Goldewijk et al., 2011; Schneider et al., 2009) has opened the way for large-scale forecasting of land-change dynamics (Güneralp et al., 2015; Nelson et al., 2010), that include the uncertainties of the underlying drivers (Güneralp and Seto, 2013).

These developments allow for a large-scale assessment of flood risk that integrates future dynamics of hazard and exposure, and includes a quantification of uncertainties. Here, we present a first of its kind country-scale flood risk assessment that integrates these methodological advances, using Indonesia as a case-study. We use probabilistic and spatially-explicit projections of new urban land to 2030, which include the uncertainties in the changes in the population and economy, the two major drivers of urban land change, as well as the uncertainty in where urban land change may occur. These projections are combined with future climate projections of both river and coastal flood hazards. We evaluate the effect of two adaptation strategies: spatial planning in flood-prone areas and enhanced flood protection. This is the first large-scale flood risk analysis that assesses the effectiveness of spatial planning based on probabilistic urban projections. The main aims of this paper are to:

- Develop a methodology based on global data to assess national-scale flood risk under current and future scenarios;
- Develop spatially-explicit and probabilistic projections of urban expansion and river and coastal flood hazard projections from 2000–2030;
- Combine the exposure and hazard projections to assess how projected changes in drivers contribute to future changes in flood risk;
- Assess to what extent spatial planning of new urban areas and enhanced flood protection can offset projected increases in flood risk.

Our case-study is Indonesia, a country that already faces high flood risk, and is undergoing rapid urbanization. While in 2000 about one third of the total population lived in urban areas, by 2010 this had increased to one half (UN, 2014). In addition, catastrophic events occur frequently, for example, wide-spread floods in 2014 resulted in estimated direct damages of ca. USD 400 million (EM-DAT, 2013).

2. Materials and methods

Here, we provide a brief overview of the applied modeling framework (Fig. 1). Details of each step are given in the following paragraphs. In short, a damage model combines the three risk elements (i.e. hazard, exposure, and vulnerability) to compute the Expected Annual Damage (EAD) expressed in million USD/year (e.g. Ward et al., 2011). Unless stated otherwise, all values in this paper are expressed in values of the year 2000 using GDP deflators of the World Bank (2014). By simulating the flood damages associated with certain exceedance probabilities, we can calculate the EAD by estimating the area under an exceedance probability loss curve (i.e. risk curve). The EADs are aggregated on a provincial level.

We use two model cascades to simulate flood hazard; river floods are based on GLOFRIS (Winsemius et al., 2013; Ward et al., 2013b), and coastal floods are based on the DIVA database (Vafeidis et al., 2008). Probabilistic urban projections based on Güneralp and Seto (2013) and Seto et al. (2012) are combined with estimates of economic value per surface area to express economic exposure. Vulnerability is represented by a depth-damage curve taken from Budiyono et al. (2014). We do not include flood protection. There are few empirical data available to estimate protection standards in Indonesia, but generally protection standards can be considered to be low (e.g. Hallegatte et al., 2013; Ward et al., 2010) since damaging floods occur frequently (EM-DAT, 2013; Marfai and King, 2007). Although absolute flood risk estimates are associated with large uncertainties (Apel et al., 2008;