Global Environmental Change 31 (2015) 217–225

Contents lists available at ScienceDirect

Global Environmental Change

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

Changing global patterns of urban exposure to flood and drought hazards

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ARTICLE INFO

Article history:
Received 10 June 2014
Received in revised form 31 December 2014
Accepted 5 January 2015
Available online

Keywords:
Infrastructure
Urbanization
Land change
Sustainability
Vulnerability
Hydrological hazards
Natural hazards

ABSTRACT

The studies that quantify the human and economic costs of increasing exposure of cities to various natural hazards consider climate change together with increasing levels of population and economic activity, but assume constant urban extent. Accurate estimates of the potential losses due to changing exposure of cities, however, require that we know where they will grow in the future. Here, we present the first-ever estimates of the changing exposure of urban infrastructure to floods and droughts due to urban land expansion from 2000 to 2030. The percentage of the global urban land that lies within the low elevation coastal zone (LECZ) increases only slightly to 13% by 2030; nonetheless, this corresponds to a 230% increase in the amount of urban land within the LECZ (from 71,000 km^2 to 234,000 km^2). In 2000, about 30% of the global urban land (i.e., nearly 200,000 km^2) was located in the high-frequency flood zones; by 2030, this will reach 40% (i.e., over 700,000 km^2). The emerging coastal metropolitan regions in Africa and Asia will be larger than those in the developed countries and will have larger areas exposed to flooding. The urban extent in drylands will increase by nearly 300,000 km^2, reaching almost 500,000 km^2. Overall, without factoring in the potential impacts from climate change, the extent of urban areas exposed to flood and drought hazards will increase, respectively, 2.7 and almost 2 times by 2030. Globally, urban land exposed to both floods and droughts is expected to increase over 250%. There are significant geographical variations in the rates and magnitudes of urban expansion exposed to floods or droughts or both. Several policy options exist to safeguard urban infrastructure from flood and drought hazards. These range from directing development away from flood- or drought-prone zones to large-scale adoption of "green infrastructure" (or "eco-efficient infrastructure"). Decisions, taken today on managing urban growth in locations exposed to these hazards, can make a big difference in mitigating likely losses due to floods and droughts in the near future.

1. Introduction

Contemporary urbanization will have far-reaching consequences for sustainability and human well-being. By 2030, it is estimated that almost 5 billion people (60% of the world's population) will live in cities compared to 2.9 billion in 2000 (47%) (UN, 2012). Where this urbanization will take place, which urban areas will grow the fastest or will end up the largest can significantly affect the number of people and infrastructure exposed to natural hazards. In particular, floods and droughts are among the most frequent, dangerous, and costly of all natural disasters, causing significant damage to infrastructure and affecting the livelihoods of millions every year.

Disasters due to water-related hazards (floods, droughts and windstorms) comprised nearly 90% of the 1000 most disastrous events between 1900 and 2006 (Adikari and Yoshitani, 2009). Economic losses due to water-related hazards increased over 500% since the early 1980s, primarily due to rapid urbanization in exposed locations (Adikari and Yoshitani, 2009). Specifically, floods and droughts accounted for 38% of the total number of natural disasters, 45% of the total casualties, more than 84% of the total number of people affected, and 30% of the total economic damage caused by all natural disasters. Flood and drought hazards also caused nearly 0.6 trillion USD worth of damage (28% of the total from all disasters) in the 20 years since 1992 (UNISDR, 2012). In 2013, floods and droughts accounted for over a quarter of all insured losses around the world (Swiss Re, 2014).

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http://dx.doi.org/10.1016/j.gloenvcha.2015.01.002

The continuing socio-economic changes in much of the developing world will increase the exposure and vulnerability of people and infrastructure to floods and droughts in the near future, which will be further amplified by climatic changes (de Sherbinin et al., 2007; Hanson et al., 2011; McDonald et al., 2011a). A recent global assessment estimated that economic exposure to coastal and fluvial flooding could increase from 27 trillion USD in 2010 to 80 trillion USD in 2050 if based on land use and from 46 trillion USD to 158 trillion USD if based on population (Jongman et al., 2012). Population and economic assets exposed to a 1-in-100-year coastal flooding event in 136 port cities across the world are expected to increase more than three and tenfold, respectively, by 2070 (Hanson et al., 2011). On the other hand, the number of urban residents in perennial shortage of water are forecasted to increase over 5 times to 160 million by 2050 due, for the most part, to population increase but also as a result of climate change (McDonald et al., 2011b).

Urban areas contain significant concentrations of infrastructure in the form of residential, commercial, and industrial structures as well as transportation, telecommunications, energy, and water treatment and delivery facilities. Floods damage infrastructure by the force of flood water, debris, and sediment associated with flooding or by landslides triggered by floods, whereas drought creates instability problems in infrastructure (e.g., due to excess pressure exerted on foundations, pipes, and joints). Both floods and droughts cause economic losses by disrupting transportation routes and cutting water and power supplies. However, although estimates of the potential economic losses to flooding due to climate change and increasing population and economic activity in existing urban areas are available (Hanson et al., 2011; Jongman et al., 2012), previous studies either did not take into account the increase in the extents of the urban areas (de Sherbinin et al., 2007; Hanson et al., 2011; McDonald et al., 2011a) or relied on aspatial simple extrapolations, ultimately based only on demographic projections (Jongman et al., 2012). Thus, so far, a detailed spatially explicit investigation of the increasing footprint of urban areas that may globally be exposed to flood and drought hazards has been lacking. Filling this knowledge gap is critical because likely urban expansion patterns are indicative of the global and regional patterns of urban infrastructure that may be at risk from flood and drought hazards.

In this study, we focus on the potential increase in the exposure of urban areas to floods and droughts due solely to urban expansion. Building on the first global urban land expansion forecasts (Seto et al., 2012; Güneralp and Seto, 2013), we focus on potential urban expansion in areas with high exposure to droughts or floods or to both. Since these issues are intimately related to hydrology, we examine the forecasted urban expansion patterns across river basins as well as by geographical regions; we specifically ask two questions:

1. What was the geographical distribution of global urban land that was exposed to floods, droughts, or both in 2000?
2. How will the global and regional patterns of urban growth in the near future affect the urban exposure to floods, droughts, or both?

2. Methods and data

In our analysis, we use the only available spatially explicit global forecasts of urban expansion in 2030 (Seto et al., 2012; Güneralp and Seto, 2013). There are several land-change models developed specifically with urban land change in mind (Pijanowski et al., 2002; Clarke et al., 2007; Patterson and Bierlaire, 2010). Few of these focus on urban land change in developing countries and present an approach suitable for data-sparse environments (Fragkias and Seto, 2007; Tayyebi et al., 2011). Importantly, these models require input maps from at least two points in time for calibration, whereas the available global urban land-cover maps are all from a single time point (Potere and Schneider, 2007). The only exception to this is the land-change model, GEOMOD, which is able to forecast change with a single input layer (Pontius et al., 2001). Therefore, absent a time-series of global urban land-cover maps, GEOMOD was used as the platform to build the land-change model to generate multiple realizations of global urban expansion patterns out to 2030 (Seto et al., 2012) that we use in this study.

The base urban map for the 2030 urban forecasts comes from the Collection 5 MODIS Land Product (Schneider et al., 2009), which reflects the global land cover around year 2000. The 2030 urban forecasts take into account both the uncertainty in the population and economic growth (two major drivers of urbanization) and varying suitability of each land parcel for urban expansion. Therefore, in the resulting urban-expansion forecasts, each parcel of land ends up with a certain probability of becoming urban. In this study, we focus on the areas with high probability of becoming urban, that is, those areas that have >75% probability of undergoing urban expansion by 2030.

We determine the extent of urban land cover in areas prone to flood or drought hazards by intersecting the urban extent maps for year 2000 and year 2030 with the low elevation coastal zone (LECZ), flood frequency, and global aridity index maps that we discuss below. We then assess the exposure of urban areas to floods and droughts in 2000 and the forecasted change in this exposure by 2030. We perform our analysis at river basin level as well as regionally and globally. We use river basins as hydrologically relevant geographic units to analyze the change in the spatial distribution of urban exposure to floods and droughts. We present the composition of each of the 16 geographic regions, which are broadly based on the United Nations world regions, in our analysis in Supplementary Table S1. We conduct all of our analyses at the resolution of the urban-expansion forecasts, 5 km $\times$ 5 km.

Supplementary Table S1 related to this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2015.01.002.

We use the data set of major river basins in vector form, developed by the Food and Agriculture Organization (FAO, 2009). This vector dataset is derived from HydroSHEDS, a more recent elevation product with a higher spatial resolution (Lehner et al., 2008) than Hydro1k (U.S. Geological Survey, 2000). Compared to Hydro1k, HydroSHEDS provides more accurate delineation of the river basins in flat regions such as coastal zones. The FAO dataset provides complete global coverage including areas north of the original HydroSHEDS extent, i.e., 60° N, obtained by merging HydroSHEDS with the HYDRO1k basin layer. Importantly, the FAO dataset provides detailed information of each river basin, including the sub-basin boundaries and their names. In order to evaluate the likely urban expansion in areas that are prone to coastal flooding hazards due to sea level rise and storm surges, we focus on the low-elevation coastal zones (LECZ), defined as "the contiguous area along the coast that is less than 10 m above sea level" (McGranahan et al., 2007). A recent meta-analysis on urban expansion indicated that urban land expansion has been occurring faster in this zone than in other areas around the world (Seto et al., 2011). In our analysis, we use the map delineating the LECZ that was made available by the Socio-Economic Data and Applications Center (SEDAC) at the Center for International Earth Science Information Network (CIESIN) (CIESIN, 2014).

To track forecasted urban expansion in flood-prone areas, we use the flood frequency map created at the Center for Hazards + -Risk Research (CHRR) and CIESIN (CHRR and CIESIN, 2005) based on the data compiled by the Dartmouth Flood Observatory (DFO, 2014). The dataset reflects the relative distribution and frequency