Estimating the physical exposure of human population and agriculture to in-land flooding at regional and global scales

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Table of Contents

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Abstract

Extreme flood events stand amongst the most frequent, widespread, and devastating natural phenomena that threaten economic and social viability. Flood damage is largely dependent on both impact factors – such as water depth and area-of-inundation – and resistance factors, like flood warning and preparedness. In-land flood protection is approached through structural and non-structural measures under the wider objective of effective and efficient river management. Risk identification is vital in the design, planning, and implementation of flood-resistant action for both policymakers and individual stakeholders. This thesis employs a unique approach to global flood-risk by first estimating in-land flood exposure, which comprises only a single pillar of overall risk, followed by a critical analysis of current policy failings and recommendations to combat the growing concerns of future flood-risk amidst climate and environmental change. Estimating the populations, urban extents, and agricultural lands exposed to in-land flooding is a crucial first-step in characterizing overall risk and informing flood mitigation policy.

First, this assessment quantifies the populations, urban extents, and agricultural lands exposed to in-land flooding across spatial and temporal scales using high-resolution flood extent data. An estimated 2.4 billion people may be exposed to in-land flooding on a global scale, representing 43 percent of the global urban population and 37 percent of the global rural population. Both globally and for regional case studies in Central and South America (collectively Latin America), Africa, and Asia, urban populations may face a larger relative threat to in-land flooding than their rural counterparts. This study also provides a first-estimation of the proportion of agriculture exposed to in-land flooding, which may be exacerbated by climate change, using crop and pastureland data. An estimated 20 percent of the world's cropland occupies floodplains, and these patterns shift for each of the regional analyses. Based on a derived flood sensitivity metric, countries such as Colombia and coastal cities in Africa could face higher flood-risk in the future. This thesis serves as an important addition to the risk assessment field and offers, in a separate chapter, a unique policy perspective to situate the results within the broader context of disaster risk reduction.

Résumé

Les évènements d'inondations extrêmes sont parmi les phénomènes naturels dévastateurs les plus fréquents et répandus à menacer la viabilité économique et sociale. Les dommages causés par les inondations sont largement dépendants de deux facteurs d'impacts – la profondeur de l'eau et la surface inondée – ainsi que de facteurs de résistance, tel que les mesures d'alerte, de prévention et de préparation. L'approche préventive prise face aux inondations riveraines s'effectue à travers de mesures structurales et non-structurales sous l'objectif de gestion efficace des cours d'eau. L'identification des risques est vitale lors de la conception, de la planification et l'exécution de mesures prises en matière de prévention pour toutes les parties prenantes. Cette thèse utilise une approche unique à l'analyse des risques d'inondations au niveau mondial en estimant en premier temps l'exposition aux inondations riveraines, constituant un des pilier des risques globaux, suivie d'une analyse critique des lacunes politiques courantes et des recommandations mises en place pour adresser les préoccupations grandissantes envers les futurs risques d'inondations liés aux changements climatiques et environnementaux. Estimer l'étendue urbaine ainsi que les populations et terres agricoles exposés aux inondations riveraines est un premier pas crucial dans la caractérisation globale de risque dans le but d'informer les politiques de mitigation des inondations.

Premièrement, cette analyse quantifie les populations, l'étendue urbaine et les terres agricoles touchés lors d'inondations riveraines aux échelles spatiales et temporelles en utilisant des données d'étendue d'inondations de haute-résolution. Il est estimé que près de 2.4 milliards de personnes seraient exposés aux inondations riveraines, soit environs 43 pourcent de la population urbaine, et 37 pourcent de la population rurale au niveau mondial. Dans le contexte mondial, ainsi que dans les études de cas régionales en Amérique du Sud et Centrale (connu collectivement comme Amérique Latine), en Afrique et en Asie, les populations urbaines sont potentiellement plus à risque face aux inondations riveraines que leurs contreparties rurales. Cette étude procure également une estimation préliminaire de la proportion de l'agriculture exposée aux inondations riveraines, chose qui pourrait être exacerbée par les changements climatiques, en utilisant des données sur les terres d'assolement et de pâturage. Environs 20 pourcent des terres d'assolement se situent sur des plaines inondables, mais cette configuration change lors des études de cas régionales. Basé sur une version dérivée du *flood sensitivity matrix*, des pays tels que la Colombie,

ainsi que les villes côtières d'Afrique pourraient faire face à de plus grands risques d'inondations dans le futur. Cette thèse apporte donc une contribution importante dans le domaine de l'évaluation des risques, et offre, dans l'un de ses chapitres, une perspective unique des politiques permettant de situer les résultats dans un plus grand contexte de réduction des risques liés aux catastrophes.

1. Introduction

1.1. Global flood-risk: past, present, and future

In the last three decades, in-land floods claimed more than 620,000 lives, displaced more than 610 million people, and exceeded 800 billion USD in economic damage on a global scale (own calculation based on Dartmouth Flood Observatory Global Active Archive of Large Flood Events). Between 1975 and 2002, the most deadly in-land flood events occurred in Venezuela (30,000 killed and more than 480,000 affected) in 1999; Afghanistan (approximately 6,300 killed and nearly 167,000 affected) in 1988; India (3,800 killed and 32 million affected) in 1978; and China (10,000 killed and 240 million affected) in the 1980 and 1998 events combined (EM-DAT; Jonkman, 2005).

In September 2009 alone, pluvial and riverine flooding impacted 600,000 people in 16 African countries, the most severely impacted being Burkina Faso, Senegal, Ghana, and Niger (Di Baldassarre et al., 2010). The 2009-2010 rainy season affected approximately 25,000 people after two other devastating flood events in 2007 and 2008. More than 1 million people were displaced by the 2007 floods throughout Uganda, Ethiopia, Sudan, Burkina Faso, Togo, Mali, and Niger, causing more than 500 deaths (Di Baldassarre et al., 2010). The following year, devastating floods also impacted Mozambique (United Nations, 2009).

Floods pose a serious threat to modern society, impacting between 20 and 300 million people each year (Hirabayashi and Kanae, 2009). By 2050, 1.2 billion people (Jongman et al., 2012) could face in-land flood exposure, whereby exposure refers to the total valuables (e.g. populations, economic assets, agriculture) threatened by flood hazards (Lugeri et al., 2010). By 2050, global economic exposure could exceed 125 trillion USD, up 250 percent from simulated exposure in 2010 (Jongman et al., 2012). The high percentage of people moving into flood-prone areas (Jongman et al., 2012) coupled with increased building and settlement in floodplains (Elliot and Pais, 2006) further exacerbate in-land flood exposure.

Due to widespread in-land flood impacts, such as loss of life (Jonkman, 2005) and economic damage (Merz et al., 2010), and their projected increase as a result of climate (Hirabayashi and Kanae, 2009; Hirabayashi et al., 2013) and land-use changes (Jongman et al., 2012), more attention is being directed toward in-land flooding, namely through risk assessments. Risk assessments seek to identify, quantify, and evaluate the risks associated with a given system

(Jonkman and Vrijling, 2008). Specifically, flood-risk assessments can include different types of flooding, such as coastal (e.g. Small and Nicholls, 2003; Nicholls, 2004) or in-land (Buchele et al., 2006; Peduzzi et al., 2009).

It should be noted that the literature does not provide consistent definitions of terminology pertinent to this study (De Wrachien et al., 2008), i.e. flood, flooding, and floodplains. For example, floods have been defined in multiple ways, including:

> "A temporary condition of surface water (river, lake, sea) in which the water level and/or discharge exceed a certain value, thereby escaping from their normal confines. However, this does not necessarily result in flooding" (Schultz, 2006).

> "An overflow or inundation that comes from a river or other body of water and causes or threatens damage. Any relatively high streamflow overtopping the natural or artificial banks in any reach of a stream" (USGS, 2013).

Similarly, flooding has been defined as:

> "…the overflowing or failing of the normal confines of a river, stream, lake, canal, sea or accumulation of water as a result of heavy precipitation by lacking or exceedance of the discharge capacity of drains, both affecting areas which are normally not submerged" (Schultz, 2006).

This thesis utilizes both terms, i.e. flood and flooding, interchangeably, but typically uses the latter. Despite the expression used, the meaning remains consistent, referring to the state of inundation of a floodplain. Floodplains are the low-lying areas surrounding a river channel that are subject to flood events and flooding processes (Tockner and Stanford, 2002).

Flood-risk assessments span disciplinary scales (e.g. De Wrachien et al., 2008; Lugeri et al., 2010; Castillo-Rodriguez et al., 2014) that approach flood-risk from multiple viewpoints including risk management (Woodward et al., 2014), mitigation (Bubeck et al., 2012), and adaptation (Harries and Penning-Rowsell, 2011). Flood-risk can be defined as a product of three singular but interdependent variables: (1) exposure; (2) hazard, or the magnitude and probability of occurrence of in-land floods (Lugeri et al., 2010); and (3) vulnerability, which refers to the existence or lack of coping mechanisms and adaptive capacity of a population (De Wrachien et al., 2008) (Fig. 1):

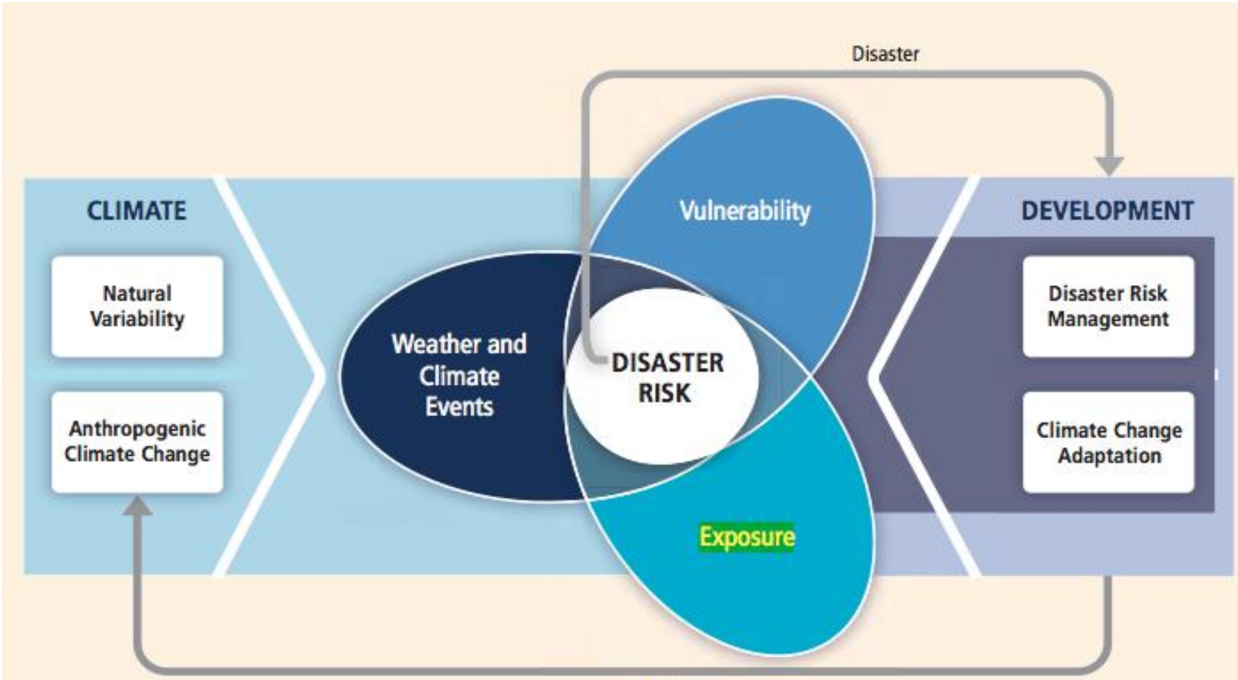

Figure 1. Schematic summary of the relationship between physical hazard, exposure, and vulnerability as components of risk (IPCC, 2012).

Assessments of in-land flood-risk have traditionally been limited to the local, regional or national scale (e.g. Pradhan, 2010; Lugeri et al., 2010; Douglas et al., 2008). However, flood assessments at the global scale are important, especially for developmental progress in low-income countries (e.g. in cost-benefit analyses of climate change adaptation strategies or greatest return-on-investment of mitigative measures) where inequality is highest. Disastrous floods disproportionately impact the developing world that lack adequate preparedness, mitigation, and adaptation strategies (Jongman et al., 2012), illustrating the global concern for current and future flood impacts.

1.2. Research scope: what is exposed to in-land flooding?

In-land flooding threatens urban and rural populations alike and can be exacerbated by climate and land-use change (Solomon, 2007; UNISDR, 2013) that influence the spatio-temporal geography of flood hazards (Pradhan, 2010). Urban populations are challenged by rising costs of infrastructure and economic assets and high concentrations of vulnerable slum dwellers (Jongman et al., 2012), particularly in developing areas. The number of flood-related fatalities have increased by one order of magnitude in Africa over the last 50 years, which largely impact low-income populations that disproportionately occupy flood-prone areas (Di Baldassarre et al., 2010). While the total population in Africa has increased by a factor of four, the increase in urban population has increased by one order of magnitude, i.e. the same growth that has been seen in flood-related fatalities. Di Baldassarre et al. (2010) attribute the rise in flood-related fatalities to intensive and unregulated settlements in flood-prone areas, specifically in slums. Several examples at the local scale show increased settlement in flood-prone areas in Africa (Hardoy et al., 2001; Douglas et al., 2008), for example in Zambia's capital city of Lusaka. Other examples of increases in unplanned human settlements have occurred in Alexandria, Egypt (Klein et al., 2003), Dakar, Senegal, and Ouagadougou, Burkina Faso, all of which were adversely affected by the September 2009 floods (Di Baldassarre et al., 2010).

These unplanned and rapid settlements, especially in urban areas, are growing at an unprecedented rate and exacerbating flood-risk in cities (Lutz et al., 2008). Both now and in the future climate, extreme river flows may increase in frequency and magnitude, particularly in urban areas (Kleinen and Pedschel-Held, 2007). In effect, more frequent flooding may occur due to widespread urbanization coupled with a potential increase in rainfall in some regions (Palmer, 2009). In-land flooding in the urban environment often has long-term ripple effects beyond the floodwaters themselves, such as water-borne, respiratory, and skin diseases (Ahern et al., 2005; Kovats and Akhtar, 2008) as a result of polluted drinking water supplies and are particularly detrimental to the public, not to mention the social and economic epicenters of society (Abhas et al., 2012).

Rural populations with subsistence livelihoods face different challenges related to in-land flooding. Those that practice floodplain agriculture depend on a delicate balance of intermittent flooding during the wet season for proper growth and maturation of crops (Opperman et al., 2009), as well as for animal grazing during the dry season (Tockner and Stanford, 2002). Agricultural development is most intensive in highly populous areas in Asia (i.e. catchments with population densities more than 200 people per km^2), where 60 to 99 percent of their respective riparian corridors have either been urbanized or converted to cropland (Tockner and Stanford, 2002). Of the 98,000 km^2 of floodplains in Bangladesh, which represents about 80 percent of its total land area, about 28,000 km^2 are cultivated, primarily by rice fields (Welcomme, 1979). However, in-land flooding beyond normal levels can cause a loss of crop, even for rice varieties, which occurred following the 1995 flood in the Mekong Delta (Fox and Ledgerwood, 1999). The Ganges and Brahmaputra rivers in India are also flood-prone areas that have been intensively cultivated (Subbiah et al., 2001).

In the Inner Delta of the Niger River, more than 550,000 people (and approximately 1 million goats and 1 million sheep) utilize the floodplain for post-flood grazing (Dugan and Dugan, 1990). The Sudd, among the largest wetlands in the world, is a crucial resource for over one million Nilotic people and several million livestock in Sudan (Scudder, 1991). About 11 percent of riparian corridors of African rivers have been intensively cultivated (Tockner and Stanford, 2002). Richter et al. (2010) determined that more than 3 million people depend on African floodplains for agriculture alone (Table 1).

TABLE 1. Summary of river-dependency in select African floodplains (Richter et al., 2010)

River basin/Country	People dependent on floodplain agriculture	References
Hadejia-Nguru Wetlands, Nigeria	1.5 million farmers, pastoralists, and fishermen	Nigerian Conservation Foundation, 2006
Kushiyara and Surma floodplain, Bangladesh	294,000 dependent on river-flow; 54% income derived from paddy cultivation	Meijer, 2007
Logone River floodplain, Cameroon	Supports 130,000 people	IUCN, 2001
Okavango delta, Botswana	33,672 in Ngamiland district	Kgomotso and Swatuk 2006; Turpie, 2008
Omo River, Ethiopia	100,000 of 500,000 living along river valley are heavily reliant on flood-recession agriculture	EEPCO, 2008a, 2008b
Rufiji River floodplain and delta, Tanzania	16,093 households	Turpie, 2000
Senegal River valley, Mali, Mauritania and Senegal	364,132	Adams, 2000
Sokoto River floodplain, Nigeria	50,000 (pre-Bakolori dam: 1975)	Hartenbach and Schuol, 2005; Ita, 1993
Tana River, Kenya	1 million depend on the river’s flooding regime for their livelihoods	Snoussi et al., 2007; Emerton, 1994
Tocantins River, Brazil	More than 100,000 people affected by loss of fisheries, floodplain agriculture, vegetation for grazing, and other resources	World Commission on Dams, 2000

Dams and other obstructions threaten food security for river-dependent communities downstream, especially in regards to food supply and vegetation used for grazing animals (Richter et al., 2010). In most years, the wetlands of northern Nigeria are known for producing a surplus of both rice and vegetables and support a large portion of the population with high nutritional levels, as well as exports for other parts of Nigeria. During droughts, rain-fed agriculture in the area is adapted to dry conditions; however, farmers and pastoralists are known to exploit floodplains during dry years for other resources (Kimmage and Adams, 1992). Through potential changes in temperature, rainfall, and runoff patterns, climate change may increase risks of floodplain degradation, jeopardizing natural buffer zones and threatening subsistence livelihoods and their food security (Tockner and Stanford, 2002).

1.3. Research objectives: assessing regional and global in-land flood exposure

Although flood-risk has gained considerable attention in recent decades (e.g. Ward et al., 2010; The World Bank, 2009), a lack of global datasets and streamlined, methodological frameworks have stifled progress in quantifying populations, urban extents, and agricultural lands, in particular, that are exposed to in-land flooding. Estimating in-land flood exposure is the first step – and arguably the most important stage – in combating the adverse effects of in-land flooding (Ahmad and Simonovic, 2011). In fact, recent extreme flood events, exponential population growth, rapid urbanization, and climate change concerns have increased the need for global methods to characterize exposure to in-land flooding with spatial and temporal components.

The aim of this study is to determine whether populations, urban extents, and agricultural lands are more concentrated in flood-prone areas than in non-flooded regions and to ultimately improve global flood-risk assessments. The overarching objective within this study is to produce global exposure estimates and to identify patterns and ‘hotspots’ of exposure to in-land flooding. The research questions seek to quantify current in-land flood exposure and sensitivity to flooding in the future, whereby a standardized increase in peak flow was prescribed as a potential outcome of global environmental change:

(1) What is the current in-land flood exposure of populations, urban extents, and agricultural lands on a global scale?
(2) Based on a derived flood sensitivity metric, which Latin American and African urban extents face the highest exposure to future in-land flooding?

This study estimates populations, urban extents, and agricultural lands exposed to in-land flooding across multiple spatio-temporal scales and datasets. A global assessment of in-land flood exposure is conducted, and then zeroed-in on Central America and South America (collectively Latin America), Africa, and Asia, to evaluate continental disparities. Each analysis relies on mapped inundation extents provided by the 'Global Inundation Extent from Multi-Satellites downscaled to 15 arc-seconds' (GIEMS-D15, Fluet-Chouinard et al., 2015) as a proxy for flood exposure. GIEMS-D15 captures global in-land flooding at the highest spatial resolution currently available using monthly observations derived from satellite remote sensing. However, the data cannot capture individual flood events (e.g. stormwater floods at the local scale). Population data from LandScan (2006) and the Gridded Population of the World (GPW, 2000) are paired with urban extents derived from the Global Rural-Urban Mapping Project (GRUMP, 2000) and the Moderate resolution Imaging Spectroradiometer (MODIS, 2001) to analyze the resulting variance in in-land flood exposure dependent upon each unique dataset combination. A comparative analysis is then carried out to understand the proportion of agriculture (both cropland and pastureland) within flood-prone areas, according to GIEMS-D15, on a global scale. Such insight is crucial in determining what fraction of the world's floodplain agriculture may be threatened by in-land flooding and to ascertain whether farmers favor planting in floodplains.

While this study provides a methodological basis for global assessments of in-land flood exposure, Chapter 6 provides a unique extension to exposure-mapping efforts by adding an additional perspective on the related topic of disaster risk reduction (DRR). This policy critique aims to: (1) address the disconnect between policy and practice within DRR using in-land flooding as a key example; and (2) outlines specific policy recommendations for future flood mitigation initiatives. The long-term goal of this study is to serve as a foundation for future initiatives that seek to spatially quantify flood-risk associated with various climate change models (Hirabayashi et al., 2013) and to locate the most vulnerable areas to future alterations in flooding patterns.

2. Review of the Literature

2.1. Flood-risk assessments: hazard, vulnerability and exposure

In terms of hydrology, floods have been studied across multiple spatial, temporal, and disciplinary scales. However, flood-risk assessments – which usually only capture one aspect of risk, i.e. hazard, vulnerability, exposure, or a hybrid of these – are a newer subject. One of the earlier in-land flood-risk assessments approximated maximum snowmelt and paired it with hydro-meteorological data (i.e. rainfall and discharge) to estimate the potential in-land flood hazard associated with three Russian river basins (Kuchment et al., 1994). Since then, the field of flood-risk assessments has continued to grow. A total of 63 flood-risk assessments were reviewed in this thesis (see Table A-1 in Appendix for complete list of reviewed literature), according to a targeted search of assessments of in-land flood hazard, exposure, vulnerability, and risk, but no specific geographic criteria.

Assessments of in-land flood hazards (e.g., Krahe et al., 2000; Pradhan, 2010; Li et al., 2013) comprised the highest proportion of the reviewed literature at 46 percent; followed by in-land flood vulnerability (e.g., Sanyal and Lu, 2005; Balica et al., 2009; Adelekan, 2011) at 43 percent; in-land flood exposure (e.g., Li et al., 2012; Ward et al., 2013; Liu et al., 2014) at 27 percent; and flood-risk (i.e., Budiyono et al., 2014; Liao et al., 2014) at 3 percent (Fig. 2). A value over 100 percent is a result of some studies that address multiple aspects of flood-risk, e.g. hazard and vulnerability. While flood-hazard assessments focus on characterizing flood frequencies both now and amidst global environmental change (e.g., Sansena, 2006; Kafle et al., 2007; Zhang et al., 2009) and flood-vulnerability assessments (e.g., Prathumchai and Samarakoon, 2006; Gao et al., 2007; Sarminingsih et al., 2014) address coping mechanisms and adaptive capacity, the aim of flood-exposure assessments (e.g., Hall et al., 2003; Balk et al., 2012; Christenson et al., 2014) is to estimate exposed assets and human capital – such as populations, urban areas, and agricultural lands – to in-land flood hazards.

The in-land flood-risk assessment literature was dominated geographically by studies in less-developed countries (LDCs; Fig. 3), specifically in Asia (e.g., Jiang et al., 2009; Gain and Hoque, 2013; Liao et al., 2014) at 49 percent; followed by studies across the European Union (e.g., Schumann and Pfutzer, 2000; Hall et al., 2003; Lindenschmidt et al., 2006) at 21 percent; studies at the global scale (e.g., Hirabayashi and Kanae, 2009; Ward et al., 2013; Christenson et al., 2014)

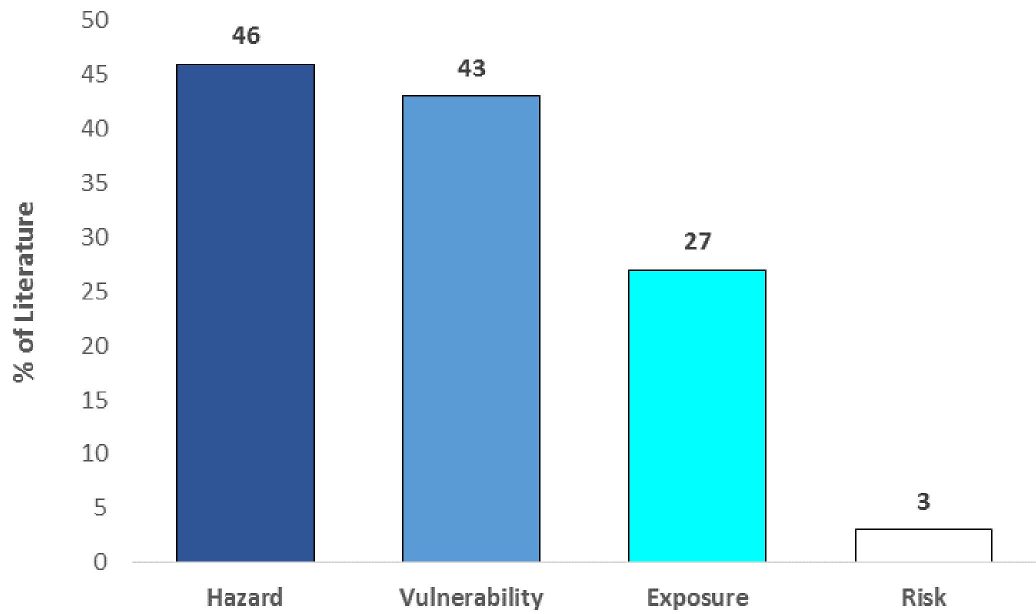

Figure 2. Percentage of literature reviewed for each component of in-land flood-risk, i.e. hazard, vulnerability, and exposure.

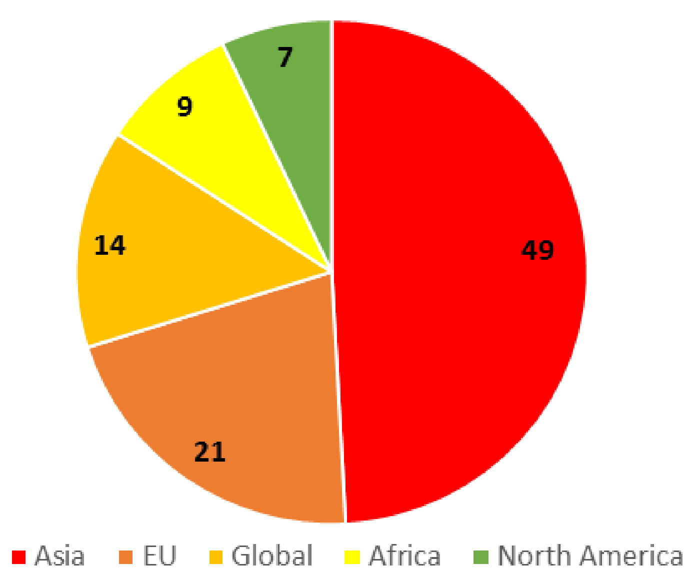

Figure 3. Spatial distribution of literature reviewed as a percentage.

at 14 percent; African studies (e.g., Douglas et al., 2008; Adelekan, 2011; Morand et al., 2012) at 9 percent; and North American studies (e.g., Haque, 2000; Elawad et al., 2005; Elliot and Pais, 2006) at 7 percent. The limited number of flood-risk assessments for North America could be a factor of the search criteria and definition of risk employed in this particular study. Despite this uncertainty, the skewed distribution toward hazard and vulnerability assessments found in this literature search, especially in LDCs, underscores the importance of improving in-land flood exposure assessments at the global scale.

2.2. Methods of quantifying exposure to in-land flooding

A few global studies have started to estimate exposure to in-land flooding for populations (Hirabayashi and Kanae, 2009; Jongman et al., 2012; Hirabayashi et al., 2013), with the dominant attention remaining on projecting very specific changes in flood frequency as a result of climate change (Kleinen and Petschel-Held, 2007; Hirabayashi and Kanae, 2009; Hirabayashi et al., 2013) to understand potential future impacts. However, these global studies only provide general numbers of future populations exposed to in-land flooding based on their respective models, which are often based on limited data that are both coarse and uncertain in nature. For example, Kleinen and Petschel-Held (2007) adopted a synthetic scenario of a former 1-in-50 year event becoming a 1-in-25 year event to characterize future flood frequency; as a result, an estimated 28 percent of the total world population would be affected by this single scenario of a change in temperature of 5 K. Since these studies employ different definitions of exposure, they also prove very difficult to compare to other assessments.

Others only include in-land floods as one of many hazards within complex risk studies (e.g. Peduzzi et al., 2009), consider exposed populations as only one of many contributory factors of overall flood vulnerability (e.g. Balica et al., 2009), or are limited in geographic scope (e.g. Balk et al., 2012; Liu et al., 2014). The extent of agriculture exposure is an even larger understudied area, especially at the global scale. Previous studies have estimated agricultural vulnerability, particularly in terms of economic damage (Merz et al., 2010) or in reference to arable lands exposed to drought hazards (Peduzzi et al., 2009); regional case studies and estimates of the impacts of flooding on agriculture also exist (Hall et al., 2005; Ngoc Chau et al., 2013; Foudi et al. 2015; Zheng et al., 2015). Economic damage estimates as a result of in-land flooding (Dutta et al., 2003) are arguably the only available proxy for current knowledge of in-land flood exposure as it relates to agricultural lands.

To-date, studies have employed numerous methods of quantifying in-land flood exposure. Areas exposed to in-land flooding have been defined in various ways, e.g. through fuzzy comprehensive assessments and fuzzy similarity methods (Jiang et al., 2009; Zhao et al., 2009) and GIS approaches using hydro-meteorological data, topography (Ma et al., 2010), and land-use and change (Li et al., 2011; Yin et al., 2013; Liu et al., 2014). Populations, economic assets (Ma et al., 2010; Li et al., 2012; Yin et al., 2013), and urban areas (Jiang et al., 2009; Liu et al., 2014) have gained more attention in in-land flood exposure assessments compared to agriculture, whereby agricultural loss and damage have served as proxies for exposure (e.g., Dutta et al., 2003; Bremond et al., 2014) due to the largely vacant literature. Merz et al. (2010) provides a comprehensive review of the potential classification of elements at-risk according to economic sectors (e.g. private households, services sector, and agriculture); different approaches for estimating the monetary value of assets exposed at different spatial scales; influencing factors in flood damage assessments, such as depth and velocity; advantages and disadvantages of empirical and synthetic damage models and relative versus absolute damage functions; and different damage models used in the industrial, residential, and agricultural sectors.

Peduzzi et al. (2009) derived a Disaster Risk Index that considered in-land flood exposure as one hazard contributing to overall flood-risk. The EM-DAT database of past flood events was used to approximate flooded areas at 5 km resolution, followed by the summation of people living in exposed areas each year. Ward et al. (2013) contributed further by integrating multiple risk indicators, including population, gross domestic product (GDP), agricultural value, and land-use, all at 30 arc-second resolution. Extending the model cascade of Winsemius et al. (2013), Ward et al. (2013) produced flood-risk maps for numerous return-periods (i.e. 2-1,000 years) on a global scale. Daily meteorological data and flood volumes (at 0.5 by 0.5-degree resolution) were inputted to an inundation model at different return periods; and stage-damage functions, which relate damage for a respective element at-risk to specific characteristics of inundation (Merz et al., 2010), were calculated for different impact indicators. Exposed population was both modeled using a downscaling process circa the year 2010 and coupled with LandScan 2008 population maps. Urban economic exposure was derived using the HYDE database of land cover (5-minute resolution) and attributing an economic value to each ‘urban’-classified grid cell. Agricultural value was estimated as a percentage of each country's GDP using the World Bank's World Development Indicators and multiplied by the fraction of inundated cells occupied by agriculture (Ward et al., 2013).

As a result, Ward et al. (2013) estimated the annual expected impacts of in-land flooding, including: 169 million people exposed (or 2.5 percent of the global population); 1.4 trillion USD exposed, which represents 2.2 percent of the global GDP; affected agriculture valued at 75 billion USD (or 0.1 percent of global GDP); urban damage potential at 834 billion USD (or 1.3 percent of global GDP); and exposed urban assets at 5.3 trillion USD (or 8.2 percent of global GDP). The model resulted in the Aqueduct Global Flood Risk Maps, a tool that can rapidly assess flood-risk in terms of different impact indicators at multiple return-periods (Ward et al., 2013); however, the model does not consider flood protection measures, has not been based on or validated against observed flood inundation extents, and is ultimately a highly uncertain model framework of in-land flood exposure.

Estimating populations exposed to in-land flooding also informed the Science for Nature and People (SNAP) Water Security Project that evaluated 68 Latin American cities with populations of at least 1 million (Tellman et al., in prep.) The aim was to better direct investments to watersheds that score at high-risk for flooding and demonstrate potential to reduce flood damages through green infrastructure (Tellman et al., in prep). Methodologies developed as a part of the SNAP project were also applied in this study.

Furthermore, this thesis models and extends the efforts of two key pieces of literature that quantify in-land flood exposure at different spatial scales: Jongman et al. (2012) at the global scale and Balk et al. (2012) for cities in Asia. Jongman et al. (2012) selected populations living in a 1-in-100-year flood zone, summing this for each country and Food Producing Unit. In-land flood exposure was estimated from the global flood frequency dataset developed for the 2009 Global Assessment Report (GAR) on Risk Reduction (ISDR, 2009). The GAR data combine hydrological models with historic flood records from the Dartmouth Flood Observatory (DFO) at 30 arc-second resolution (or 1 km at the equator). The hydrological model used in the GAR dataset estimates monthly discharge for a limited number of gauging stations and may deviate from actual observation data. Sudden changes in elevation or land cover may also lead to over- or underestimation of the floodplain in the GAR model. These estimates do not consider flood protection measures, which may also drive overestimation of flood-prone areas. The Balk et al. (2012) analysis also utilized the GAR data and quantified flood exposure in terms of land area and population in Asian megacities. Cities exposed to in-land flooding were areas that have flooded at least twice in the past 100 years, and the populations occupying these flood-prone areas were then summed for each city.

Jongman et al. (2012) quantified flood exposure between 1970 and 2050 on a global scale, and for 2010, the total population exposed to a 1-in-100 year flood exceeded 805 million. The largest absolute exposure, or the actual magnitude of exposure estimates, occurred in Asia. Based on the simulated absolute exposure, 73 percent of the total exposed population resided in Asian countries in 2010 (Jongman et al., 2012). However, the largest simulated relative exposure, as compared to an area's total population, over the period of 1970-2010 was in Sub-Saharan Africa at 188 percent (Jongman et al., 2012). On a global scale, the amount of assets in flood-prone areas has steadily increased with the highest total monetary value in Asia (i.e., 17 trillion USD) in 2010. In addition to highest absolute exposure, Asia showed the largest relative increase in economic exposure of 4300 percent, compared to a 2900 percent increase in North Africa. These significant increases in relative economic exposure occurred due to simultaneous growth in GDP per capita (averaging 1163 percent in Asia) and population (averaging 92 percent in Asia) between 1970 and 2010 (Jongman et al., 2012).

The model also suggests a larger population growth in flood-prone areas than total population growth worldwide (Jongman et al., 2012). Jongman et al. (2012) assumed that the areas exposed to a 1-in-100 year flood in 1970 would be the same areas exposed in 2050 and applied the World Bank's population and GDP per capita projections (Hughes et al., 2010) to extrapolate their estimates of current exposure into the future. Based on this assumption, a simulated 1.05 billion people could be exposed by 2050, a 31 percent increase from current estimates (Jongman et al., 2012). In addition, the value of assets could reach 126 trillion USD by 2050, a 250 percent increase from current levels. Sub-Saharan Africa is simulated to have the highest exposed population growth of approximately 104 percent in relative terms. The collective increase in global economic exposure, a result of a rise in GDP per capita and population, is simulated to increase by more than 300 percent. The largest increase in economic exposure occurs in Asia by 370 percent, followed by Sub-Saharan Africa and North Africa. In fact, all of the regions included in the Jongman et al. (2012) study demonstrated a higher increase in relative economic exposure than populations exposed from 1970 to 2010. Based on the simulated data, the absolute increase in inundated surface area occurs in Asia, with an increase in 9200 km^2. Sub-Saharan Africa demonstrated the largest relative increase in inundated area at 633 percent, followed by Asia with a 220 percent relative increase (Jongman et al., 2012).

Studies show that nearly 50 percent of flood-related fatalities and 90 percent of impacted persons between 1980 and 2006 were in Asia, with growing impacts on individual and property damage (Hoyois et al., 2007; Adikari et al., 2010). Based on their findings, Balk et al. (2012) argued that Asia was the most flood-vulnerable continent in the world. Asian cities are far more densely populated than cities in the Americas and Africa and also house higher total populations: "The average urban area (of urban settlements of 5,000 persons or more) has 720 persons per square kilometer in Asia, as compared to about 500 in Africa" (Balk et al., 2012).

In Asia alone, 250 million urban dwellers were exposed to in-land flooding in 2010. By 2025, Balk et al. (2012) estimated that urban dwellers exposed to in-land flooding may reach 350 million in Asia. Based on UN (2010) projections of population growth between 2000 and 2025, Asian cities will be populated by an additional 1 billion inhabitants, followed by an additional 1 billion between 2025 and 2050. This is a much higher growth than in rural areas, which will likely see a decline in population between 2025 and 2050, as well as the expected population increase in developed countries. In fact, more than 50 percent of urban population growth worldwide will likely occur in Asian cities. The highest growth is seen in some of the poorest communities that reside in environmentally riskier areas that will likely experience the brunt of climate and environmental change both now and in the future (Balk et al., 2012).

Although Asia has been described throughout the literature as the most flood-vulnerable continent, the risks are not uniform across all countries (Balk et al., 2012) or social strata. Adikari et al. (2010) specify that cities in southern Asia are the most vulnerable to flood-related impacts due to higher populations and larger fraction of urban dwellers living in slums, which are inherently more susceptible to flood impacts due to intensive and unregulated settlement of often environmentally riskier regions. In fact, almost 45 percent of southern Asian cities are comprised of slum inhabitants (Adikari et al., 2010). High-risk areas to in-land flooding, i.e. frequencies of every other year, in Asian cities with at least 10,000 inhabitants are concentrated in three countries: Bangladesh, China, and India (Balk et al., 2012). The World Water Development Report 2 (WWDR2) as a part of the World Water Assessment Program (WWAP, 2006) also found Bangladesh, India, and Vietnam as the most flood-vulnerable.

The aforementioned studies simulated the absolute exposure of urban populations in Asia; however, equally important to consider are estimates of exposed populations as fractions of the total urban population in Asian countries, i.e. the relative exposure. Balk et al. (2012) concluded that nearly 75 percent of Cambodia's urban population were at-risk to in-land flooding. About 35 percent of Vietnam's urban population were at-risk, with comparable flood-risk in Bangladesh, Lao, and Thailand. Although China often demonstrates the highest absolute exposure estimates, the relative exposure generated by Balk et al. (2012) found that about 20 percent of the country's urban population may be at-risk of in-land flooding, compared with 12 percent of India's urban population.

In addition to absolute and relative flood exposure, the adaptive capacity at both the national and local scales are not uniform across countries in Asia. In particular, Bangladesh's diminished state capacity and economy will likely exacerbate an already heavy burden of environmental vulnerability to floods (Balk et al., 2012). Both formal and informal institutions at the national, state, and local levels also influence and shape individual vulnerability, all of which are multifaceted across space and time (Adger 1999; Adger et al. 2005). This drives particular group's access to critical resources (Adger 1999) and protection from flood disasters who are often forced to live in environmentally hazardous areas due to economic exclusion and lack of resilient livelihoods in slum dwellings. In the midst of climate and environmental change, low-income areas – such as Africa and Asia – demonstrate the highest opportunity costs related to adaptation strategies compared to their developed counterparts (Chinowsky et al., 2011). Although adaptation is necessary amongst various institutions, the coping ability of individual social groups is essential in minimizing flood-related impacts. However, individual groups are exposed to involuntary risks (Blaikie et al., 2014), further compounding the already marginalized state of certain communities. Despite initiatives to protect urban assets from flood disasters at the national scale – such as in Thailand and Vietnam – these have been at the expense of agricultural sectors and rural communities (Manuta et al., 2006; Nikitina, 2005).

Developing sustainable and multiscalar approaches to flood mitigation – whether through zoning, early warning systems, or housing regulations – are paramount in addressing the ever-increasing flood exposure in these regions. Consequently, Africa and Asia – both of which are characterized by high flood-risk currently and in future projections – serve as case studies throughout the analyses in this thesis.

3. Methodology

3.1. General approach

The methodology in this thesis is modelled after the Jongman et al. (2012) and Balk et al. (2012) studies as a continuation of the body of literature and employs additional methodological frameworks developed as part of the SNAP project. Furthermore, this study utilizes GIEMS-D15, a new global inundation map at higher spatial resolution than available in any previous study. The main methodological steps of this assessment are to:

(1) Measure if urban floodplain development (i.e., urban extent) is more prevalent inside floodplains than outside and how this compares to rural floodplain development both globally and regionally;

(2) Quantify whether urban or rural populations are more highly concentrated in floodplains;

(3) Estimate population numbers exposed to in-land flooding across the world for multiple datasets;

(4) Calculate the percentage (land area) of floodplains comprised of agriculture by using two cropland datasets (circa the years 2000 and 2005) and one for pastureland (circa the year 2000);

(5) Compute the percent of total cropland and pastureland exposed to in-land flooding;

(6) Derive a flood sensitivity metric for Latin America and Africa that relates monthly maximum discharge to inundated area as a proxy for future response to change in peak flow.

ArcGIS 10.2 serves as the Geographic Information System (GIS) platform for the calculations. The population analyses capture how in-land flood exposure varies spatially across local, national, and global spectrums; while the agriculture analyses explore in-land flood exposure at the global scale, as well as for the continental case studies. Identifying populations within flooded areas (i.e. using GIEMS-D15 as a proxy for in-land flood exposure) is crucial in the dissemination of exposure estimates to stakeholders across multiple scales and dimensions.

3.2. Data

3.2.1. Global Inundation Extent from Multi-Satellites – Downscaled to 15 arc-seconds

Global inundation extents, or flood zones, are the key ingredients to address the predominance of populations, urban extents, and agricultural lands exposed to in-land flooding. The Global Inundation Extent from Multi-Satellites – Downscaled to 15 arc-seconds (GIEMS-D15) data provide the foundation of all of the analyses conducted in this study. GIEMS-D15 uses the process of downscaling to convert coarse inundation observations over a 15-year period-of-record (POR, 1990-2005) form multiple satellites to 15 arc-second (~ 500 m at the equator) resolution (Fig. 4). Topographic and hydrographic variables from the HydroSHEDS database (Lehner et al., 2008) assisted the downscaling process to predict surface water distribution, and the Global Lakes and Wetlands Database of permanent water bodies (Lehner & Döll, 2004) was used to supplement missing satellite observation data (Fluet-Chouinad et al., 2015). Using a high-resolution inundation probability map, GIEMS-D15 represents where inundation is spatially more

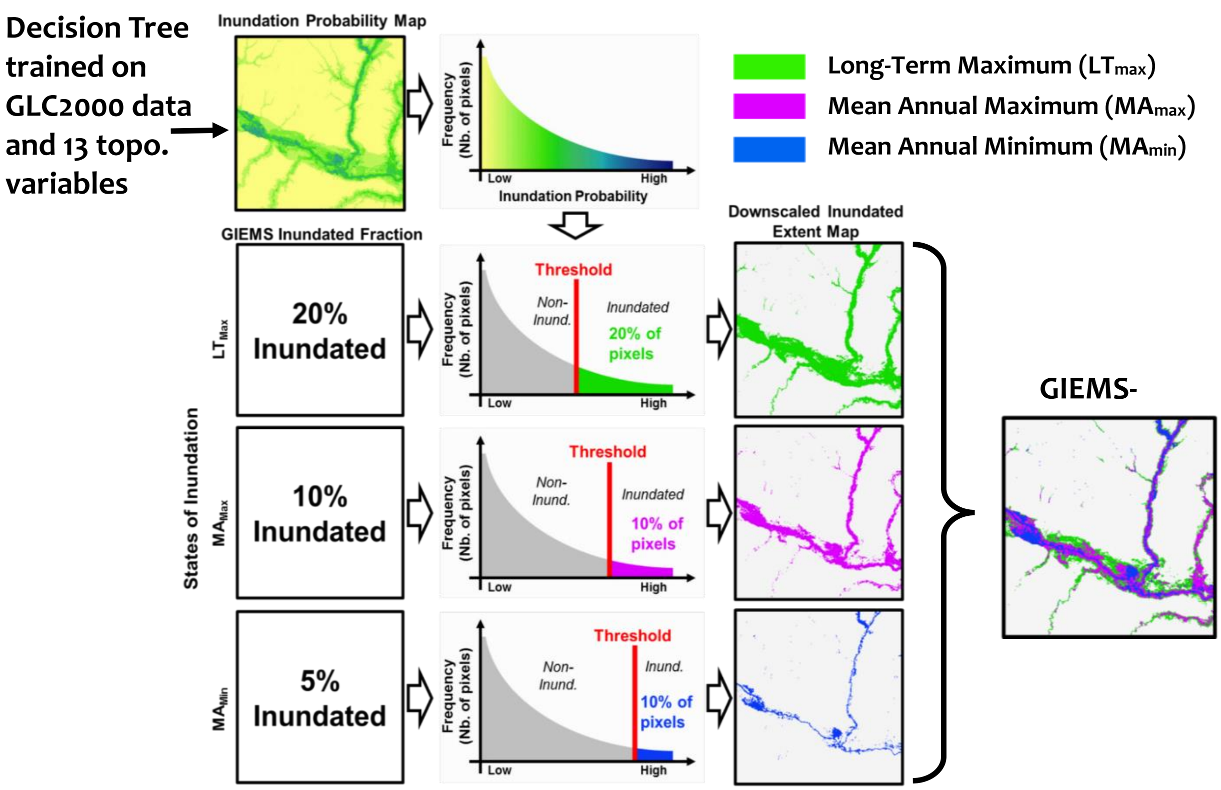

Figure 4. Downscaling process for GIEMS-D15 dataset (adapted from Fluet-Chouinard et al., 2015).

likely on a global scale at three temporal states of inundation, or zones: (1) mean annual minimum (MA_{min}), representative of the dry season; (2) mean annual maximum (MA_{max}), depicting wet season conditions; and (3) long-term maximum (LT_{max}), reached during more infrequent, larger flood events (Fluet-Chouinard et al., 2015).

GIEMS-D15 depicts areas of natural floodplains and wetlands but does not consider vulnerability. For example, it is understood that in reality, countries with sufficient protection against peak river discharge will not likely be flooded (Ward et al., 2013). While GIEMS-D15 includes actual flood observations over its 15-year POR, the downscaling process follows local likelihoods that may prioritize the natural floodplain even if structures (e.g. levees and dams) protect these areas (B. Lehner, pers. comm., 2015). Although the dataset is best interpreted as capturing the naturally exposed (as opposed to vulnerable) areas that lie within floodplains, each GIEMS-D15 zone brings different caveats related to exposure and potential vulnerability of those impacted, e.g. varying levels of awareness, preparedness, and resilience across space and time. In fact, the MA_{min} and MA_{max} are at higher probability of occurrence, as they are assumed to inundate at some point in any given year; while the LT_{max} is exposed more infrequently (B. Lehner, pers. comm., 2014). For example, agriculture in the MA_{min} zone experiences inundation year-round, so farmers may be greater prepared or more adaptive than, say, farmers in the LT_{max} zone. Agriculture in the LT_{max} is exposed to in-land flooding infrequently; however, when inundation occurs, the impacts are likely more unexpected and severe.

Irrespective of these limitations, GIEMS-D15 simulates inundation patterns on a global scale based on observed satellite imagery and inclusion of topographic variables at the highest spatial resolution currently available, and it can serve as a proxy for in-land flood exposure. Beyond the three inundation zones of GIEMS-D15, monthly means of inundation extents were produced using the same methodology as GIEMS-D15. While these are not part of the publicly available product (B. Lehner, pers. comm., 2015), they were provided for this project. Complete monthly data were only available for Latin America and Africa at the time of this assessment.

3.2.2. LandScan 2006 and Gridded Population of the World (GPW) 2000

LandScan 2006 (most recent version accessible for the purpose of this study) and GPW 2000 provide absolute population count data for each grid cell, both at 30 arc-second spatial resolution. The basis of these estimates are sourced from different datasets and methodological approaches. Compared to GPW, LandScan takes a highly modeled approach to mapping global population. While GPW uses non-spatial population estimates according to census records in individual administrative boundaries (Balk et al., 2006), LandScan measures 'ambient' population, or the average location of individuals across seasons, days of the week, and even the time of day (Dobson et al., 2000). The dominant advantage of GPW is that it focuses on obtaining the highest possible resolution of population data; whereas LandScan acquires relatively coarse-level population inputs along with other ancillary data (i.e. road networks, satellite images of nighttime lights, elevation, slope, and land cover) that are fitted to a complex model (Dobson et al., 2000). The specific parameters and calibration methods of this model have not been published, so the shortcomings of the data are more difficult to assess. GPW faces different challenges in accurate population attribution within various administrative boundaries (Balk et al., 2006). For example, a small island chain may only have one population estimate for the entire region; GPW would then divide the population by the total area, which assumes normal population distribution across the island. Despite all of these drawbacks, both LandScan and GPW offer global population estimates necessary for the purposes of this study and support a range of in-land flood exposure assessments.

3.2.3. Global Rural-Mapping Project (GRUMP, 2000) and Moderate resolution Imaging Spectroradiometer (MODIS, 2001)

Urban extents derived from GRUMP (2000) and MODIS (2001) were used for the purposes of this study and have been used in previous flood-risk assessments (e.g. Christenson et al., 2014; Balk et al., 2012; Tellman et al., in prep.). GRUMP has a spatial resolution of 30 arc-seconds, or 1 km at the equator, while MODIS offers 500 m spatial resolution (i.e., similar to the spatial resolution of GIEMS-D15). GRUMP, an affiliated product of the GPW database, uses nighttime satellite imagery to mask out high-concentrations of light across the landscape (Balk et al., 2006; Balk et al., 2012). The light dispersion in nighttime imagery makes urban extents appear more widespread (Balk et al., 2006) and may overestimate the urban environment (Potere and Schneider, 2007). MODIS-derived urban extents exploit temporal and spectral information sourced from one year of MODIS observations and defines urban areas using a global training database and an ensemble decision-tree classification algorithm (Schneider et al., 2010).

GRUMP and MODIS data are binary, i.e. pixels are either urban or not, with no associated city data. In other words, urban and rural areas are clearly identified; however, it is impossible to attribute a certain urban pixel or conglomeration of pixels to a particular city without ancillary data. GRUMP provides a separate dataset of settlement points of 5,000 inhabitants or more that includes individual city names. By extracting major cities (with populations of 1 million or more), GRUMP and MODIS urban polygons can be attributed to the settlement point that falls inside their respective boundaries. A total of 213 major cities worldwide meet the criteria of at least 1 million inhabitants and a one-to-one relationship between city point data and the respective urban polygons. MODIS was found to be the most accurate delimitation of global urban extents (Potere and Schneider, 2007) but does not include suburbs, which tends to lead to lower urban population estimations than GRUMP. Due to limitations of both datasets, both the GRUMP and MODIS urban extents were coupled with the two population grids to evaluate four unique combinations of in-land flood exposure (Table 2). This holistic approach provides an estimated range of the total population that may be exposed to in-land flooding.

TABLE 2. Dataset combinations for in-land flood exposure

Urban Masks	Population Count Grids
GRUMP (2000)	GPW (2000)
GRUMP (2000)	LandScan (2006)
MODIS (2001)	GPW (2000)
MODIS (2001)	LandScan (2006)

3.2.4. Validation

The Dartmouth Flood Observatory (DFO) database includes major inundation events globally over an approximate 30-year POR (i.e., 1985-2014) and serves as one validation tool in this study. The DFO monitors and evaluates past and current inundation events with data sourced from government and non-governmental organization outlets, inundation models, media reports, satellite imagery, and many other quantitative and qualitative resources. Each inundation event includes information regarding the geographic location (at the country scale), the number of confirmed fatalities, and the number of displaced persons.

3.2.5. Earthstat global cropland and pastureland data

A total of three agricultural maps were analyzed for in-land flood exposure: (1) Earthstat Cropland Data (2000); Earthstat Pastureland Data (2000); and Earthstat Cropland Data (2005).

Note that the most recent version of Earthstat is currently only available for cropland (D. Plouffe, pers. comm., 2015). Earthstat provides global crop and pastureland fractions at 5-minute spatial resolution, or approximately 10 km at the equator (Ramankutty et. al, 2008), as well as the fraction of land occupying each pixel. The Earthstat data are in floating point format, displayed on a scale from 0 to 1 that represents the fraction of each pixel occupied by cropland or pastureland (collectively referred to as agriculture).

The Earthstat database combines national and agricultural census records with satellite imagery, and extrapolations are made circa the year 2000 to fill missing data. The data were compiled for arable lands, permanent crops, and permanent pastures consistent with their respective definitions, according to the Food and Agriculture Organization (FAO). The FAO definition of arable land includes “land under temporary crops (double-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than 5 years). The abandoned land resulting from shifting cultivation is not included in this category. Data for arable land are not meant to indicate the amount of land that is potentially cultivated” (FAOSTAT, 2013). Permanent crops include “land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee and rubber; this category includes land under flowering shrubs, fruit trees, nut trees and vines, but excludes land under trees grown for wood or timber” (FAOSTAT, 2013). Permanent pastures are defined as “land used permanently (5 years or more) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land). The dividing line between this category and the category ‘Forest and woodland’ is rather indefinite, especially in the case of shrubs, savannah, etc., which may have been reported under either of these two categories” (FAOSTAT, 2013).

Earthstat’s spatial resolution is relatively coarse and underestimates agriculture near water bodies, since pixels with greater than 50 percent of water were omitted from the analysis (D. Plouffe, pers. comm., 2015). The combined satellite imagery in the land cover data may also produce errors due to noise and other interferences in the feedback reflectance (D. Plouffe, pers. comm., 2015).

With these known limitations, a new Earthstat cropland map was produced at McGill University which is available to this study. It (1) offers higher spatial resolution at 1 minute (~ 2 km at the equator); (2) provides a more current representation of global agriculture, i.e. circa the year 2005; and (3) uses MODIS imagery at 500 m resolution to identify water bodies to more accurately delineate water from land, and as a result, pixels with greater than 50 percent of water are not omitted.

3.2.6. HydroSHEDS

HydroSHEDS is a mapping product that represents hydrographic features, including river networks and watershed boundaries, across the globe (Lehner et al., 2008). For all regions south of 60°N latitude, HydroSHEDS is derived from elevation data from the Shuttle Radar Topography Mission at 3 arc-second (~ 90 m at the equator) resolution. The HydroSHEDS product is available at multiple scales and estimates a long-term average discharge for all rivers, downscaled from a coarse, global hydrological model (Lehner and Grill, 2013). Within this thesis, HydroSHEDS was used at 15 arc-second (~ 500 m at the equator) resolution to meet accuracy and computing requirements and to match the resolution of the core dataset, GIEMS-D15.

3.3. GIS analyses

3.3.1. Pre-processing steps

Step 1:

To accurately analyze the data, i.e. for populations, urban extents, and agricultural lands, all datasets were disaggregated to match the resolution of the core inundation dataset, GIEMS-D15, at 15 arc-second (~500 m at the equator) resolution; and population counts in the original pixels were divided amongst the disaggregated pixels.

Step 2:

Individual areas of interest were then isolated and extracted for the purposes of this study and included:

(1) Two *urban masks*: unique grids whereby a value of ‘1’ was assigned to areas classified as ‘urban,’ according to (1) GRUMP and (2) MODIS, and all areas outside of each were given ‘NoData;’

(2) Two *rural masks*: grids that represent rural areas, i.e. regions outside of (1) GRUMP and (2) MODIS urban extents, were given a value of 1, and all areas classified as urban were given NoData.

(3) 213 individual cities (based on GRUMP and MODIS-derived urban extents where a one-to-one relationship between city point data and their respective urban polygon existed, as well as a population size of at least 1 million); and,

(4) Country boundaries, according to the Database of Global Administration Areas (GADM, Hijmans, 2010).

Step 3:

Each GIEMS-D15 zone was separated, producing individual grids for (1) the MA_{min}, (2) the MA_{max}, (3) the LT_{max}, and (4) the non-flooded zone, i.e. areas outside of the GIEMS-D15 zones. All areas outside of each respective zone were reclassified as NoData. For example, all pixels uniquely within the MA_{min} received a value of 1, and all values outside of the MA_{min} were reclassified as NoData. The same procedure was conducted for the MA_{max}, LT_{max}, as well as the non-flooded zone.

Step 4:

A land area grid at 15 arc-second resolution was produced for a more accurate representation of pixel size, which is skewed due to latitudinal differences, i.e. pixels in geographic projection become smaller in width as they approach the poles. This land area grid represents pixel size in km^2 and was later utilized in computing urban, rural, and agricultural land area exposed to in-land flooding.

3.3.2. Calculation of urban and rural area

Flood-related impacts manifest differently in rural and urban environments. Floods across rural landscapes often impact larger areas, but urban inundation events typically impact more populous communities (Wheater and Evans, 2009). Due to widespread urbanization, it is unclear whether urban centers face disproportionate exposure to in-land flooding compared to rural environments. In other words, do urban spaces comprise a greater proportion of land area (within the GIEMS-D15 zones) as compared to rural areas? This study estimates both global and region-specific proportions of in-land flood exposure in the urban and rural contexts.

First, the GRUMP and MODIS binary data were compared to weigh the discrepancies between their urban and rural masks. Each of the GRUMP and MODIS urban and rural masks were multiplied by the 15 arc-second land area grid (in km^2), and then multiplied by the MA_{min}, MA_{max}, LT_{max}, and non-flooded grids. The GRUMP urban mask found that 29 percent of urban areas are exposed to in-land flooding; while the MODIS urban mask estimated 34 percent. The GRUMP rural mask found that 12 percent of rural areas are exposed to in-land flooding; while the MODIS rural mask estimated 13 percent. Due to the moderate deviation between the binary GRUMP and MODIS extents, only MODIS data were further used for this objective.

3.3.3. Calculation of agricultural area

The agriculture analyses followed a similar approach to quantify the total cropland and pastureland in GIEMS-D15 zones. The original Earthstat 2000 data provide the fraction of agriculture that occupies the land in each pixel, so it was crucial to also determine what fraction of land occupies each pixel. For example, the fraction of cropland in a particular pixel may be 50 percent, whereas only 50 percent of the same pixel is even occupied by land. The correct conclusion would be that 25 percent of the entire pixel is occupied by cropland, rather than the raw value provided by Earthstat (2000) cropland data. Thus, the Earthstat cropland and pastureland (2000) data were multiplied by the fraction of each pixel that was occupied by land to extract the correct fraction of agriculture occupying each pixel. This step was not necessary for the new Earthstat (2005) cropland data, since it already considers the fraction of land area in each pixel and provides the true fraction of cropland in each pixel.

To generate the three agriculture fraction grids, each agricultural layer was multiplied by the 15 arc-second land area grid (in km^2) and totaled for each GIEMS-D15 zone. The percent area of each GIEMS-D15 zone comprised of agriculture was computed for the two cropland and pastureland areas. In addition, the percentages of total cropland and pastureland in each GIEMS-D15 zone were calculated on a global scale.

3.3.4. Calculation of population numbers

LandScan and GPW values were extracted where they coincided within each GIEMS-D15 zone. Each GIEMS-D15 zone was multiplied separately by both the LandScan population and GPW grids. This produced eight separate population grids that represent (1) the population count in the MA_{min}, (2) the population count in the MA_{max}, (3) the population count in the LT_{max}, and (4) the population in the non-flooded zone for both LandScan and GPW. With unique population grids for each GIEMS-D15 zone, the zonal statistics tool in ArcMap was utilized to calculate the total population (in each GIEMS-D15 zone) within each of the spatial extents produced in the pre-processing steps, including: (1) GRUMP and MODIS urban masks; (2) the rural masks; and (3) 213 individual cities worldwide. The GRUMP and MODIS urban and rural masks, as well as the 213 individual cities, each generated four estimates according to unique dataset combinations (Fig. 2).

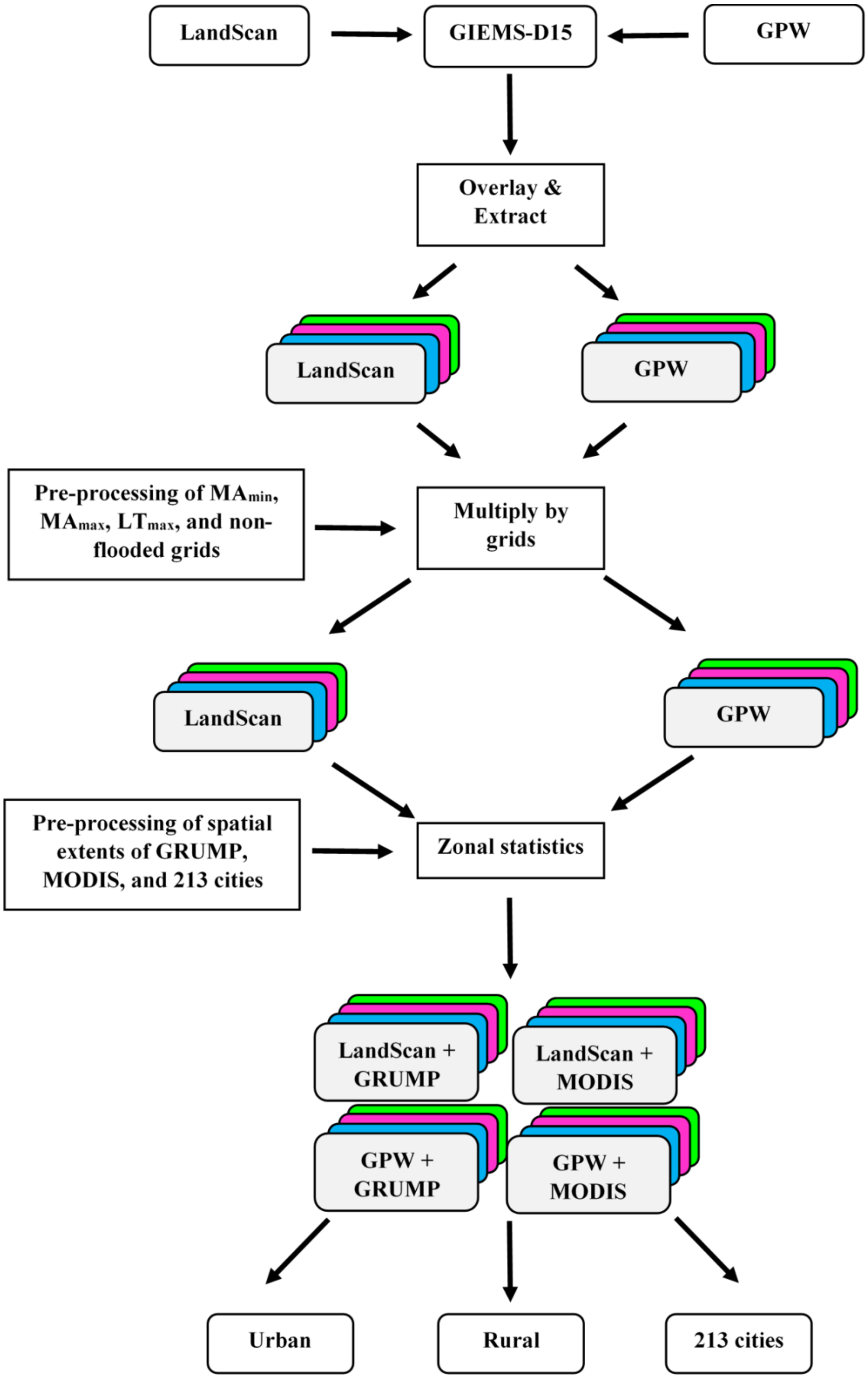

Figure 5. Schematic overview of methodology to calculate population numbers. Boxes with rounded corners represent inputs/outputs, and rectangles represent methodological steps.

3.3.5. Calculation of Disproportionate Exposure (D_E) index

Absolute exposure estimates offer a baseline for future flood-risk assessments and the potential for relative exposure analyses. However, absolute exposure of major cities around the world hold inherent biases to those cities with larger populations, especially in Asian megacities. To reconcile these discrepancies, a disproportionate exposure index was calculated for each GRUMP and MODIS urban extent by comparing the ratio of exposed population in each GIEMS-D15 zone to the respective ratio of inundated land area. Balk et al. (2012) suggest that the percentage of area exposed to in-land flooding within city limits can serve as an indicator of urban vulnerability. Although this study does not fully adopt this idea, the concept was considered in calculating the fraction of urban area exposed in each GIEMS-D15 zone, which gave rise to the disproportionate exposure (D_E) index (Equation 1):

$$\boldsymbol{Eq.\,1.} \qquad \boldsymbol{D_E = \frac{P_E}{A_E}}$$

where P_E is the fraction of urban population exposed to in-land flooding, according to GIEMS-D15; and A_E is the fraction of urban area exposed to in-land flooding, according to GIEMS-D15. The index is unitless. An index of 1 means equal distribution of exposure to in-land flooding; a value smaller than 1 signifies a higher concentration of population outside of GIEMS-D15 zones; and a value larger than 1 means a higher concentration of populations exposed to in-land flooding. The D_E index was calculated for the 213 major cities, offering insight to the biophysical exposure that each city may face.

3.3.6. Calculation of Flood Sensitivity (F_S) index

A flood sensitivity (F_s) metric was derived as a coarse, first-level proxy of in-land flood exposure under future scenarios. The F_s index is based on the assumption that, at any location, the specific increase in inundated area between the two highest flow months is characteristic of the spatial flooding pattern of a location; this change in inundation can be used as a proxy that indicates a location's sensitivity to a standardized increase in future flood discharge and its respective increase in inundated area. The F_s metric (Equation 2) was only calculated for Latin American and African cities (with populations of at least 750,000) to capture moderate to large urban centers.

To calculate the F_s index, first, the discharge of the largest river in each city was extracted for the 12 months of the year (data drawn from the HydroSHEDS product; Lehner and Grill, 2013) and ranked from highest to lowest monthly discharge. The combined inundated area (MA_{min}, MA_{max}, and LT_{max}) was multiplied by the 15 arc-second land area grid (in km^2) to yield the total land area exposed to in-land flooding. These values were calculated for each city and ranked from highest to lowest monthly inundated area. The highest and second highest months (i.e. month 12 and month 11 respectively) for maximum discharge and inundated area were then related in the following equation:

$$\textbf{Eq. 2.} \qquad \boldsymbol{F_S = \frac{(I_{12} - I_{11})/A_{city}}{(Q_{12} - Q_{11})/MQ}}$$

where I_x is the inundated area (in km^2) within the city limits in month x; A_{city} is the area of the city (in km^2); Q_x is the average discharge in month x (in cubic meters per second), and MQ is the long-term average discharge (in cubic meters per second). In this equation, the numerator shows the relative change in inundated area (in percent of total city area) between months 12 and 11, while the denominator shows the relative change in discharge (in percent of MQ) between months 12 and 11. The index is unitless. An index of 1 means that a certain percentage of change in discharge leads to the same percentage of change in inundated area (e.g., 10 percent more discharge yields 10 percent more inundation); a value larger than 1 means that a certain relative change in discharge leads to a larger change in inundation (e.g., 10 percent more discharge yields 20 percent more inundation); and a value smaller than 1 means that a certain relative change in discharge leads to lower change in inundation (e.g., 10 percent more discharge yields 5 percent more inundation). Thus, the higher the index the higher the sensitivity to increased flooding due to a standardized increase in discharge.

4. Results and Discussion

4.1. Exposure of urban and rural land area

Both globally and for all of the continental case studies, the absolute, rural area exposed to in-land flooding (according to the GIEMS-D15 zones) was magnitudes higher than in smaller scale, urban areas. In terms of relative exposure, urban land area produced higher estimates than in the rural environment (Figs. 6-10).

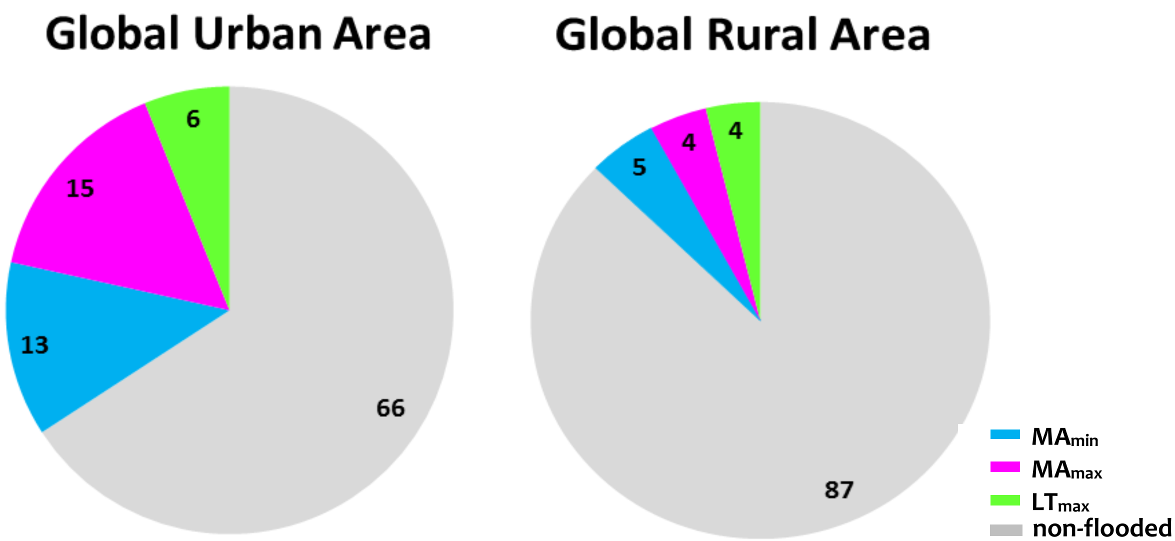

Figure 6. Proportion of total global land area within each GIEMS-D15 zone in the urban and rural context.

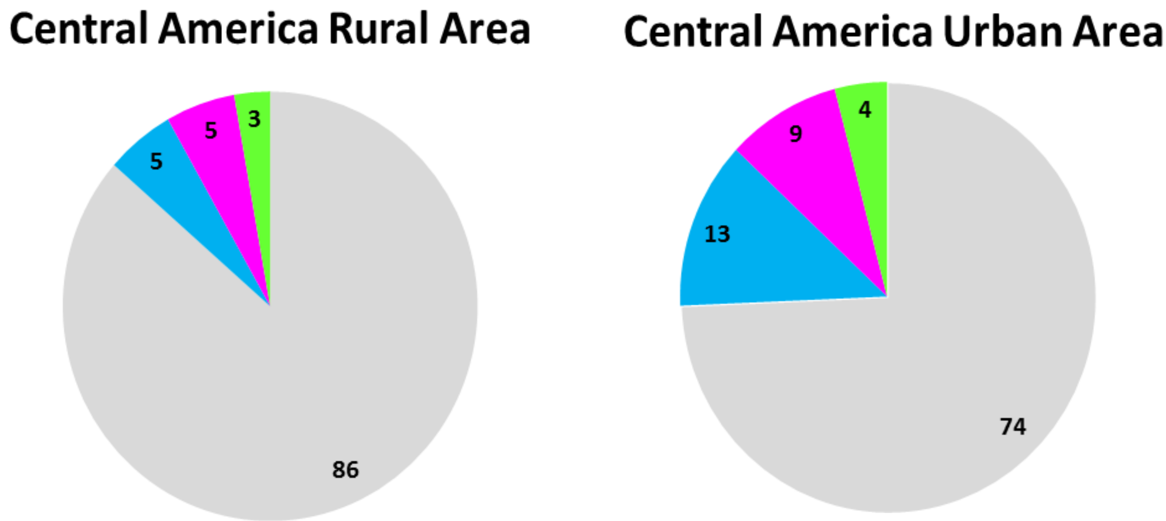

Figure 7. Proportion of total Central American land area within each GIEMS-D15 zone in the urban and rural context.

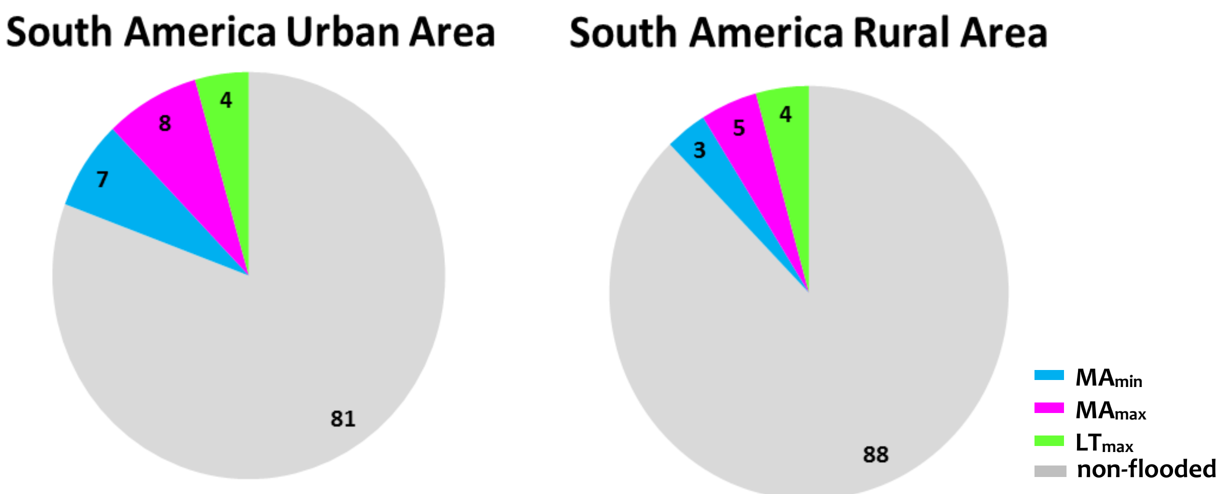

Figure 8. Proportion of total South American land area within each GIEMS-D15 zone in the urban and rural context.

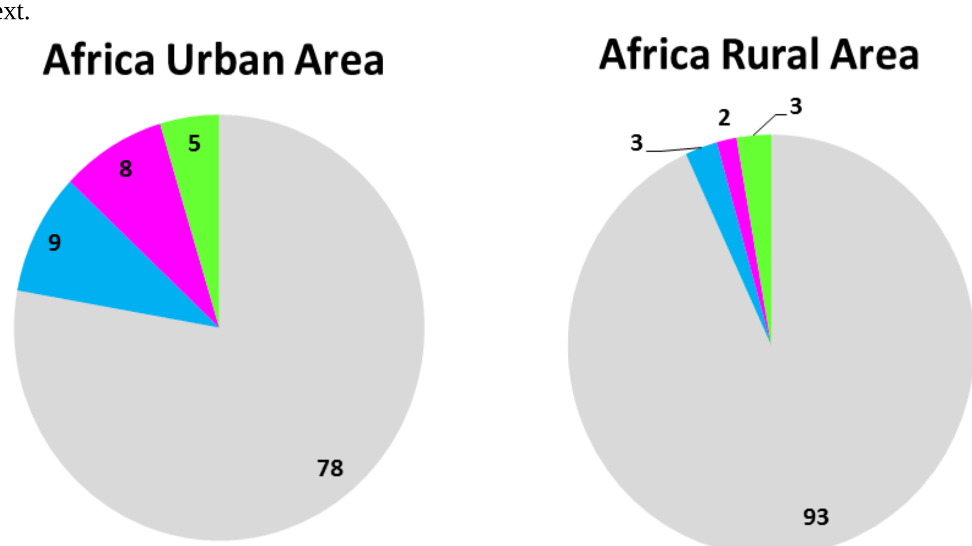

Figure 9. Proportion of total African land area within each GIEMS-D15 zone in the urban and rural context.

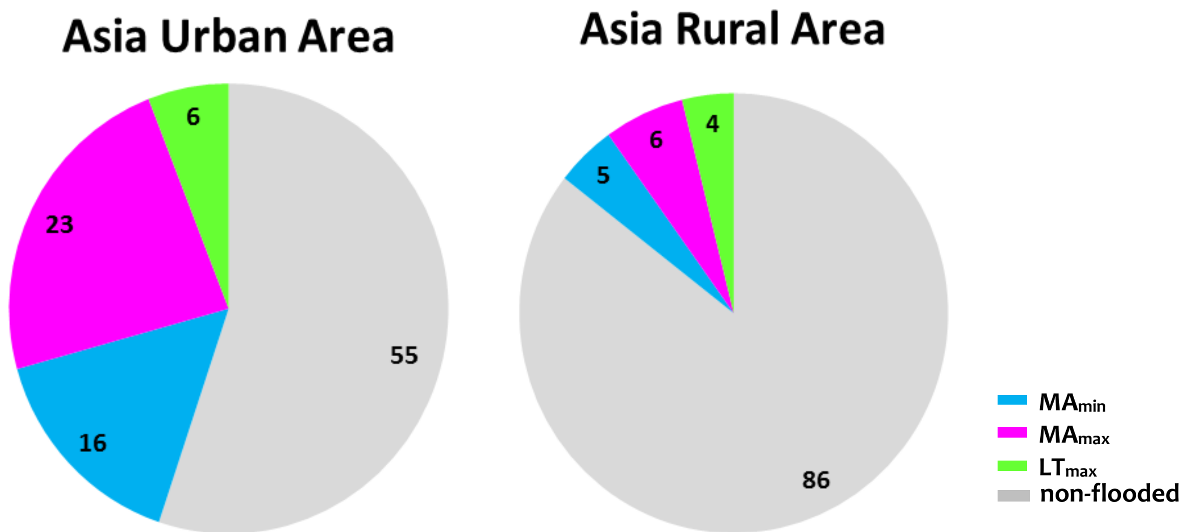

Figure 10. Proportion of total Asian land area within each GIEMS-D15 zone in the urban and rural context.

Based on relative exposure estimates, 34 percent of global urban area is exposed to in-land flooding, while it affects only 13 percent of rural landscapes. These trends begin to change in the continental assessments. In Central America, 26 percent of the urban landscape is exposed and only 13 percent of rural land area. South America, on the other hand, exhibits the smallest magnitude difference between the urban and rural land proportions, as well as the smallest proportion of urban area exposed; 19 percent of South America's urban area is exposed and 12 percent of its rural land area. The discrepancies between the Central and South American results underscore the need to disaggregate these regions from the typical 'Latin America' approach. Of all the case studies, Africa demonstrates the smallest proportion of its rural land area exposed to inundation. Like global and Central American patterns, however, the proportion of Africa's urban area exposed (22 percent) is much higher than the rural land exposure (8 percent of total land area). Finally, the proportion of Asia's urban land area exposed is the highest of all the case studies at 45 percent, while only 15 percent of Asia's rural area is exposed, similar to global trends. In the subsequent section, each continent will be placed under a microscope to extract further patterns of in-land flood exposure.

4.2. Population numbers

An estimated 2.4 billion people (average of all dataset combinations) may be exposed to in-land flooding on a global scale (Table 3), more than double the estimates produced by Jongman et al. (2012). In fact, total population estimates vary with each dataset combination. In the urban context, GRUMP urban masks generate higher total population estimates across the board; while for rural areas, MODIS captures higher total populations overall. This is likely a derivative of GRUMP urban extents including metropolitan areas in their definition; while MODIS only includes city centers in its urban definition, thus classifying suburban populations as rural.

Rural landscapes comprise 97 to 99 percent of global land area (based on GRUMP and MODIS rural masks, respectively). Comprising only a fraction of global land area, urban dwellers demonstrate a higher proportion of their total population exposed to in-land flooding (i.e., in the MA_{min}, MA_{max}, and LT_{max} combined) compared to rural inhabitants (Table 3). While rural areas

TABLE 3. Urban and rural population exposure estimates

Region	Dataset Combinations	Total Urban Pop. Exposed	Total Urban Pop.	Urban Pop. Exposed (% of Total)	Total Rural Pop. Exposed	Total Rural Pop.	Rural Pop. Exposed (% of Total)
Central America	GRUMP_GPW	12,287,983	69,177,534	18	15,142,436	99,955,396	15
	GRUMP_LandScan	24,508,200	124,146,988	20	11,120,948	58,406,453	19
	MODIS_GPW	4,806,060	24,534,060	20	23,387,055	145,623,334	16
	MODIS_LandScan	17,088,841	79,554,393	21	18,699,383	103,278,965	18
	AVERAGE	14,672,771	74,353,244	20	17,087,455	101,816,037	17
South America	GRUMP_GPW	29,874,284	140,629,720	21	22,125,994	202,414,253	11
	GRUMP_LandScan	59,731,269	258,033,143	23	13,062,881	105,047,286	12
	MODIS_GPW	17,004,542	69,946,549	24	35,998,180	274,259,844	13
	MODIS_LandScan	52,400,112	226,061,962	23	20,736,756	137,512,562	15
	AVERAGE	39,752,552	173,667,843	23	22,980,953	179,808,486	13
Africa	GRUMP_GPW	44,270,191	144,045,077	31	84,193,784	638,341,479	13
	GRUMP_LandScan	95,120,544	307,383,827	31	74,699,416	573,624,791	13
	MODIS_GPW	12,117,962	48,933,688	25	119,406,997	737,019,985	16
	MODIS_LandScan	56,118,054	195,746,975	29	114,090,870	685,802,909	17
	AVERAGE	51,906,688	174,027,392	29	98,097,767	658,697,291	15
Asia	GRUMP_GPW	490,769,256	872,028,960	56	1,137,919,984	2,765,393,332	41
	GRUMP_LandScan	937,297,595	1,702,179,322	55	1,100,245,724	2,205,503,371	50
	MODIS_GPW	207,618,708	331,223,905	63	1,430,160,735	3,316,231,492	43
	MODIS_LandScan	570,351,107	1,054,235,592	54	1,470,681,121	2,857,406,684	51
	AVERAGE	551,509,166	989,916,945	57	1,284,751,891	2,786,133,720	46
TOTAL (average of all regions)		657,841,177	1,411,965,423	47	1,422,918,066	3,726,455,534	38
Global	GRUMP_GPW	775,674,272	1,855,818,196	42	1,326,026,762	4,109,515,445	32
	GRUMP_LandScan	1,379,651,277	3,193,764,621	43	1,251,525,585	3,199,741,693	39
	MODIS_GPW	349,232,058	762,951,047	46	1,772,689,057	5,225,091,750	34
	MODIS_LandScan	885,213,287	2,115,365,208	42	1,752,210,850	4,285,594,816	41
	AVERAGE	847,442,724	1,981,974,768	43	1,525,613,064	4,204,985,926	37

exhibit higher absolute exposure estimates (i.e. an average of 1.5 billion for all dataset combinations), relative exposure indicates that about 43 percent of the global urban population may be exposed to in-land flooding, with approximately 37 percent of the total rural population exposed (Fig. 11). These high percentages for the globe are largely driven by the continent of Asia, and for all other continents included in this study, estimates are lower.

Figure 11. The total global population in urban and rural environments according to each dataset combination, i.e. GRUMP and GPW, MODIS and GPW, GRUMP and LandScan, and MODIS and LandScan, as well as the average exposure for all datasets.

With this global inclination, four continental case studies were conducted for regional comparisons following the same methodology (Figs. 12-15).

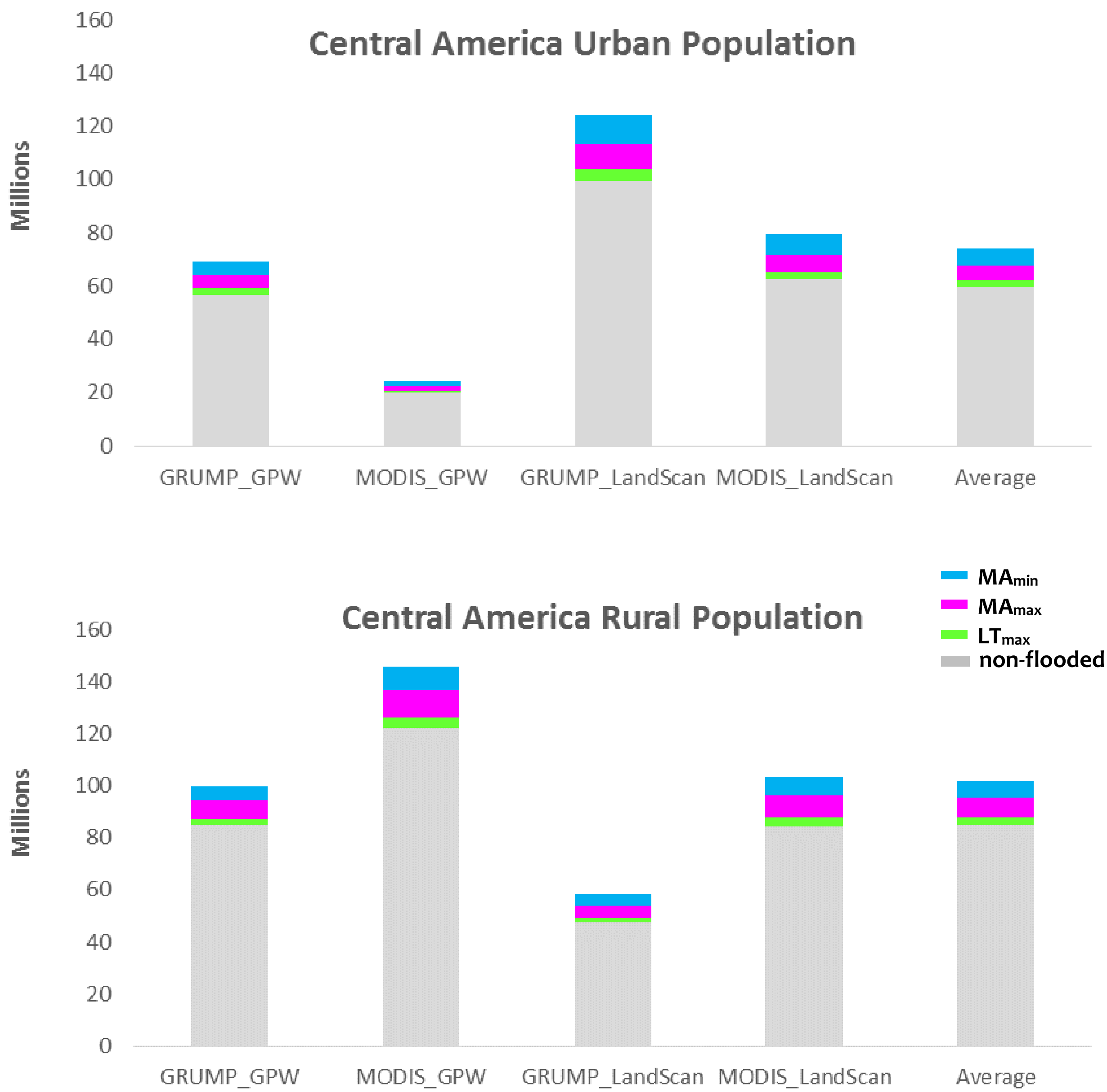

Figure 12. The total Central American population in urban and rural environments according to each dataset combination, i.e. GRUMP and GPW, MODIS and GPW, GRUMP and LandScan, and MODIS and LandScan, as well as the average exposure for all datasets.

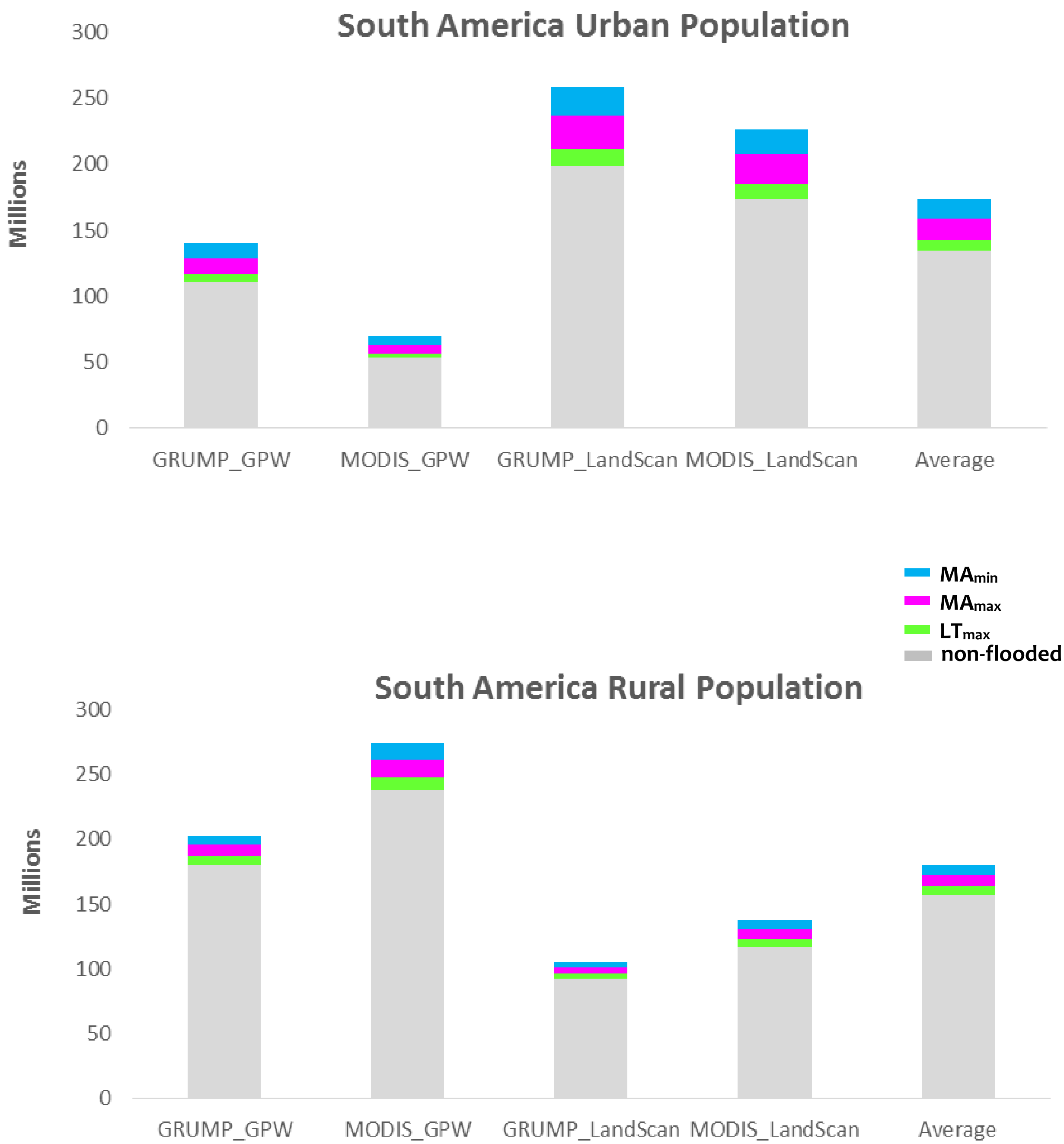

Figure 13. The total South American population in urban and rural environments according to each dataset combination, i.e. GRUMP and GPW, MODIS and GPW, GRUMP and LandScan, and MODIS and LandScan, as well as the average exposure for all datasets.

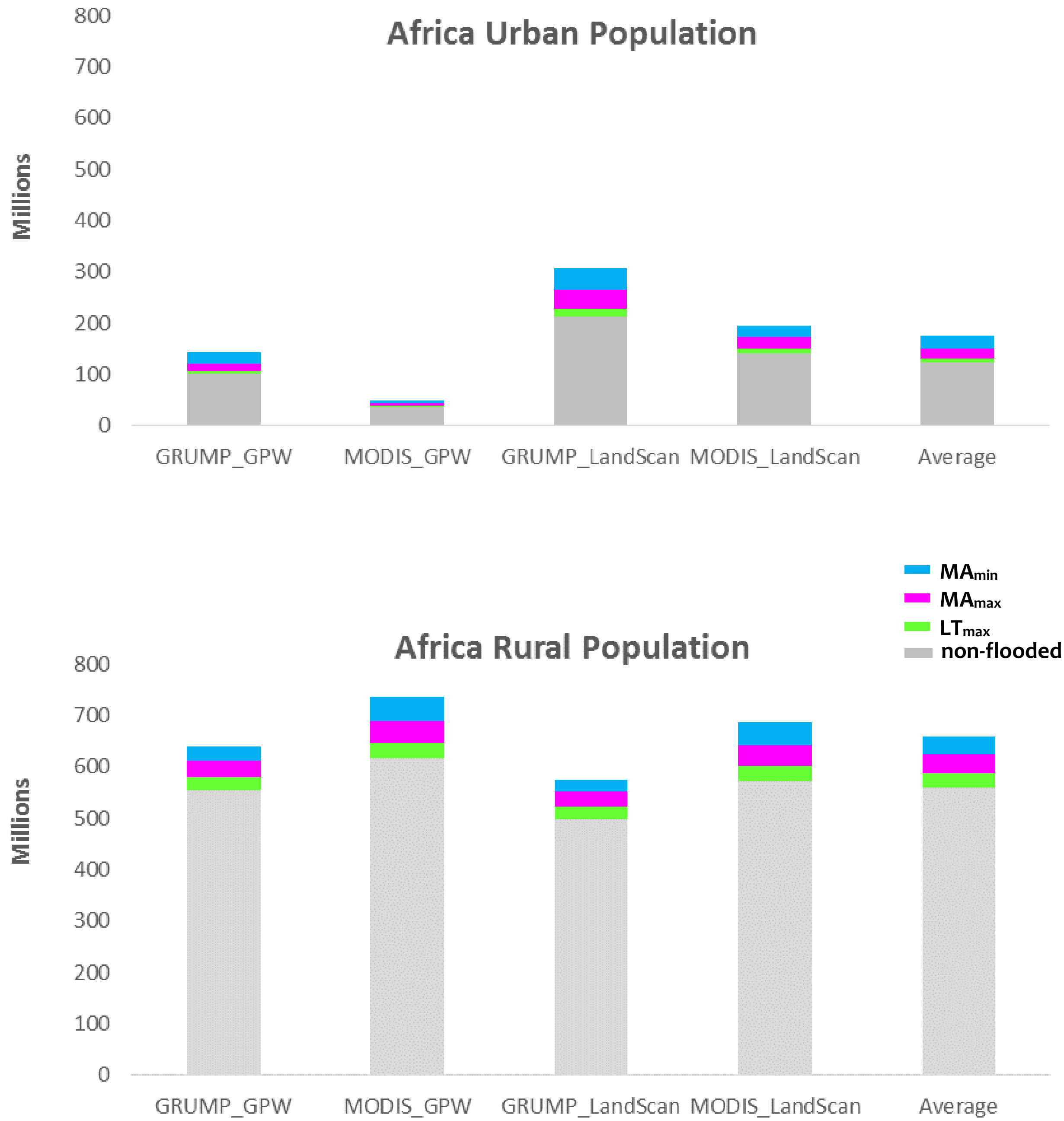

Figure 14. The total African population in urban and rural environments according to each dataset combination, i.e. GRUMP and GPW, MODIS and GPW, GRUMP and LandScan, and MODIS and LandScan, as well as the average exposure for all datasets.

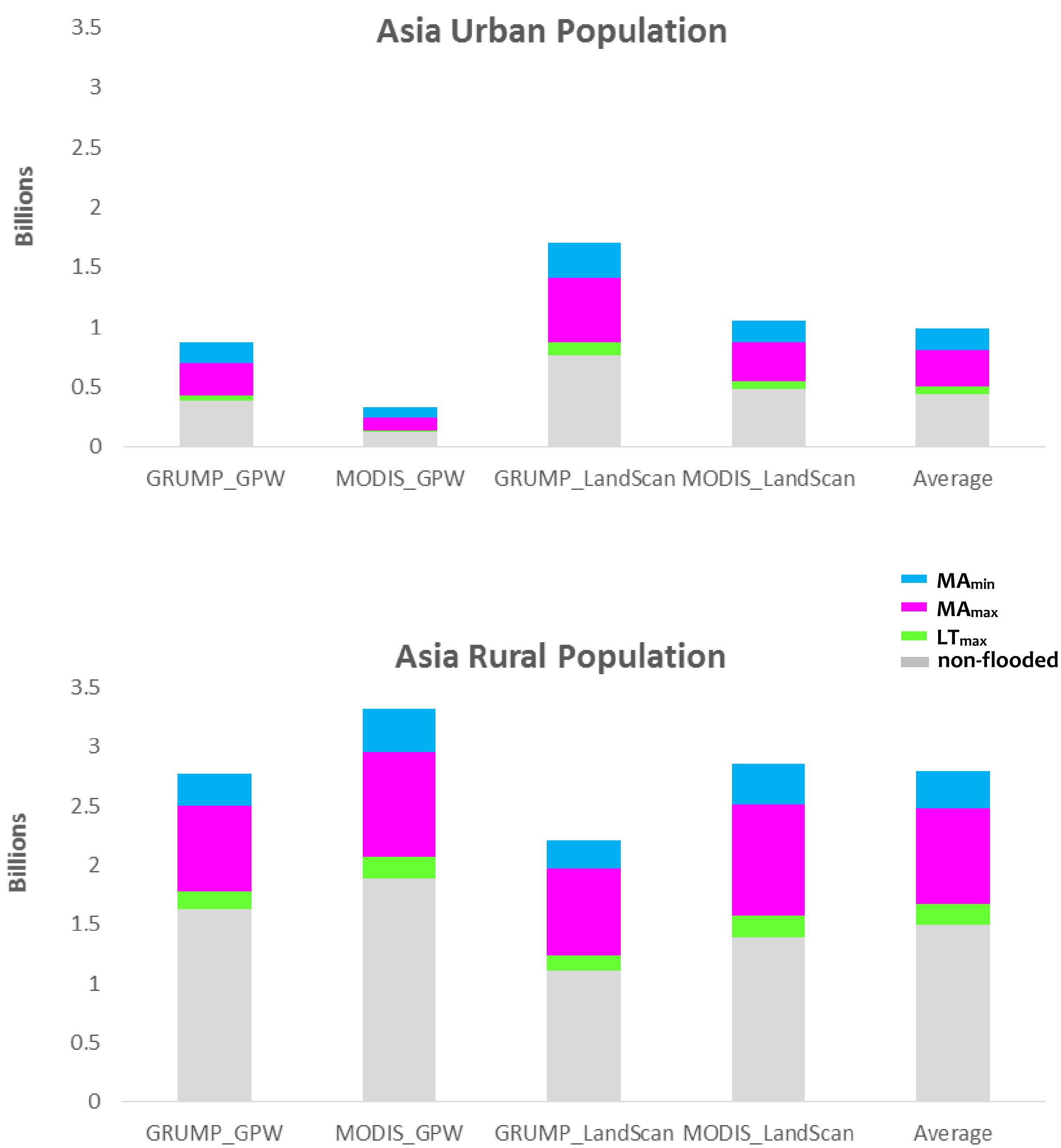

Figure 15. The total Asian population in urban and rural environments according to each dataset combination, i.e. GRUMP and GPW, MODIS and GPW, GRUMP and LandScan, and MODIS and LandScan, as well as the average exposure for all datasets.

Central America, South America, Africa and Asia all demonstrate their own unique trends regarding urban and rural exposure (Figs. 12-15). Each region shows higher proportions of urban dwellers exposed to in-land flooding than their rural counterparts at varying magnitudes. While rural areas exhibit higher absolute exposure estimates, the relative exposure estimates tell a different story for each region.

In Central America, the disparity between absolute exposure estimates of urban and rural environments (i.e. an average of almost 15 million exposed in urban spaces and 17 million in rural areas) is much smaller than global trends. Relative exposure indicates that about 20 percent of Central America's urban population is exposed to in-land flooding (with approximately 17 percent of the total rural population exposed), both of which are smaller than comparable global proportions. In South America, the difference between absolute exposure estimates of urban and rural environments is more paramount than in Central America. In fact, by averaging the dataset combinations, nearly 40 million are exposed in urban spaces and only 23 million in rural areas. This is the only case study by which the absolute exposure estimates in the urban masks are higher than in rural areas. Relative exposure also indicates that an average of 23 percent of South America's urban population is exposed to in-land flooding (with approximately 13 percent of the total rural population exposed). Once again, relative exposure estimates in urban South America are higher than in rural environments.

African trends of population exposure are similar to those on the global scale and for Central America, i.e. the data estimate higher absolute exposure in the rural context but higher relative exposure in urban environments. An average of 393 million rural inhabitants may be exposed to in-land flooding and nearly 52 million in cities. Africa holds the second highest absolute exposure estimates of all the case studies for both rural and urban space. Relative exposure indicates that about 30 percent of Africa's urban population is exposed to in-land flooding (with approximately 15 percent of the total rural population exposed), both of which are smaller than comparable global proportions.

Lastly, Asia generated the highest absolute and relative exposure estimates for rural and urban space; an average of 1.3 billion rural Asians may be exposed to in-land flooding and more than 550 million urban dwellers. Relative exposure shows that about 57 percent of Asia's urban population may be exposed to in-land flooding (with approximately 46 percent of the total rural population exposed), both of which are higher than comparable global proportions.

4.3. Exposure in 213 major cities

On the basis of global inundation extents (the aggregate of all GIEMS-D15 zones) and population incidence, estimates of in-land flood exposure range from 142 to 288 million (based on GPW circa the year 2000) and 275 to 424 million (based on LandScan population data circa the year 2006) for the 213 major cities in this assessment (Table 4). By 2050, these numbers are projected to increase as a function of rapid population growth in urban centers, especially in developing countries (Jongman et al., 2012).

TABLE 4. Total population exposed (in millions) for the 213 cities

	GRUMP (2000)	MODIS (2001)
GPW (2000)	288	142
LandScan (2006)	424	275

After quantifying the total population exposed for each of the 213 major cities worldwide, they were ranked from highest to lowest. The Top 10 cities (Fig. 16) with highest absolute exposure dominantly span Asia with select cities in Brazil and France. Manila tops out with approximately 13 million of its urban population exposed to in-land flooding. This represents 90 percent of its total urban population. However, as stated previously, GIEMS-D15 represents areas exposed to in-land flooding based on natural topography. Thus, the exposure estimates do not explicitly reflect

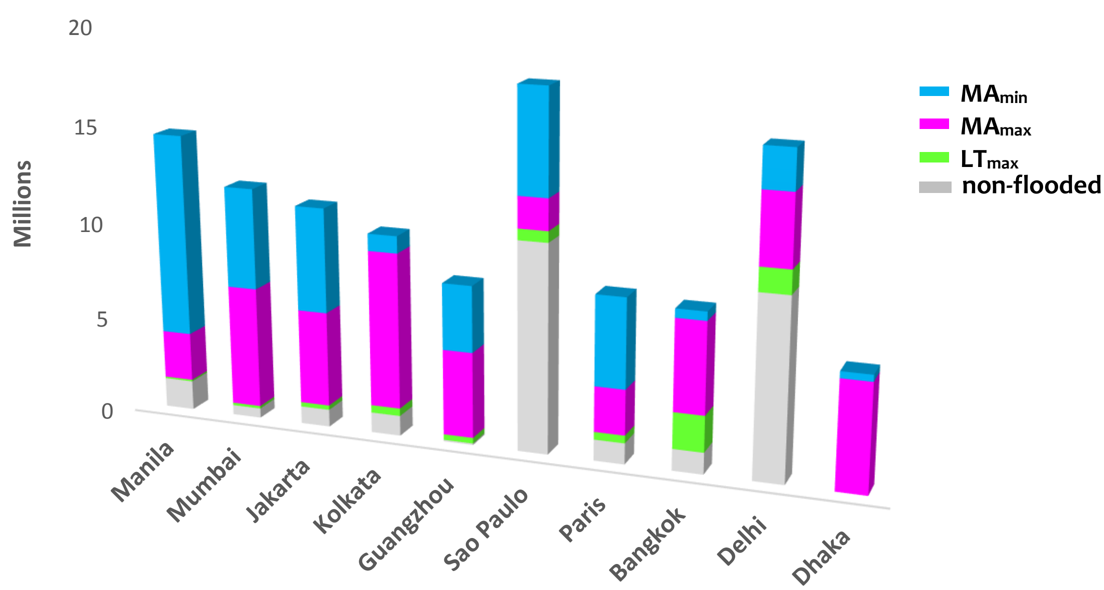

Figure 16. Top 10 urban extents with highest absolute exposure estimates and the total population in each GIEMS-D15 zone.

any mitigative measures (e.g. dams and levees) that minimize flooding in these cities. For instance, Paris yielded higher absolute exposure to inundation than Dhaka. In reality, based on DFO records between 1990 and 2005, Bangladesh suffered the loss of nearly 145,000 people and more than 112 million displaced persons; while France experienced about 230 fatalities and less than 394,000 displaced persons for the same time period. This demonstrates bias in the exposure estimates that are largely driven by the total population of each city (i.e. higher exposure is often correlated with higher total population). The exposure hotspots are also clustered geographically, specifically in Asia (Fig. 17) and along the coasts (Figs. 18 and 19). Not only can these patterns be attributed to many factors (e.g. widespread urbanization and high population density in Asian cities), but also, the GIEMS-D15 dataset tends to overestimate inundated area around coastlines (i.e. where inundation is influenced by coastal flooding and cannot be properly delineated).

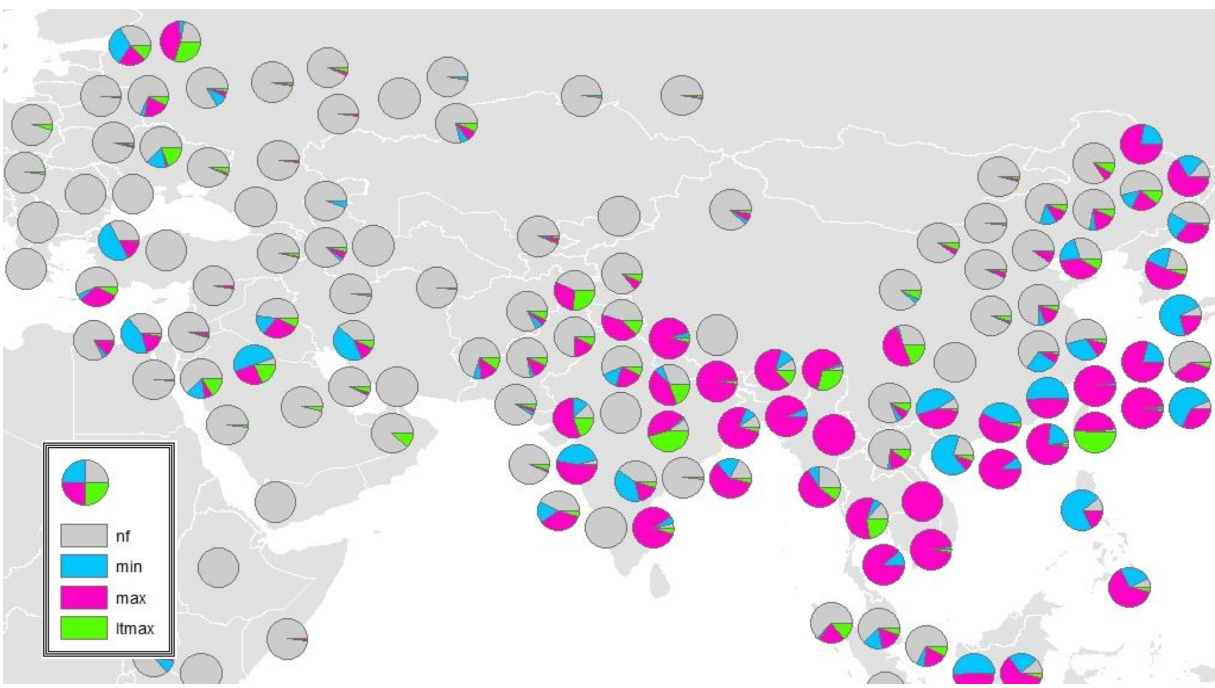

Figure 17. Ratio of flood exposure in each GIEMS-D15 zone for Asian cities, whereby 'nf' represents non-flooded areas; 'min' refers to the MA_{min}; 'max' refers to the MA_{max}; and 'ltmax' represents the LT_{max}.

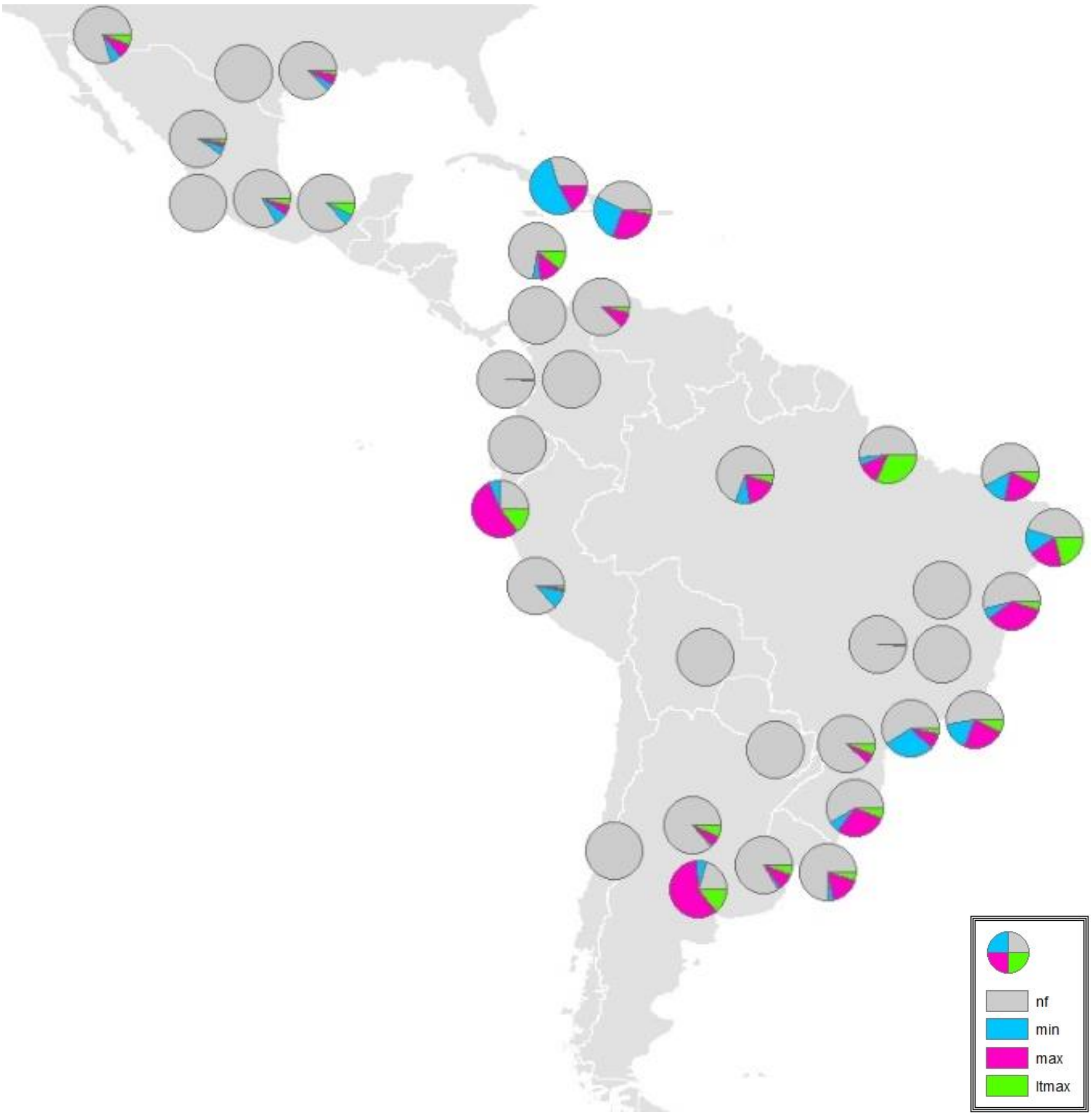

Figure 18. Ratio of flood exposure in each GIEMS-D15 zone for Latin American cities, whereby 'nf' represents non-flooded areas; 'min' refers to the MA_{min}; 'max' refers to the MA_{max}; and 'ltmax' represents the LT_{max}.

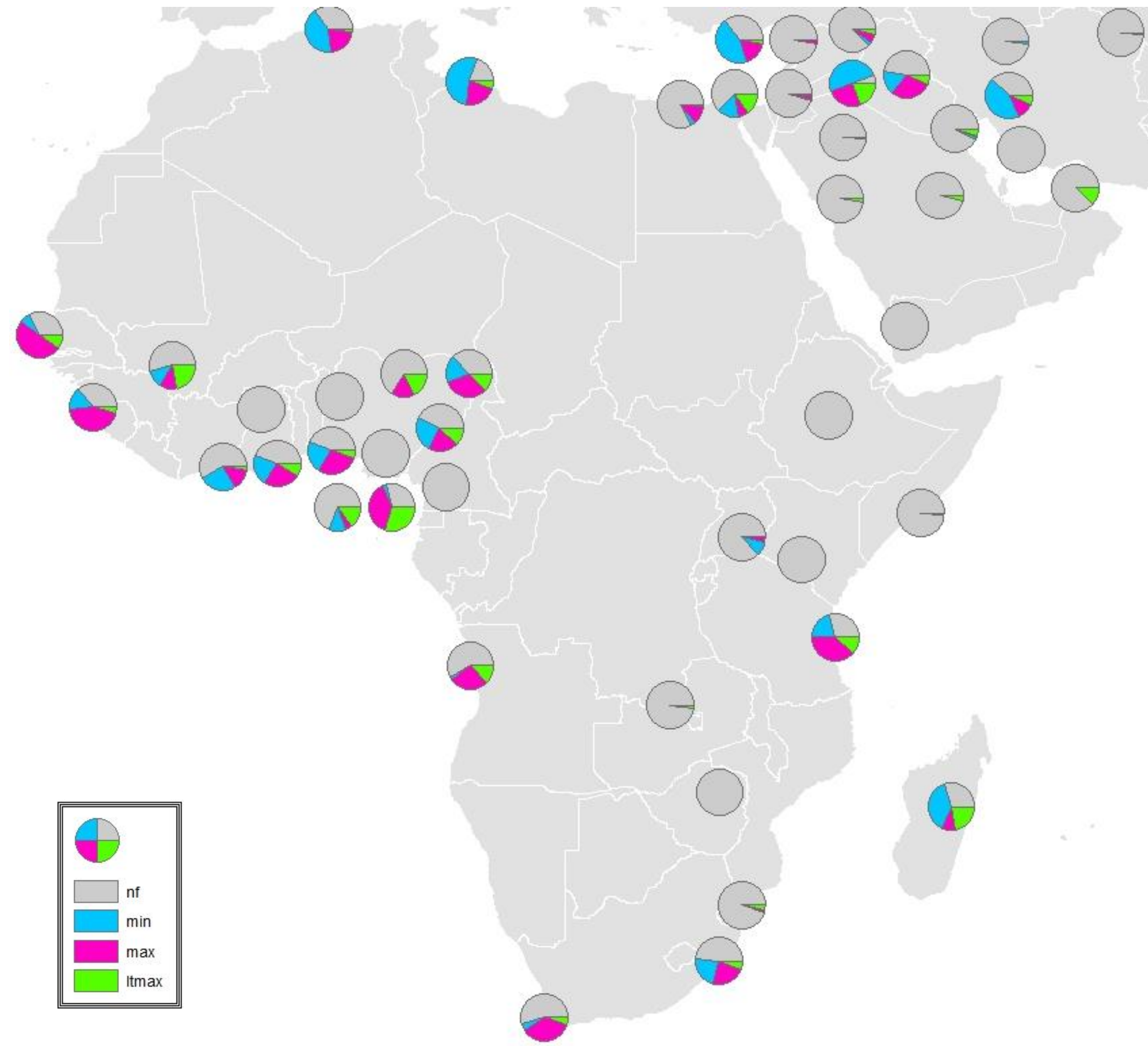

Figure 19. Ratio of flood exposure in each GIEMS-D15 zone for African cities, whereby 'nf' represents non-flooded areas; 'min' refers to the MA_{min}; 'max' refers to the MA_{max}; and 'ltmax' represents the LT_{max}.

Each of the 213 cities produced four distinct exposure estimates. Of these, a sample of 20 urban extents with the highest and lowest fraction of their total urban population exposed were displayed to demonstrate the magnitude of discrepancy amongst the various dataset combinations (Fig. 20).

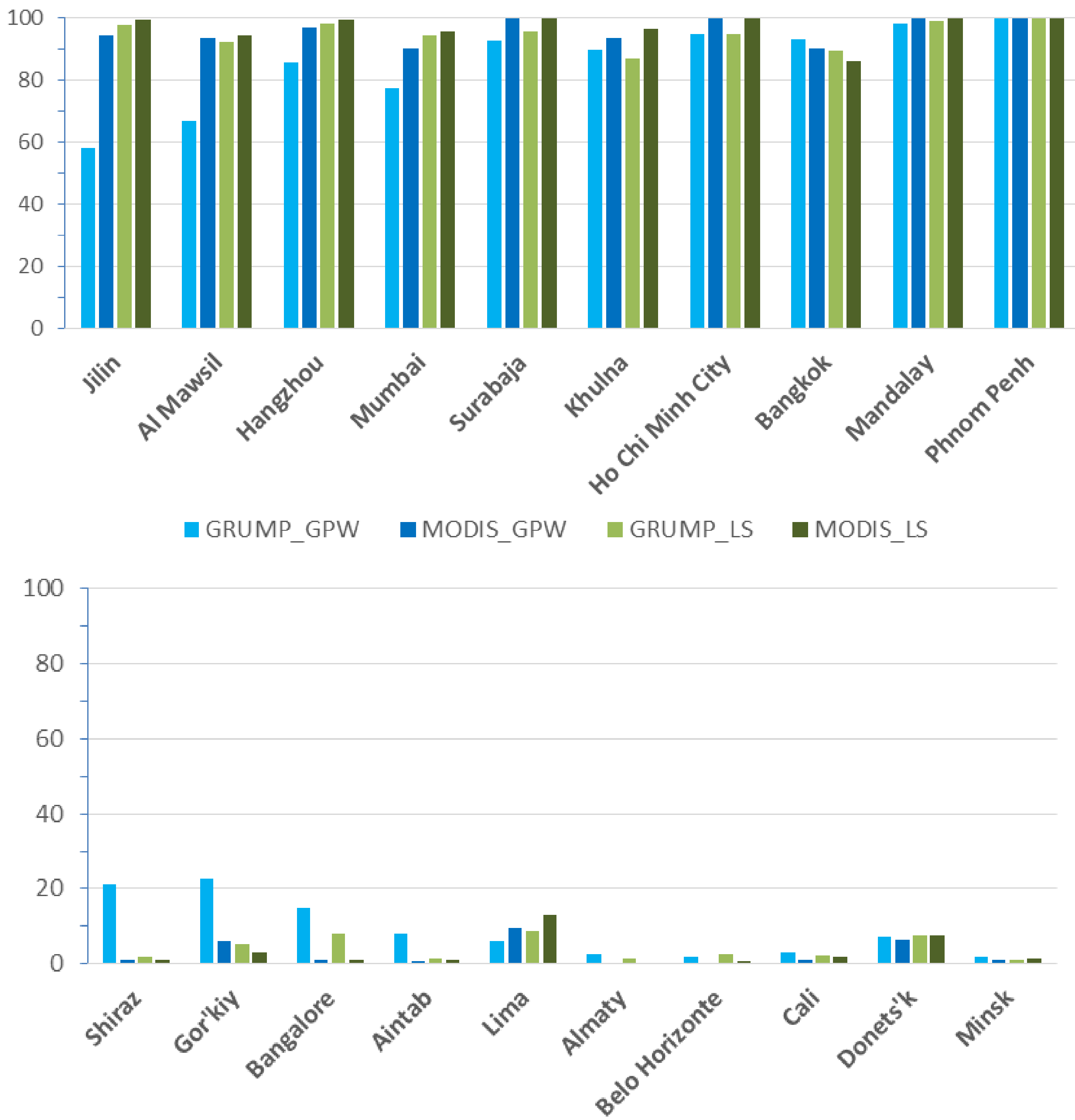

Figure 20. Ratio of flood exposure of 20 cities with varying degrees of deviation amongst the four dataset combinations, as well as diverse fractions of their total urban populations exposed to in-land flooding based on GIEMS-D15 estimates.

Jilin, China, shows the highest standard deviation. Depending on which dataset combination used, the proportion of in-land flood exposure ranges from 58 to 100 percent of its total population. For Khulna, Bangladesh, the difference between exposure estimates is less, varying from 87 to 97 percent of its total population. Moreover, the Phnom Penh, Cambodia, population ranks at 100 percent exposed for all four dataset combinations, demonstrating the exposure variability between both cities themselves and different datasets.

The D_E metric offers insight to relative exposure and how critical areas vary geographically (Fig. 21). For example – in the case of Jilin, China – nearly 100 percent of its population is exposed to in-land flooding; while only 88 percent of its urban area is within one of the GIEMS-D15 zones. This suggests that the population is more highly concentrated in flood-prone areas compared to the land area within GIEMS-D15 zones. The difference between the population and area ratios provided a D_E metric for the 213 cities (Figs. 22-25). Of the Top 50 cities ranked by highest D_E, 56 to 86 percent reside in developing countries; 22 to 48 percent in Asia; 10 to 16 percent in Africa; and 10 to 18 percent in South America, all of which are dependent on the dataset combinations used. This provides a small glimpse into the lack of uniformity of exposure across urban centers, countries, and continents. While the D_E metric offers insight to geographic hotspots, another important indicator of relative exposure is to assess the urban population exposed as a fraction of each country's total urban population, i.e. according to the 213 major cities in this study only (Fig. 26).

Figure 21. D_E values for 213 cities in this study according to MODIS (blue) and GRUMP (red) urban extents with GPW (darker shades) and LandScan (lighter shades) population data. The symbol size in the legend represents a D_E value of 1.6; symbols of this size and larger signify a higher concentration of populations exposed to in-land flooding (according to GIEMS-D15 zones). Smaller symbol sizes generally represent either equal distribution or higher concentration of populations outside of GIEMS-D15 zones.

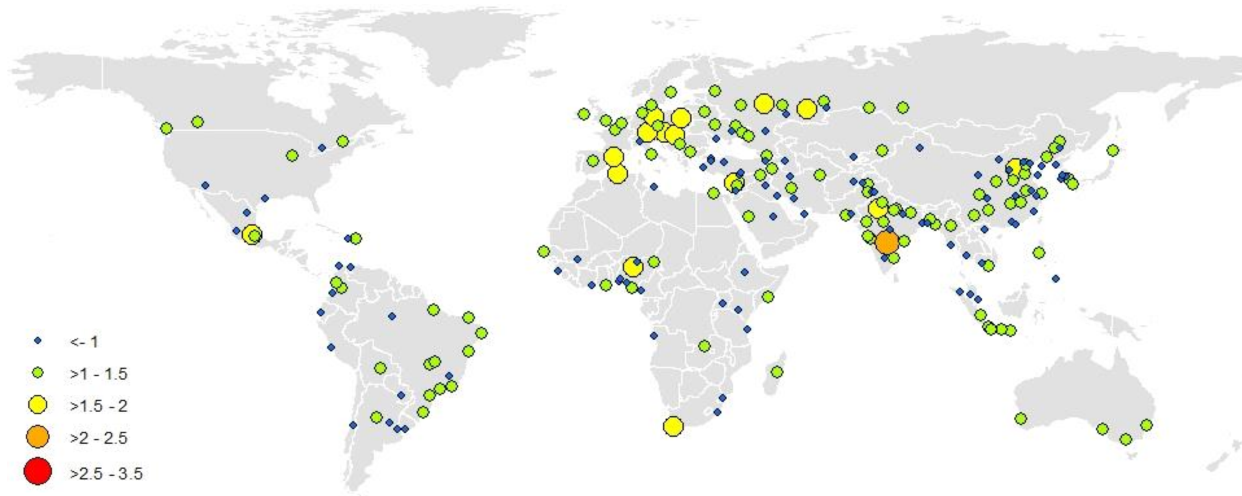

Figure 22. 213 cities from lowest to highest D_E delimited by GRUMP urban extents and GPW. An index of 1 means equal distribution of exposure to in-land flooding; a value smaller than 1 signifies a higher concentration of population outside of GIEMS-D15 zones; and a value larger than 1 means a higher concentration of populations exposed to in-land flooding.

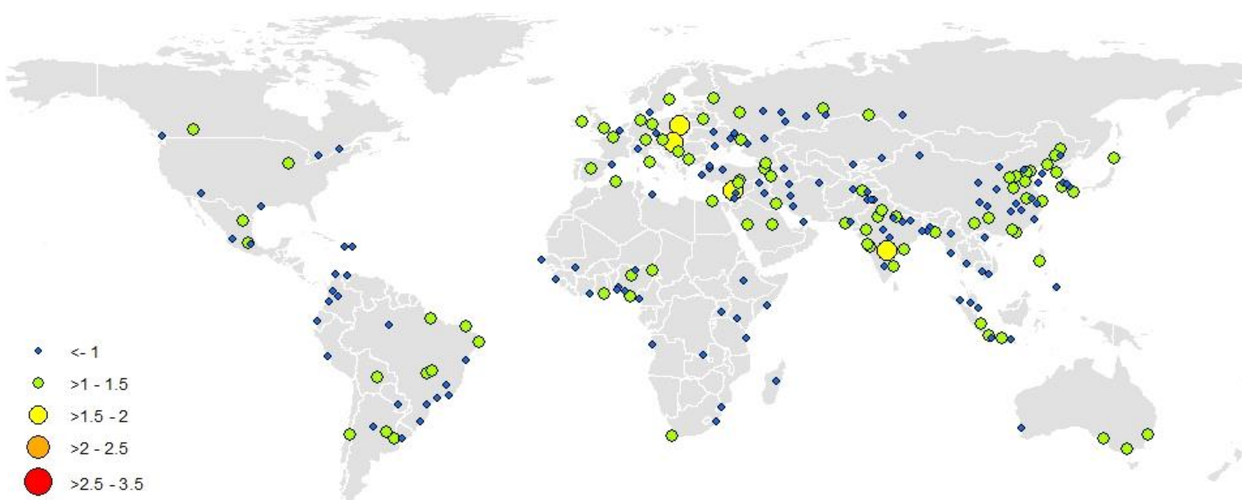

Figure 23. 213 cities from lowest to highest D_E delimited by MODIS urban extents and GPW. An index of 1 means equal distribution of exposure to in-land flooding; a value smaller than 1 signifies a higher concentration of population outside of GIEMS-D15 zones; and a value larger than 1 means a higher concentration of populations exposed to in-land flooding.

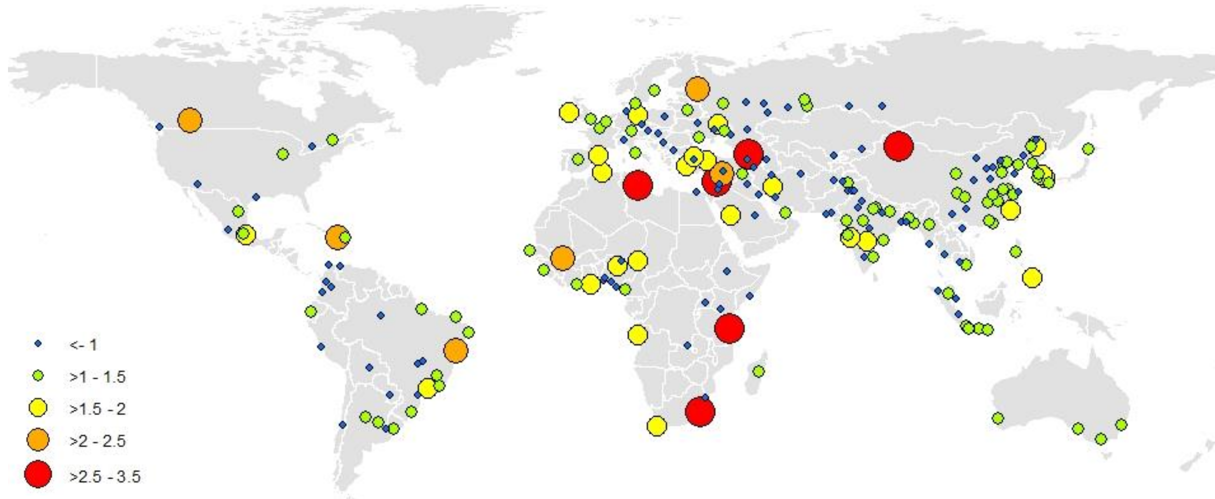

Figure 24. 213 cities from lowest to highest D_E delimited by GRUMP urban extents and LandScan. An index of 1 means equal distribution of exposure to in-land flooding; a value smaller than 1 signifies a higher concentration of population outside of GIEMS-D15 zones; and a value larger than 1 means a higher concentration of populations exposed to in-land flooding.

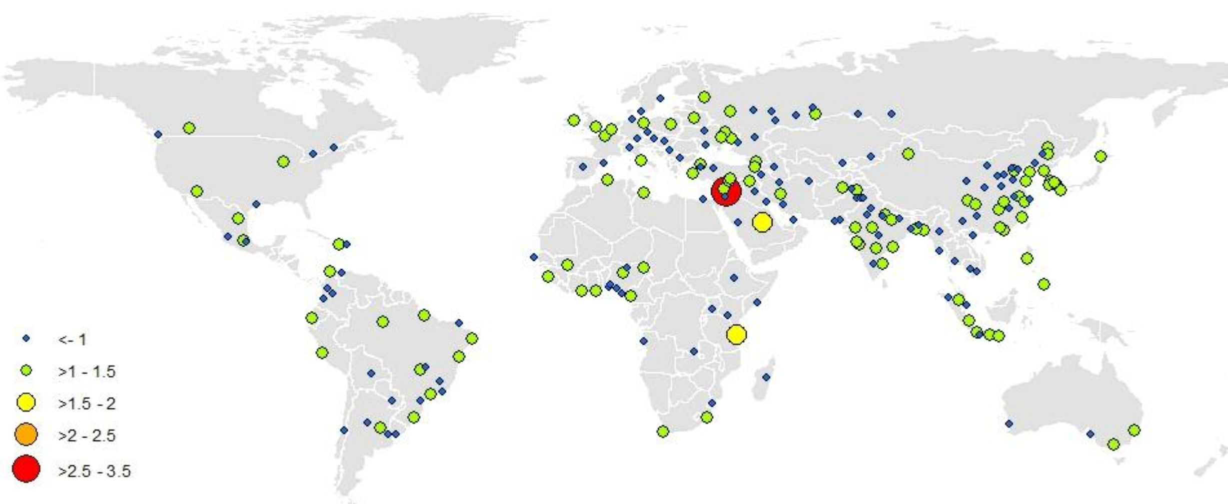

Figure 25. 213 cities from lowest to highest D_E delimited by MODIS urban extents and LandScan. An index of 1 means equal distribution of exposure to in-land flooding; a value smaller than 1 signifies a higher concentration of population outside of GIEMS-D15 zones; and a value larger than 1 means a higher concentration of populations exposed to in-land flooding.

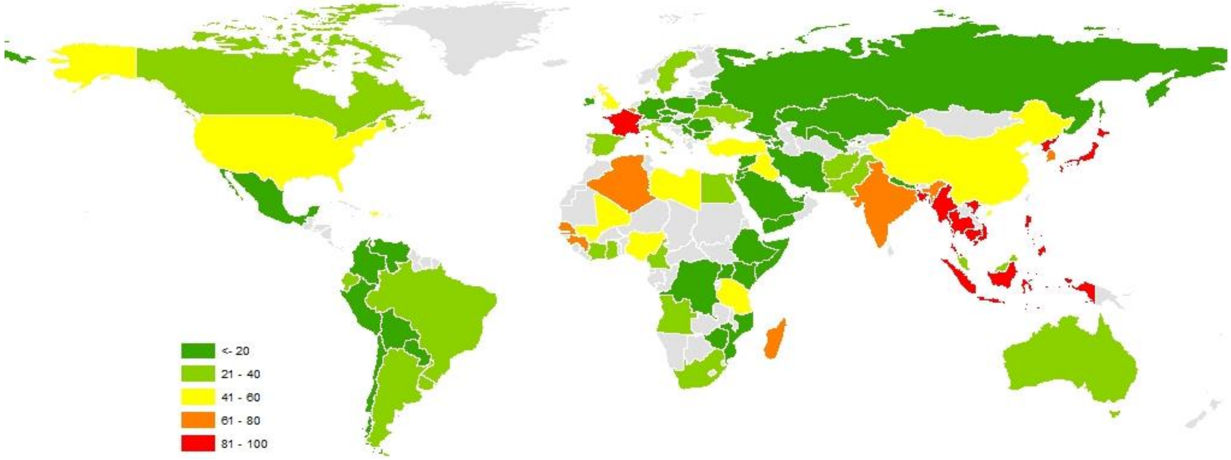

Figure 26. Exposed urban population as a percentage of total urban population per country (average of all four dataset combinations).

Each result tells a different story. Estimates of D_E are generally highest when delimited by GRUMP urban extents as compared to MODIS derived urban extents (Figs. 21 - 25). In general, LandScan yields higher estimates of D_E than GPW across the globe. The disparity between dataset combinations also varies geographically. Regions in Western Asia, as well as Coastal and Western Africa, show relatively large differences between datasets; while smaller inequity is found between datasets in parts of North America and Australia (Fig. 21), potentially an outcome of more consistent population data in developed nations.

Of all the dataset combinations, the minimum D_E index is 0.06 in Addis Ababa, Ethiopia, meaning that the city's population is more concentrated outside of GIEMS-D15 zones. The maximum D_E index is 3.3 in Dar es Salaam, Tanzania, meaning that the city's population is more concentrated within GIEMS-D15 zones compared to non-flooded areas. The GRUMP and LandScan dataset combination had the largest range of D_E estimates, generating the highest D_E index in Dar es Salaam, as well as the second lowest D_E of 0.07 in Shiraz, Iran.

Considering relative exposure, i.e. in relation to a country's total urban population (Fig. 26), Cambodia, Vietnam, Bangladesh, Thailand, and Japan are the top 5 exposed countries to in-land flooding (ranging from 85 to 100 percent of their total urban population exposed). Senegal, Madagascar, Guinea, Algeria, and Tanzania are the top 5 countries in Africa, with between 60 and 70 percent of their total urban population exposed. The high proportion of urban exposure in France (Fig. 26) is likely a derivative of high estimates in Paris, the only city in France that was included in this study (i.e. based on the criteria of at least 1 million people and a one-to-one relationship between city point data and its respective urban polygon). These maps alone show the variability of exposure and how it can be skewed depending on the parameters and units used. Regardless, this study is able to tease out the areas most critically exposed to in-land flooding based on both urban population estimates and land area ratios.

4.4. Validation of population assessments

With the exposed urban population estimates and disproportionate exposure (i.e. absolute and relative exposure) based on these GIS analyses, other literature were identified for means of comparison. The 16 matching city records in the Balk et al. (2012) study and the GIEMS-D15 dataset were extracted for direct, by-number comparisons (Table 5). The 16 cities spanned eight different countries and were plotted in four regression models (for each of the four GIEMS-D15 dataset combinations) to draw further comparison (Fig. 27).

TABLE 5. By-number comparisons of Balk et al. (2012) findings and GIEMS-D15 estimates

City Name	Country	GIEMS-D15 (GRUMP + GPW)	GIEMS-D15 (GRUMP + LandScan)	GIEMS-D15 (MODIS + GPW)	GIEMS-D15 (MODIS + LandScan)	Balk Estimates (GRUMP 2000)
Dhaka	Bangladesh	9,447,411	11,179,682	3,346,978	5,846,864	5,400,650
Phnom Penh	Cambodia	1,020,323	1,178,781	404,557	866,841	988,020
Tianjin	China	3,135,634	4,180,873	1,507,820	3,384,494	2,753,680
Wuhan	China	1,306,837	5,585,209	309,626	4,306,219	5,282,380
Shanghai	China	8,506,237	6,853,663	5,370,469	5,545,051	3,701,250
Nanjing	China	1,992,754	4,402,468	203,685	2,701,920	2,217,720
Changsha	China	1,987,312	2,838,487	687,710	2,221,856	1,126,470
Hangzhou	China	2,657,116	5,088,334	593,078	2,191,234	1,152,880
Patna	India	1,516,226	2,804,435	403,512	1,826,137	1,110,040
Delhi	India	8,862,870	9,249,571	5,464,440	6,861,717	2,702,590
Kolkata	India	14,435,982	15,904,220	7,127,379	9,245,557	2,298,870
Palembang	Indonesia	1,059,387	929,990	606,278	815,585	1,115,160
Manila	Philippines	10,195,380	16,100,038	7,478,792	12,942,756	2,939,830
Pusan	South Korea	451,793	422,871	15,442	14,924	1,218,670
Hanoi	Vietnam	2,700,153	2,829,981	925,143	1,308,930	887,231
Ho Chi Minh City	Vietnam	5,290,214	5,726,877	2,887,359	3,708,540	2,811,610

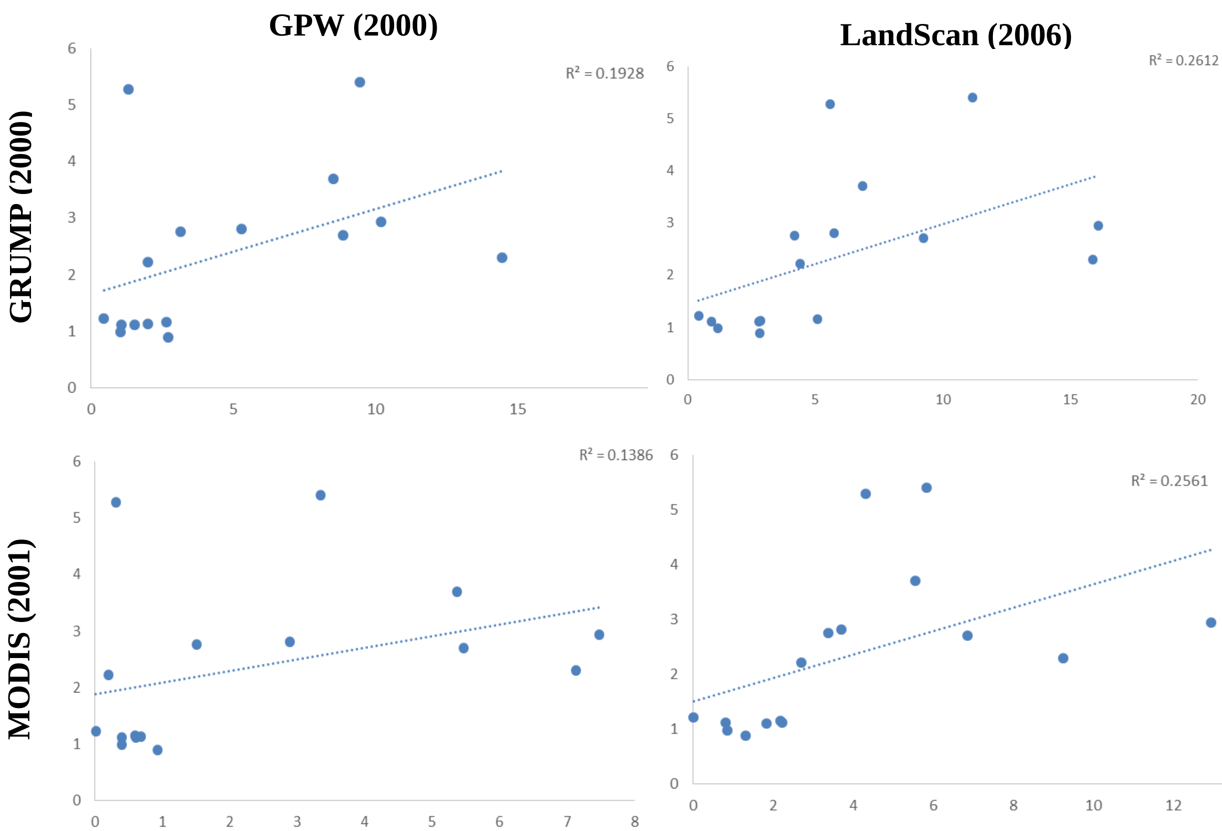

Figure 27. Regression plots comparing the exposed population (in millions) in Asian cities according to: (1) four GIEMS-D15-generated estimates (x-axes) and (2) the Balk et al. (2012) study findings (y-axes).

Balk et al. (2012) defined in-land flood exposure as areas susceptible to at least a 1-in-50 year flood. The aggregate of the GIEMS-D15 zones (i.e. the MA_{min}, MA_{max}, and LT_{max}) is most appropriate to compare to the Balk-derived estimates, as the LT_{max} is designed to represent a less frequent event but of an unknown return-period. The r-squared values of all show little to no correlation between the two variables. Both the GIEMS-D15 method and the Balk et al. (2012) study use GRUMP urban extents coupled with GPW population that excludes much of the population in some cities (based on visual inspection and clear spatial mismatching). In cities such as Pusan, South Korea, Wuhan, China, and Palembang, Indonesia, Balk et al. (2012) generated higher estimates of in-land flood exposure than the GIEMS-D15-based method; while GIEMS-D15 generated higher estimates in cities like Shanghai, China, Delhi, India, and Kolkata, India. Still, it is unclear whether either method generates reasonable estimates of in-land flood exposure compared to actual impacted persons in historic flood events.

Based on DFO confirmed fatalities and displaced persons from 1990 to 2005, the total deaths reached 443,623 and 417,314,511 displaced persons globally for the 88 impacted countries (see Table A-2 in Appendix for raw data). The data show the statistics aggregated for each country: (1) the exposed urban population according to the GIEMS-D15 method; (2) the fraction of exposed urban population (since the city results can be easily attributed to individual countries) compared to the total city population according to LandScan (2006) estimates and MODIS urban extents; (3) the confirmed fatalities between 1990 and 2005 drawn from DFO records; (4) the confirmed displaced persons between 1990 and 2005 derived from DFO archives; (5) and the confirmed impacted persons between 1990 and 2005, found by adding the fatalities and displaced persons. Since the GIEMS-D15 dataset has a POR from 1990 to 2005, it is appropriate to compare exposure estimates to DFO events in the same timeframe.

In addition to the raw data, a logarithmic plot was used to further compare the confirmed impacted people drawn from the DFO archive to the GIEMS-D15 estimates of exposed urban population for each country (Fig. 28). India and China, two of the most populous and exposed countries according to GIEMS-D15 estimates, also yield large numbers of confirmed impacted people recorded by DFO. Some of the largest outliers are shown in Nepal, Zimbabwe, Austria,

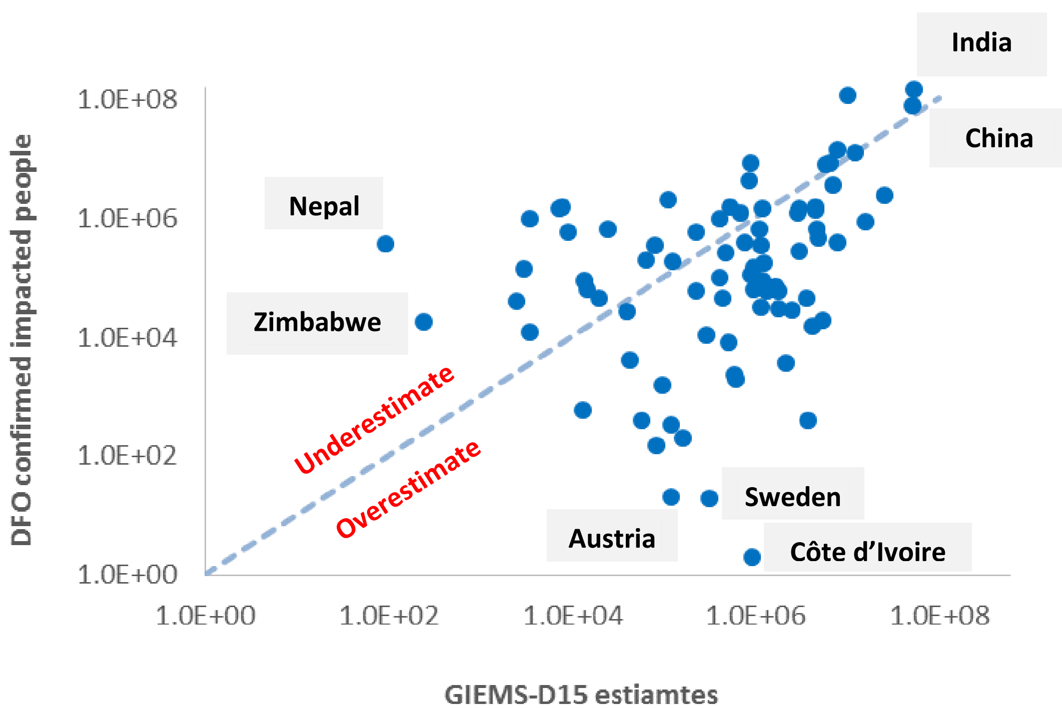

Figure 28. Comparison of GIEMS-D15 exposure estimates to confirmed DFO impacted persons between 1990 and 2005 for each country. Points above the 1-to-1 line denote underestimation of GIEMS-D15 compared to actual impacted persons; points below represent overestimation.

Sweden, and Côte d'Ivoire (i.e. the Ivory Coast). The under- and overestimation in these countries can be attributed to a variety of factors.

First, in developing countries – like Nepal and Zimbabwe – the confirmed impacted persons over the last 30 years is orders of magnitude higher than the in-land flood exposure estimates generated from GIEMS-D15. Developing regions typically experience higher displaced persons and fatalities as a result of flooding due to limited mitigative measures and adaptive capacity, which are not reflected in exposure estimates. Countries such as Sudan, Kenya, the Philippines, and Vietnam, among many others also show this trend. This demonstrates the importance of vulnerability and limitations of only quantifying natural exposure. In developed countries – like Austria and Sweden – the opposite trend is paramount. Millions of people are 'naturally' exposed to flooding based on biophysical factors, according to the GIEMS-D15 method; however, with infrastructure and mitigative practices, the confirmed impacts over the last 30 years are much less than the estimated population exposed to in-land flooding. This underscores the limitations of GIEMS-D15, which only represents typical conditions or natural floodplains but does not explicitly account for flood mitigation. Put simply, countries that are not necessarily the most naturally exposed to flooding have experienced the highest displaced individuals and fatalities over the last 30 years. The contrary is also true. Countries that are the most naturally exposed, in the case of developed nations, do not experience the highest impacts due to advanced adaptive, coping, and mitigative capabilities.

While comparison between GIEMS-D15 estimates and DFO archives is informative, the utility of these datasets are completely different in nature. The DFO records single-day floods that are not captured in long-term satellite imagery, which is the basis of the GIEMS-D15 dataset. The DFO also covers both in-land and coastal sources of flooding; and in the comparison with GIEMS-D15, the confirmed impacted persons may have been impacted by tsunamis or tropical cyclones rather than riverine inundation. The GIEMS-D15 dataset cannot properly differentiate inundation from in-land or coastal sources, e.g. in the case of Côte d'Ivoire. This can lead to under- or overestimation. The GIEM-D15 method simply attempts to measure natural, in-land flood exposure based on monthly values, which cannot capture short-term flood events and are not designed to pinpoint potentially impacted persons at a certain location. The basis of GIEMS-D15, as an agglomeration of satellite imagery, is not adequate to replicate the important role of DFO in recording local scale, singular flood events.

4.5. Exposure of agricultural lands

The same general patterns of in-land flood exposure are evident in the agriculture results. Approximately 20 percent of the world's cropland is within floodplains, as determined by GIEMS-D15 zones, all of which only comprise 13 percent of the total global land area excluding Antarctica. This suggests a disproportionate exposure of cropland in floodplains compared to areas outside of the GIEMS-D15 zones. In contrast, only about 8 percent of pastureland is exposed to in-land flooding (Fig. 29).

Just considering the GIEMS-D15 zones, the MA_{max} demonstrates the highest absolute exposure for cropland, while the MA_{max} and LT_{max} tie for highest exposure for pastureland. In addition to absolute estimates, the proportional (or relative) exposure in each unique GIEMS-D15 zone yields interesting results (Fig. 30). For both cropland 2000 and 2005 data, the MA_{max} demonstrates the highest proportion of contained cropland area at 27 percent, followed by the LT_{max} (15 percent), MA_{min} (12 percent) – and lastly – non-flood areas (10 percent). This seems to

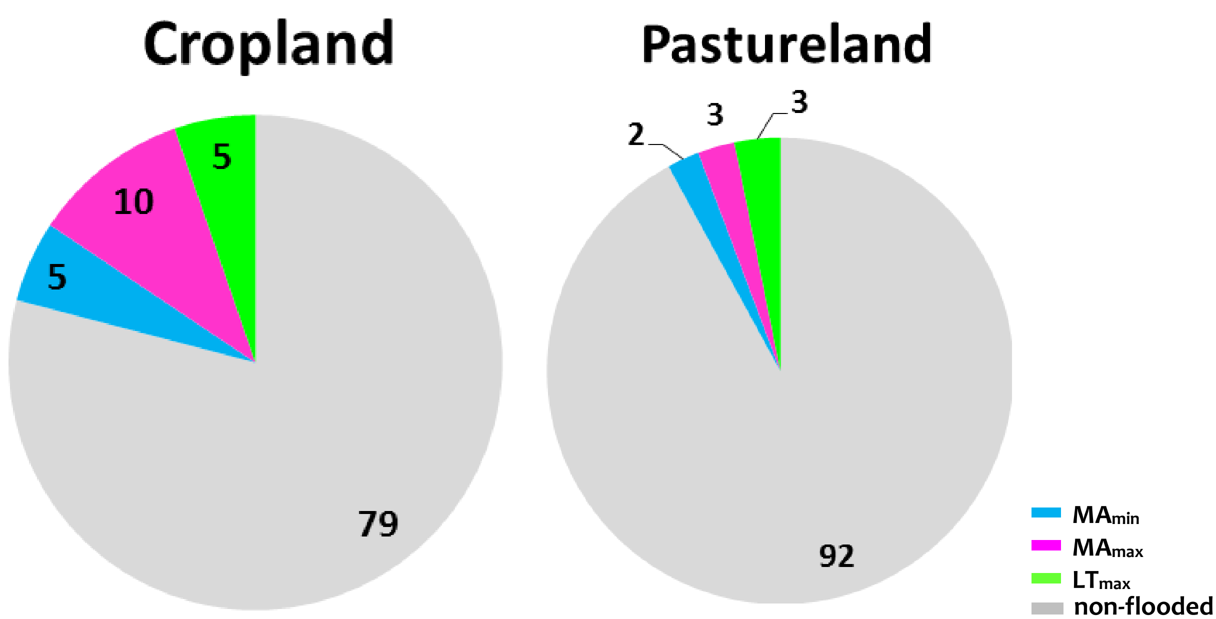

Figure 29. Global results: percent of total crop (2005 data) and pastureland area in each GIEMS-D15 zone.

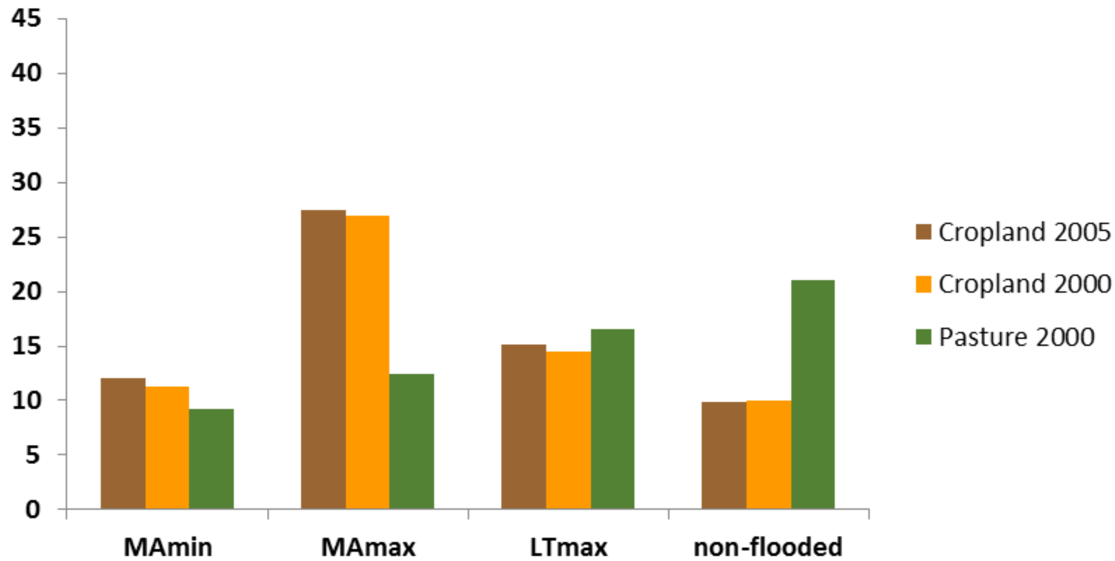

Figure 30. Global results: percent area of each GIEMS-D15 zone comprised of agriculture.

fit the storyline inherent to both the frequency of inundation and the adaptive capacity for farmers that plant in each zone. Put simply, the MA_{min} is always inundated and can be too risky for vulnerable crops, such as soybeans; while the LT_{max} experiences infrequent inundation, rendering it less suitable for regular and intensive cropland agriculture. For pastureland, the highest proportion is found in non-flood regions (21 percent), followed by LT_{max} (17 percent), MA_{max} (12 percent), and MA_{min} (9 percent). Since these results only provide insight into global trends, several continental analyses were conducted to evaluate the fraction of agriculture that lies within GIEMS-D15 zones.

Four regions were evaluated individually, including (1) Central America; (2) South America; (3) Africa; and (4) Asia to compare the differences in regional and global patterns (an overview of resulting trends is provided in Fig. 31).

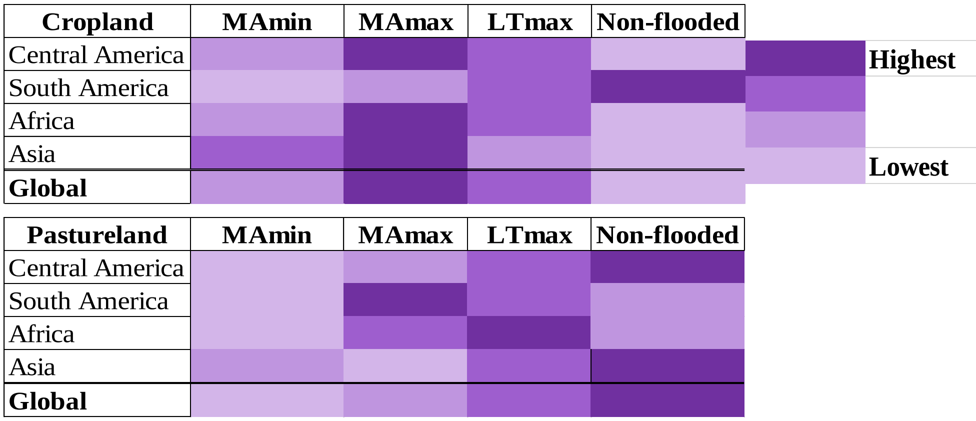

Figure 31. Global and regional summary: highest to lowest fractions of agriculture in each GIEMS-D15 zone.

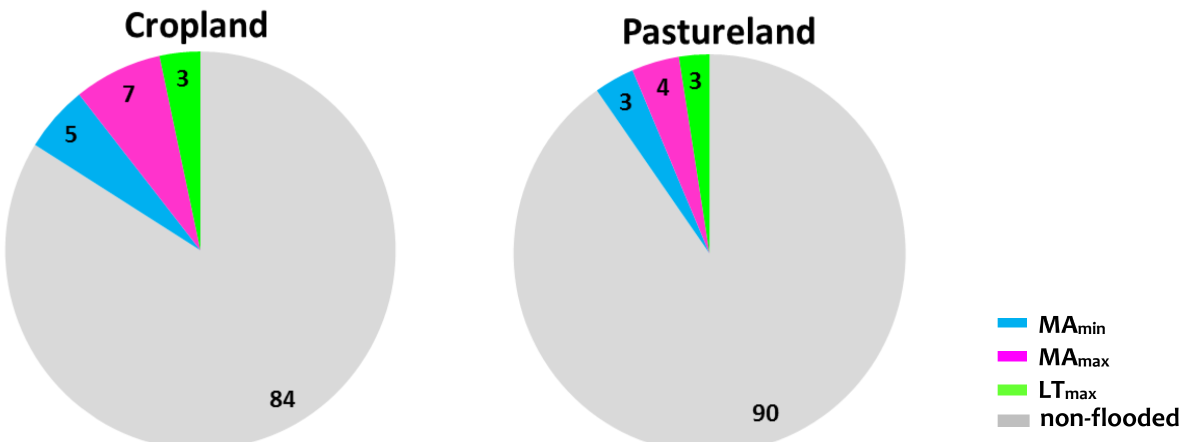

Figure 32. Central America results: percent of total crop (2005 data) and pastureland area in each GIEMS-D15

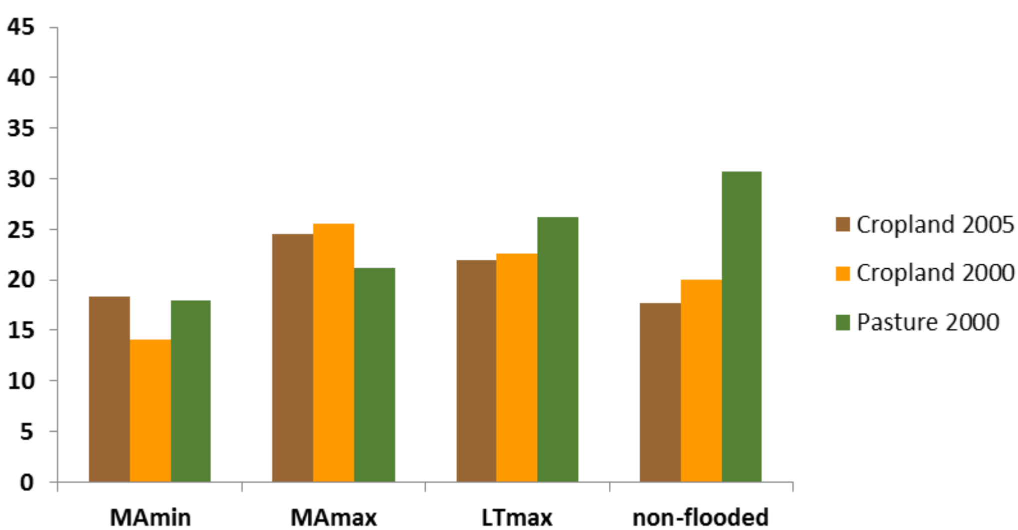

Figure 33. Central America results: percent area of each GIEMS-D15 zone comprised of agriculture.

Based on the results for Central America, approximately 2.7 million km^2 are dry land, with more than 360,000 km^2, or about 14 percent of its total land area, comprising Central American floodplains. More than 485,000 km^2 are under crop production in Central America, with more than 78,000 km^2 of that area, or about 16 percent, within one of the GIEMS-D15 zones. Of the 780,000 km^2 of pastureland in Central America, about 10 percent is within one of the GIEMS-D15 zones.

Just considering the GIEMS-D15 zones, the MA_{max} has the highest absolute exposure for cropland and for pastureland. In addition to absolute estimates, the proportional (or relative) exposure in each unique GIEMS-D15 zone yields interesting results (Fig. 33). For both cropland 2000 and 2005 data, the MA_{max} demonstrates the highest exposure proportional to its total land area at 25 percent, followed by the LT_{max} (22 percent), MA_{min} (18.3 percent) – and lastly – non-flood areas (17.7). Based on the percentage of each zone comprised of cropland, all of the GIEMS-D15 zones are favored for crop production in Central America compared to regions outside of floodplains. For pastureland, the highest proportion relative to land area is in non-flood regions (31 percent), followed by highest relative exposure in the LT_{max} (26 percent), MA_{max} (21 percent), and MA_{min} (18 percent).

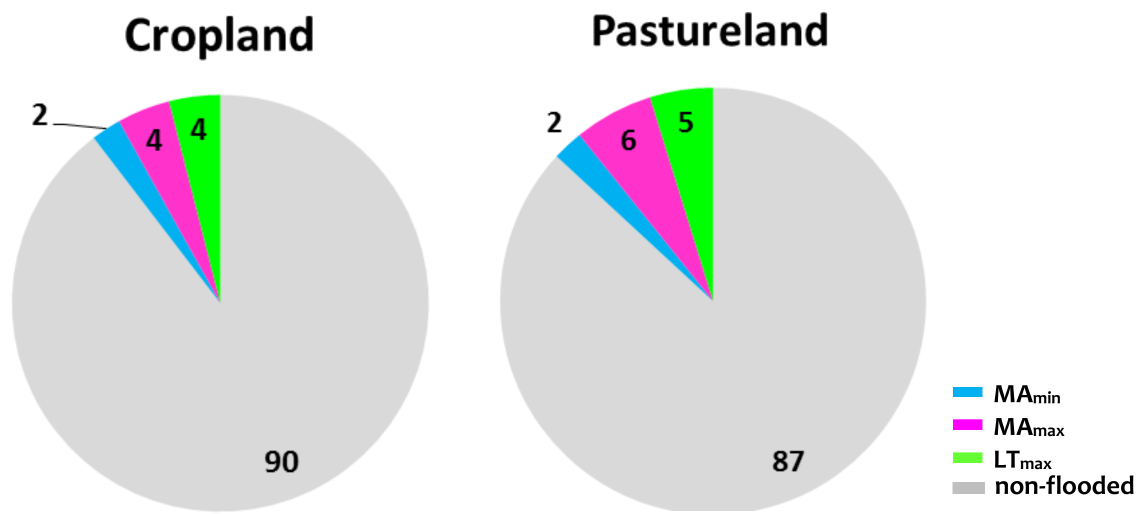

Figure 34. South America results: percent of total crop (2005 data) and pastureland area in each GIEMS-D15

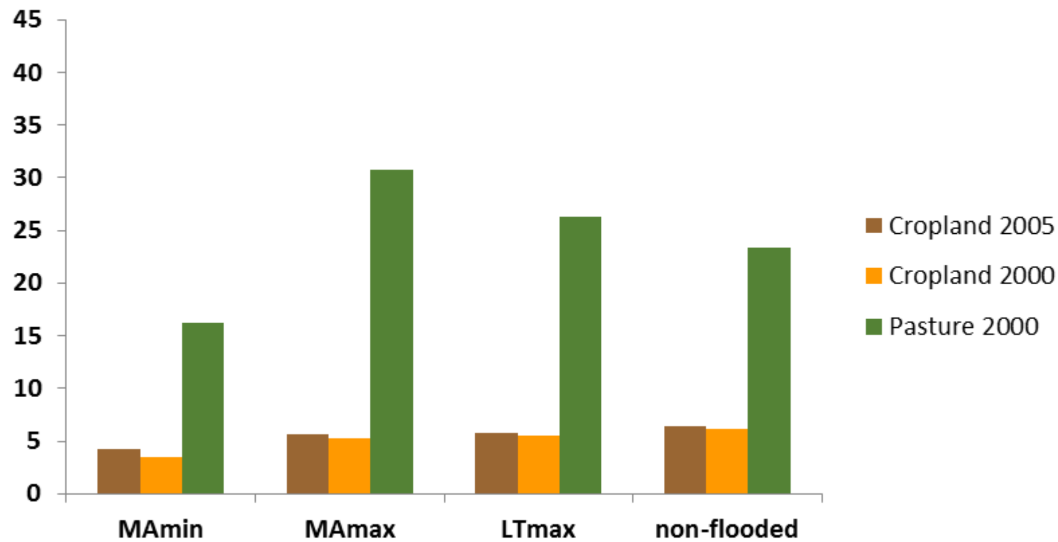

Figure 35. South America results: percent area of each GIEMS-D15 zone comprised of agriculture.

Based on the results for South America, approximately 17.8 million km^2 are dry land, with more than 2.2 million km^2, or about 12 percent of its total land area, comprising South American floodplains. More than 1.1 million km^2 are under crop production in South America, with more than 116,000 km^2 of that area, or about 10 percent, within one of the GIEMS-D15 zones. Of the 4.2 million km^2 of pastureland in South America, about 13 percent is within one of the GIEMS-D15 zones.

Just considering the GIEMS-D15 zones, the MA_{max} has the highest absolute exposure for cropland and for pastureland (with the LT_{max} just decimal points behind). In addition to absolute estimates, the proportional (or relative) exposure in each unique GIEMS-D15 zone yields interesting results (Fig. 35). For both cropland 2000 and 2005 data, non-flood regions have the highest proportion of cropland based on total land area at 6.4 percent, followed by the LT_{max} (5.8 percent), MA_{max} (5.6 percent), and the MA_{min} (4.3 percent). Based on the percentage of each zone comprised of cropland, none of the GIEMS-D15 zones are individually favored for crop production compared to regions outside of floodplains. For pastureland, the highest proportion relative to land area is in the MA_{max} (31 percent), LT_{max} (26 percent), non-flood regions (23 percent), and the MA_{min} (16 percent).

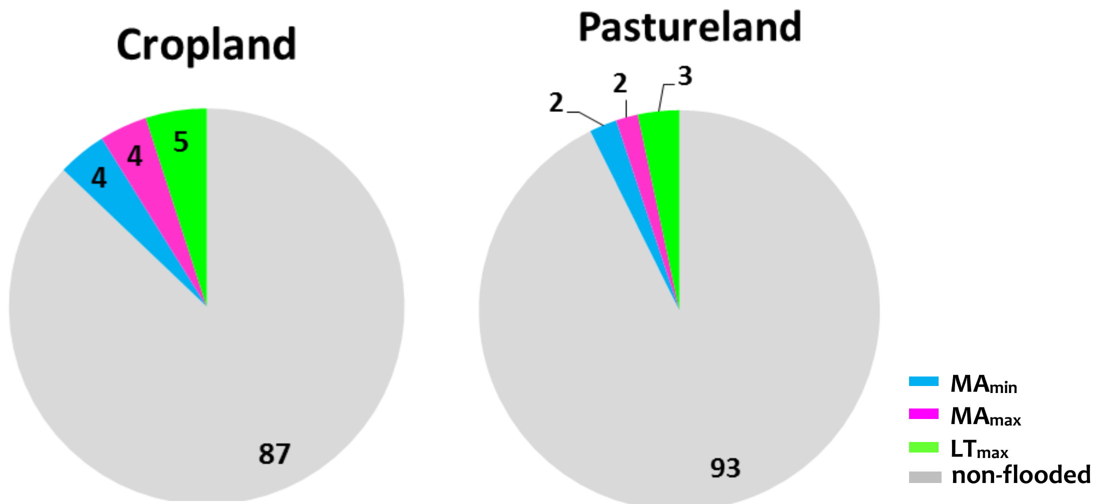

Figure 36. Africa results: percent of total crop (2005 data) and pastureland area in each GIEMS-D15 zone.

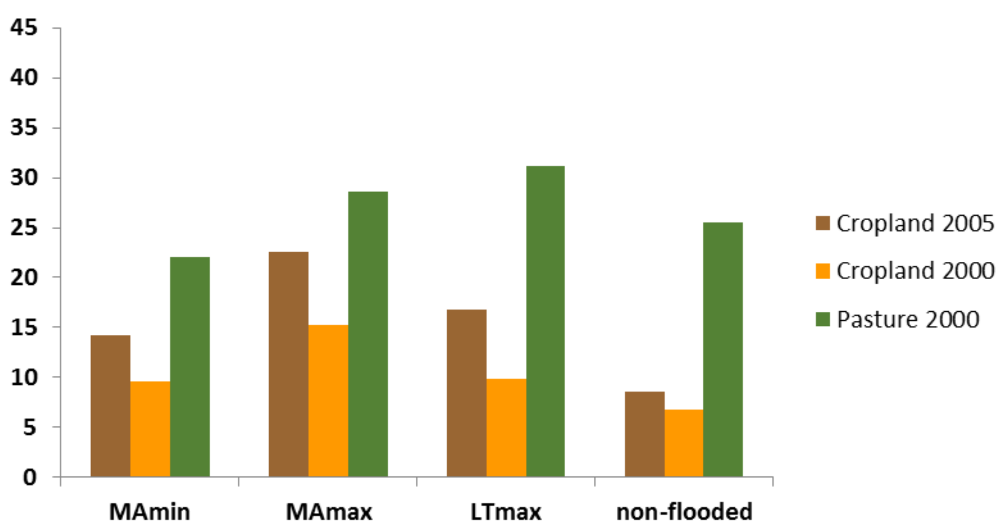

Figure 37. Africa results: percent area of each GIEMS-D15 zone comprised of agriculture.

Based on the results for Africa, approximately 30 million km^2 are dry land, with nearly 2.1 million km^2, or about 7 percent of its total land area, comprising African floodplains. More than 2.7 million km^2 are under crop production in Africa, with more than 350,000 km^2 of that area, or about 13 percent, within one of the GIEMS-D15 zones. Of the 7.6 million km^2 of pastureland in Africa, only about 7 percent is within one of the GIEMS-D15 zones.

Just considering the GIEMS-D15 zones, the LT_{max} has the highest absolute exposure for cropland and for pastureland (with the MA_{max} and MA_{min} just decimal points behind). In addition to absolute estimates, the proportional (or relative) exposure in each unique GIEMS-D15 zone yields interesting results (Fig. 37). For both cropland 2000 and 2005 data, the MA_{max} has the highest proportion of cropland based on total land area at 23 percent, followed by the LT_{max} (17 percent), MA_{min} (14 percent), and non-flooded regions (9 percent). Based on the percentage of each zone comprised of cropland, floodplains are favored in Africa, perhaps a result of widespread desert in the non-flooded region. For pastureland, the highest proportion relative to land area is in the LT_{max} (31 percent), MA_{max} (29 percent), non-flood regions (26 percent), and the MA_{min} (22 percent).

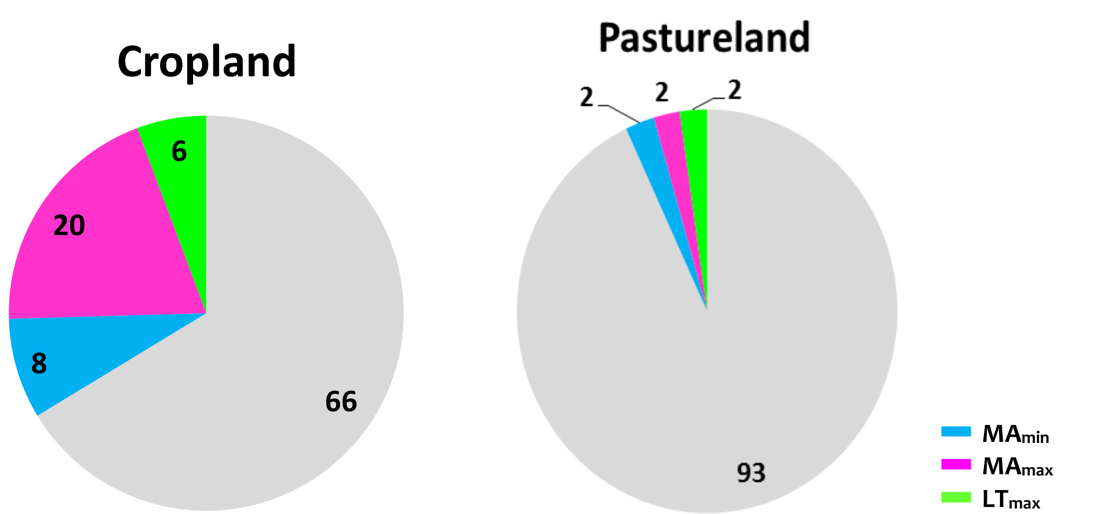

Figure 38. Asia results: percent of total crop (2005 data) and pastureland area in each GIEMS-D15 zone.

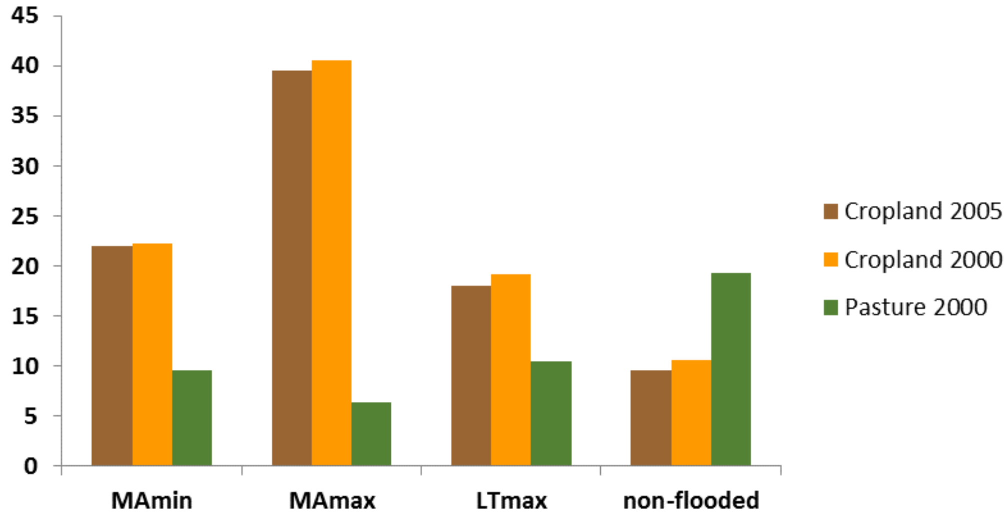

Figure 39. Asia results: percent area of each GIEMS-D15 zone comprised of agriculture.

Based on the results for Asia, approximately 44.5 million km^2 are dry land, with more than 6.5 million km^2, or about 15 percent of its total land area, comprising Asia's floodplains. More than 5.4 million km^2 are under crop production in Asia, with more than 1.8 million km^2 of that area, or about 34 percent, within one of the GIEMS-D15 zones. Of the 7.9 million km^2 of pastureland in Asia, only about 7 percent is within one of the GIEMS-D15 zones (similar to the African pastureland results).

Just considering the GIEMS-D15 zones, the MA_{max} has the highest absolute exposure for cropland by far, with nearly equitable pastureland exposure among other zones. In addition to absolute estimates, the proportional (or relative) exposure in each unique GIEMS-D15 zone yields the highest results (Fig. 39). For both cropland 2000 and 2005 data, the MA_{max} has the highest proportion of cropland based on total land area at 41 percent, followed by the MA_{min} (22 percent), LT_{max} (18 percent), and non-flooded regions (10 percent). Based on the percentage of each zone comprised of cropland, floodplains are more prominently favored in Asia than in Africa, or elsewhere, which is largely attributed to widespread floodplain agriculture and rice paddies. Even for crops that are purposefully in flood zones, such as rice paddies, it is important to quantify in-land flood exposure, since these specific crops are dependent on a particular level of inundation that may shift as a result of climate and environmental change.

4.6. Future sensitivity

Figures 40 and 41 show the F_s index for select cities in Latin America and Africa, where larger dots represent a higher sensitivity to changes in inundated area due to a standardized change in flood discharge and are denoted in red, followed by orange, yellow, green, and blue, with decreasing sensitivity. Latin American cities demonstrate overall higher flood sensitivity than African cities. F_s values in Latin America range from 0.08 in Merida, Mexico, to 70 in Brasilia, Brazil; while African cities range from 0 for several cities (e.g. Dakar, Senegal; Maputo, Mozambique; Abidjan, Ivory Coast) to 34 in Monrovia, Liberia. The value of 0 is likely an artifact inherent in the GIEMS-D15 dataset. Only three cities in Africa (out of 53 in this study) generate F_s values above 1: (1) Monrovia, Liberia (F_s of 34); (2) Algiers, Algeria (F_s of 2.6); and (3) Port Elizabeth, South Africa (F_s of 1.2). Conversely, 65 cities in Latin America (out of 70 in this study) generate F_s values above 1. Areas of high flood sensitivity also tend to be along coasts, possibly as a result of overestimation of inundated area inherent in the GIEMS-D15 data.

While the F_s metric compares the highest flood month and the second highest flood month in relation to inundated area, the results do not identify which months are actually represented (e.g. January or November) and whether these months adhere to known seasonal peak flows. The F_s results are simply a first-order investigation of potential sensitivity to inundation that carries inherent uncertainty from the input data and has not been validated by any ancillary datasets. The long-term objective is to calculate F_s for all regions of the world, including rural and urban environments, and to identify means of validation to adapt and further develop the calculation of F_s.

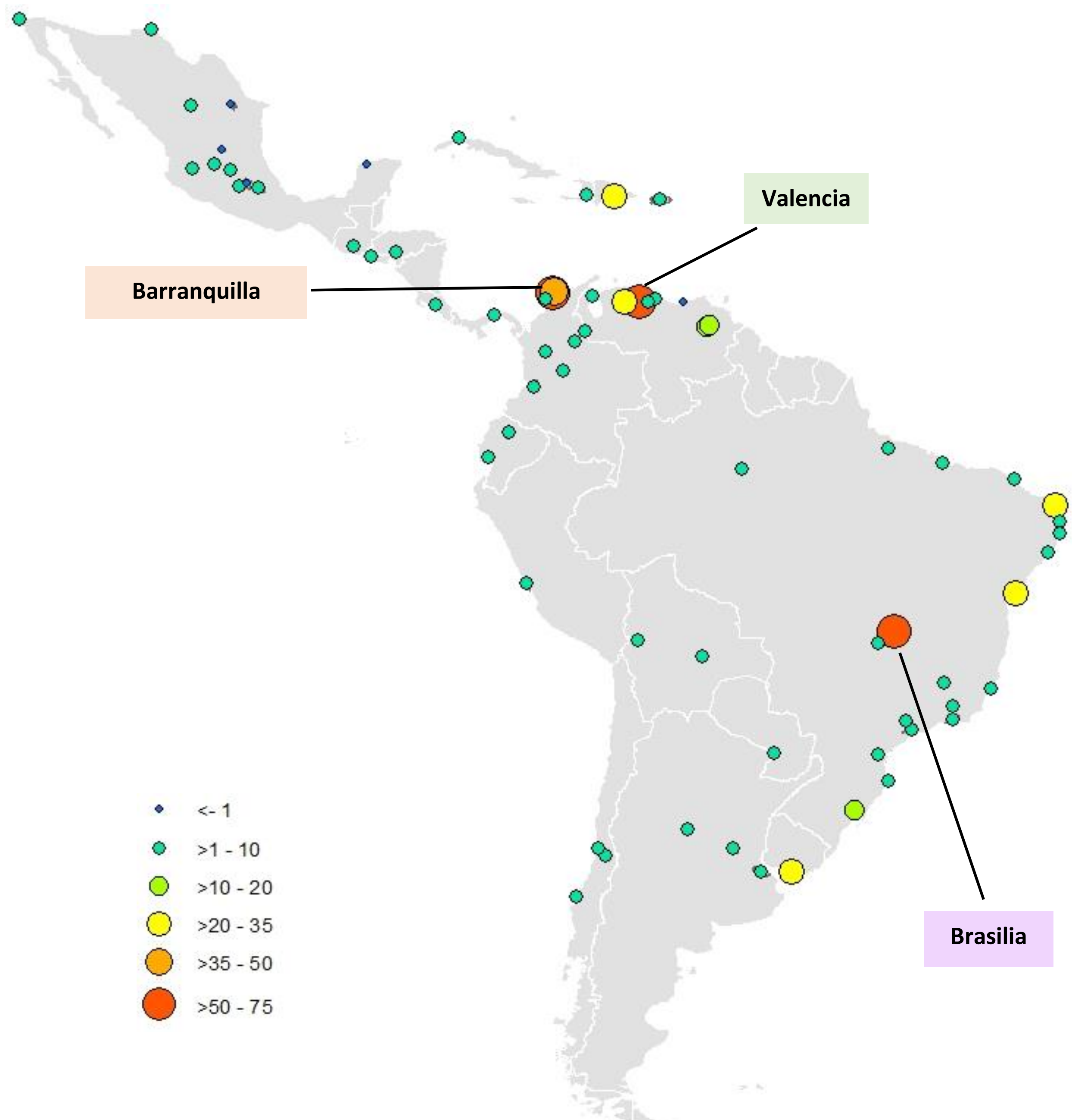

Figure 40. Flood sensitivity (F_s) values for Latin American cities. An F_s index of 1 means that a certain percentage of change in discharge leads to the same percentage of change in inundated area (e.g., 10 percent more discharge yields 10 percent more inundation); a value larger than 1 means that a certain relative change in discharge leads to a larger change in inundation (e.g., 10 percent more discharge yields 20 percent more inundation); and a value smaller than 1 means that a certain relative change in discharge leads to lower change in inundation (e.g., 10 percent more discharge yields 5 percent more inundation).

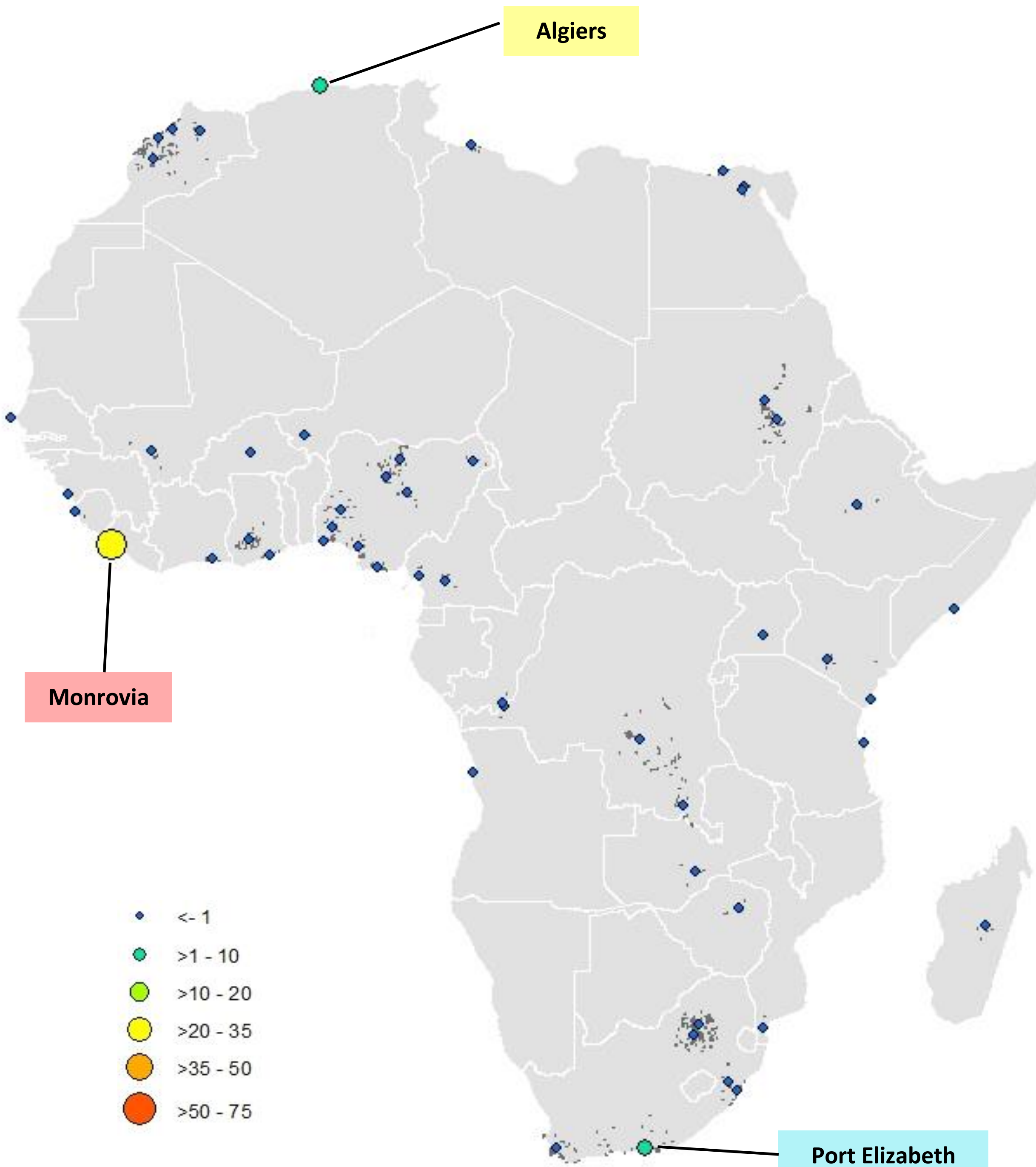

Figure 41. Flood sensitivity (F_s) values for African cities. An F_s index of 1 means that a certain percentage of change in discharge leads to the same percentage of change in inundated area (e.g., 10 percent more discharge yields 10 percent more inundation); a value larger than 1 means that a certain relative change in discharge leads to a larger change in inundation (e.g., 10 percent more discharge yields 20 percent more inundation); and a value smaller than 1 means that a certain relative change in discharge leads to lower change in inundation (e.g., 10 percent more discharge yields 5 percent more inundation).

4.7. Key uncertainties and shortcomings

The dominant drawbacks of this study include (1) notable variability in the datasets, as well as technical obstacles related to the methodology and (2) lack of conclusive validation. As the core dataset, the limitations of GIEMS-D15 are further explored. This study cannot accurately determine to what extent the exposure estimates are driven by the coast. This is particularly important, since GIEMS-D15 estimates at the coast are uncertain and have not been validated (Fluet-Chouinard et al., 2015). Furthermore, the source of inundation in GIEMS-D15 cannot be properly identified. The inundation patterns could represent wetlands, floodplains, or rice cultivation that is prominent in Asia. Inundated areas are differentiated by the separate GIEMS-D15 zones. However, the LT_{max} cannot be attributed to a particular frequency of occurrence, which is important for flood mitigation, emergency managers, and individual stakeholders. The LT_{max} is particularly uncertain, since it represents a geomorphologically-derived extent. Although the probability of occurrence cannot be defined, it typically has an inverse relationship with vulnerability, which may ultimately drive true impacts of flooding.

The methodology also introduces other apparent errors and even skews the results in some cases. Technically, there should be little, if any, people or agriculture within the MA_{min} zone, as it is expected to be inundated year-round. Populations and agriculture are often directly next to freshwater bodies, and due to technical issues and resolution placement, these values may end up being projected into the MA_{min}. However, GIEMS-D15 does capture other wetlands where people and agriculture may actually co-exist in the MA_{min}, e.g. rice paddies, which may contribute to the high exposure in Asia. The publicly available version of Earthstat circa the year 2000 underestimates agriculture near water bodies (D. Plouffe, pers. comm., 2015), which has implications for this study as it measures agriculture within global floodplains. As a result, the true extent of floodplain agriculture may be higher than estimated.

Both of the population datasets have evident shortcomings. In particular, the spatial resolution and quality of administrative boundaries affects population distribution efforts. Technical and spatial inaccuracies of administrative boundaries leads to areas of population omission and commission, particularly around coastlines; this results in over- or under-representation of true population values (Rose and Bright, 2014). For example, for cities alongside rivers that form administrative boundaries, the associated populations may be incorrectly placed on the opposite side of the boundary, which leads to over- and under-estimation of populations surrounding the river (Rose and Bright, 2014). This misplacement of cities around administrative boundaries could have large effects and skew exposure of populations to flooding in this assessment.

Census data and administrative boundaries in developing areas are not as reliable as elsewhere, and this affects all population distribution efforts used in this study, i.e. LandScan and GPW. For areas with poor population data, LandScan will distribute the total population in the particular administrative boundary based on locational likelihoods, which has high uncertainty as to where people are actually residing (Rose and Bright, 2014). When finer resolution population data are not available, GPW attributes population estimates uniformly in a particular region (Balk et al., 2006). This does not allow for identification of 'hotspots' of exposure in these areas, which is one of the objectives of this study. Since these data poor regions are arguably the most vulnerable, this has implications for exposure- and, more broadly, risk-mapping efforts (Rose and Bright, 2014).

The performance of GPW and LandScan has also been assessed in recent literature (Tatem et al., 2011; Mondal and Tatem, 2012; Hall, Stroh, & Paya, 2012; Rose and Bright, 2014). In a study comparing population estimates of the Skåne region in Sweden, GPW overestimated population in cities and underestimated in the transition zone between urban and rural space (Hall, Stroh, & Paya, 2012). When compared to ground-truth population data in the region, LandScan outperformed GPW, with r^2 values of 0.59 and 0.34, respectively. GPW was described as "generally poor" for this region. For LandScan, a "southwest-northeast gradient pattern" was apparent. In the north, LandScan population was over-estimated while in the south it was under-estimated (Hall, Stroh, & Paya, 2012). Hall, Stroh, & Paya (2012) correlate this pattern with the forest and agricultural regions in Skåne. On a global scale, LandScan performed the best (Hall, Stroh, & Paya, 2012), and GPW was shown to have issues with accurate total population numbers. Such population modelling efforts may misplace where these populations are actually living by projecting census data into areas where no one lives. This has implications for exposure mapping and disaster relief efforts that need to enforce mitigation initiatives and deliver critical resources.

Another study measured populations at-risk to sea level rise and coastal flooding using LandScan and GRUMP population (Mondal and Tatem, 2012), an affiliated product of the GPW database. At the continental level, these datasets showed little variation for populations at-risk. However, for individual countries, more differences became apparent. Some of the highest deviations occurred in small island countries, by which most of their land area was susceptible to flood-risk. Less deviation between the datasets was found in developed areas, such as Europe and the U.S. (Mondal and Tatem, 2012). Large differences between the two population grids were also found in African countries where the resolution and quality of input census data are more variable. The greatest deviations were found for African and Asian countries; differences ranged from 6 to 39% of their total population at-risk. For countries like Indonesia and Japan, the deviation between datasets was upwards of 1 million (Mondal and Tatem, 2012).

In this global assessment of in-land flood exposure, some cities demonstrated ranges of in-land flood exposure from 58 to 100 percent of their total population, while others showed no deviation between the dataset combinations. Between the four dataset combinations, the highest standard deviation in the city analyses was in Tripoli (26.2); followed by Dnipropetrovs'k (25.7) and Dar es Salaam (25.0). Approximately 19 percent of the cities included in the analyses (i.e. 213 on a global scale) have a standard deviation less than 1 across the four dataset combinations. Nearly 50 percent of the cities have a standard deviation greater than 5 between the datasets.

For cities in Asia, the exposure estimates generated in this study are both higher and lower than those presented in Balk et al. (2012). The highest variance occurs with the GRUMP and LandScan dataset combination. In this case, the GIEMS-D15 method estimates 16 million people exposed in Kolkata, whereas Balk et al. (2012) estimates 2.3 million exposed. The lowest variance occurs with the GRUMP and GPW dataset combination, where GIEMS-D15 estimates 1 million people exposed in Phnom Penh and Balk et al. (2012) estimates 988,000. Balk et al. (2012) estimates are higher for Wuhan (5.3 million exposed) and Palembang (1.1. million exposed) compared to the GIEMS-D15 method (average of all dataset combinations), which estimates 2.9 million and 853,000 exposed, respectively. The comparison with Balk et al. (2012) shows the variability in exposure estimates dependent upon each unique dataset. It is not surprising that the GIEMS-D15 estimates are most similar when using the GRUMP and GPW dataset combination, since these are core datasets utilized in Balk et al. (2012).

Less deviation was found at the global and continental scales in this study, similar to the Mondal and Tatem (2012) findings. The highest standard deviation occurred in Asia (4.4), followed by a global standard deviation of 4.0 between the dataset combinations. The average standard deviation at large-scales (i.e. continental and global) was around 2.0. Smaller deviations are potentially a result of the global extent of the datasets utilized in this study. GIEMS-D15, LandScan, and GPW are all designed for global scale analyses, and at best, regional assessments. Thus, the smaller the scale, say at the city level, the more uncertain and variable these global datasets become.

Based on the findings in this assessment, different dataset combinations show various strengths and weaknesses and can be used to serve different purposes. LandScan seems to be most useful for risk-mapping for natural and humanitarian disasters. GPW may be best-suited for understanding general exposure in the long-term, since it captures where people are actually residing. Compared to previous assessments, the GIEMS-D15 exposure estimates seem to be reasonable at global and continental scales. However, the important caveats discussed must be considered in the interpretation of all of the results presented.

5. Summary of Analyses

The newly developed GIEMS-D15 dataset coupled with population and urban extent data allow for high-resolution analyses of in-land flood exposure as it relates to rural and urban space. The interpretation of in-land flood exposure estimates must be treated individually based on the probability of flood occurrences and the level of vulnerability associated with each GIEMS-D15 zone, i.e. as the probability of flood occurrences decreases, vulnerability may increase. For instance, although potentially exposed, populations residing and working in the LT_{max} zone likely have less mechanisms to adapt and cope when extreme events do occur. This may result in greater impacts that, however, occur infrequently. The principal results and their respective caveats can be summarized by the following points:

1. GIEMS-D15 zones comprise a higher proportion of urban land area (in km^2) than in the rural environment across all regions and dataset combinations. Specifically, evidence of exposure hotspots find roots in Asian and African urban areas, all of which face additional social, economic, and other environmental vulnerabilities.
2. Urban dwellers exhibit higher proportions of their total population in flood-prone areas, as defined by GIEMS-D15 zones. Both globally and for the regional case studies, urban populations face a larger relative threat to inundation than their rural counterparts. Interestingly, South America also showed higher absolute exposure estimates for their urban population than in the surrounding rural areas.

3. By the same token, absolute and relative estimates (including D_E) paint different pictures of in-land flood exposure across local, regional, and global scales. The results further vary depending on the unique dataset combinations used and their inherent definitions, temporal, and spatial resolutions.
4. GIEMS-D15 estimates varied in comparison to Balk et al. (2012) estimates of exposure in Asian cities, potentially due to the overall difference between the GIEMS-D15 and GAR input datasets and their respective derivation. While estimates produced in this study do not contradict DFO records of impacted persons, DFO is not the most appropriate means of validation for the GIEMS-D15 estimates. Nonetheless, GIEMS-D15 offers additional opportunities for characterizing global and regional in-land flood exposure, taking into account the inherent biases that may drive over- or underestimation in some cases.

GIEMS-D15 also facilitates exploration of floodplain agriculture production and exposure across multiple scales. This study offers a preliminary look into the extent of agricultural lands exposed to in-land flooding on a global and regional scale. Prior to this study, quantifiable evidence that demonstrates higher proportions of global cropland in floodplains had yet to surface, rendering methods of validation difficult.

Globally and for each of the continental case studies (excluding South America), all of the GIEMS-D15 zones were favored for crop production in relation to their respective non-flooded land areas. Global estimates of the percentage of total cropland reach 20 percent in floodplains (as defined by GIEMS-D15). Asia displays the highest proportion of cropland in floodplains at 34 percent (as defined by GIEMS-D15); followed by Central America (15 percent), Africa (13 percent), and South America (10 percent). Asia's combined exposure and land area drive the global exposure estimates.

Pastureland trends were much more variable across regions; the highest exposure rankings manifested in each of the GIEMS-D15 zones for at least one continental case study (excluding MA_{min}). Global estimates of the percentage of total pastureland border 8 percent in floodplains (as defined by GIEMS-D15). South America displays the highest proportion of pastureland in floodplains at 13 percent (as defined by GIEMS-D15); followed by Central America (10 percent), Africa (7 percent), and Asia (6 percent).

Equally important as current in-land flood exposure, future threats of inundation must be further explored. The F_s metric only serves as a preliminary investigation of how maximum discharge and inundated area may relate in the urban context. These crude results suggest that coastal cities could be most sensitive to change, i.e. inundated area changed the most with a one unit increase in peak flow, especially in Latin America. Despite the high uncertainties and current lack of validation, an advanced version of the F_s metric could be tested and applied to both rural and urban space on a global scale once all monthly inundation data are available.

Future work should take these results a step further by conducting an in-depth study of what the findings and indicators mean on-the-ground in these regions. Exposure mapping is the first step for a variety of environmental, economic, and social applications, such as: potential impacts of river modification through diversions and other obstructions, economic damage and loss estimation, measures of social strata effects, and disaster risk reduction (DRR), all of which can be assessed across multiple spatial and temporal scales. In the subsequent chapter, one of these examples will be explored, namely DRR.

6. Bridging the Gap between International Policy and Local Practice: New Frameworks in Combatting Global Flood-Risk

6.1. Preface

Thus far, the analyses have assessed in-land flood exposure across regional and global scales and the associated caveats, uncertainties, and data variability. Such assessments are crucial in translating growing scientific knowledge into action both through policy and practice across multiple scales and interest groups. Meaningful tools, such as exposure mapping, provide unique opportunities in improving flood mitigation efforts when paired with a much-needed revamp of DRR policy, joined here in Chapter 6. As an extension of the research objectives, Chapter 6 situates this thesis in the broader context of DRR, one example of the application of flood exposure mapping, by providing a policy critique and recommendations to improve DRR initiatives relevant to flood-risk. Chapter 7 will provide even closer ties between the two topics, underscoring the importance of flood exposure mapping and its contribution to flood mitigation policy.

6.2. Context for global flood disasters

Despite the inherent unpredictability of some flood hazards, severe devastation and death can and ought to be mitigated. Preventable death and devastation was, and continues to be, a growing concern, with the 1990s marking a decade for DRR. Despite valiant efforts from international organizations, national policy, and grassroots organizations, a disconnect continues to exist between individual actions of these groups that operate concurrently in isolation of one another. In reality, these interest groups lack a platform for dialogue, with no network to share and create mutual instruments to ultimately characterize and frame flood-risk. They often ignore other forms of knowledge vital in reducing risk from all vantage points.

To make genuine strides toward flood mitigation, both top-down and bottom-up approaches must be integrated across multiple scales concurrently, while utilizing policy measures and instruments relevant and meaningful to all groups involved, who have different yet no less legitimate perspectives. Moreover, it is crucial to evaluate the current failings of policy action, the foundation of some flood mitigation efforts. Such analysis sheds light on contributory factors that have resulted in minimum progress in mitigating flood hazards in less-developed countries (LDCs) especially.

6.3. The social construct of ‘natural’ flood disasters

In recent decades, two competing discourses on flood disasters have emerged: the hazard and vulnerability perspectives. The former, and most dominant, paradigm treats flood hazards as extreme, rare occurrences that only become disasters when the public fails to ‘adjust,’ largely as a result of insufficient risk perceptions and preparedness (Dixit, 2003; Adger 1999; Burton et al., 1978). For example, many disaster management initiatives across Asia have adopted this paradigm (Manuta and Lebel, 2005), in which flood disasters are largely handled by technocratic, state-centered approaches that fail to adequately address the needs of impacted communities in the decision-making process (Dixit, 2003). State and regional institutions in LDCs often intervene using structural and technological measures to control and contain floods, which have proved to be inadequate during extreme and unpredictable events. In fact, floods tend to only capture the attention of policymakers and local authorities once they occur and are only dealt with when another strikes. This inaction is symptomatic of:

- City planners uninformed about flood control;
- Disorganization at federal and state (or departmental) level on flood management;
- Insufficient technical information on the topic for engineering graduates;
- Political losses for public administrators when implementing non-structural control (zoning), as the public is often expecting a hydraulic structure;
- Public uninformed about flood control;
- In some places there is no interest in preventing flooding; they prefer to address issues as they occur, handing out resources free-of-charge (Manuta and Lebel, 2005).

Flood mitigation is not only dependent on structural and technological means, but also, it is dependent on the representational narratives, frames, and definitions within which these disasters operate that drive social vulnerability. It is crucial to understand, because social, political, and economic institutions are imbued with differing levels of power that render some groups more vulnerable than others (Ostrom, 1990). Thus, the vulnerability paradigm argues that flood disasters disproportionally impact communities that already face everyday inequalities through inadequate access to resources and protection (Dixit, 2003; Blaikie et al., 2014). The vulnerability approach has jump-started initiatives that recognize the social construction surrounding flood disasters and investigate the core causes of communal vulnerability (Blaikie, 2006).

6.4. Representational narratives of disasters and implications of legibility

Policy framing is a means of "selecting, organizing, interpreting and making sense of a complex reality to provide guideposts for knowing, analyzing, persuading, and acting" (Rein and Schon, 1993). Accordingly, policy frames socially construct the situation, define the contributory factors, and bargain the appropriate courses-of-action (Rein and Schon, 1993). In the face of uncertainty and contentious viewpoints, theses narratives reveal the associated assumptions and value-judgments that ultimately influence decision-making and flood mitigation policy.

Problem-framing and representations of both legibility and needs affect the construction of flood policy (Bornstein et al., 2013). From disaster representation of community needs to reconstruction post-disaster, the planning and implementation process creates new roles and responsibilities for international, national, local, and other interest groups. The process of policy framing, planning, and implementation occur within a political context where power is unevenly distributed between interest groups. The institutions that operate within the social, political, and economic contexts and the power relations amongst them can further marginalize already socially vulnerable groups (Ostrom, 1990).

State bureaucratization uses standardized tools to consolidate power through monitoring and command-and-control measures, thereby making their position in power ‘legible’ (Scott, 1998). In fact, simplifying complex realities and replacing local knowledge with the needs of the state render some social and environmental characteristics legible and others illegible. The representational narratives then create new material relations that are then translated into state institutions, laws, and norms, such as structural measures and zoning to mitigate flood hazards. Standardizing state actions through built realities and legibility allow the state to act effectively through policy and practice (Bornstein et al., 2013).

Construction of complex realities and legibility are also shaped by global inequalities that are disproportionately higher in LDCs. For most-developed countries (MDC), states are able to consolidate power, control, and implement standardized policy and practice to lessen the adverse effects of flood hazards. However, LDCs are largely managed by states that are weak, fractured, and unable to effectively plan and implement flood mitigation policy; constraints on the state’s power are further influenced by global intervention that mask out the state’s power (Ferguson, 2005).

6.5. Identifying the gaps in international DRR policy

National flood mitigation policy has dominantly focused on command-and-control, top-down approaches that heavily rely on scientific knowledge and government intervention; this largely ignores the invaluable role of local knowledge in reducing flood impacts (Gaillard, 2013). Only policy on the international level has considered the alternate viewpoint of the vulnerability approach, namely through the Hyogo Framework for Action (HFA) 2005-2015.

In 2005, 168 countries signed the HFA, a comprehensive action plan to reduce disaster risk on a global scale (Enia, 2013). The decade-long initiative developed measures for assessing DRR and monitored the policy’s progress in five priority areas:

1. Make DRR an international, national, and local priority with strong institutions as a basis for implementation; for example, by building river basin authorities;
2. Identify disaster risks and improve early detection and monitoring; for example, by implementing gauging stations in largely vacant rivers, especially in LDCs;
3. Create disaster resilient generations at all levels through education and human ingenuity;
4. Minimize contributory risk factors that exacerbate natural disasters, such as environmental and social vulnerability related to flood hazards; and,
5. Ensure disaster preparedness at all possible levels (Ferguson, 2005).

During the initial five years of HFA enactment, some of the most deadly global floods occurred, including the 2004 spring floods that impacted Haiti and the Dominican Republic. The past decade also propagated more scientific reports linking extreme events with global climate change (Solomon, 2007). Thus, it is important to understand how some of the most severe natural disasters in history have occurred under the HFA's metaphorical watch.

The United Nations Office for Disaster Risk Reduction (UNISDR) conducted a mid-term review in 2010-2011 and concluded that HFA progress was uneven across the world, "reflecting broad economic and institutional differences among regions and countries" (UNISDR Advisory Group of the Mid-Term Review, 2011). In effect, such non-binding treaties do not ensure or enforce desired outcomes at the state or local levels; in fact, priority actions remain too vague to be implemented in the multidimensional and highly contextual state-frameworks.

Assessments of HFA priorities can inform states of where more participation and enforcement are needed. This could help assess how feasible or to what degree states can easily implement flood mitigation efforts. Initiatives that are more easily attainable can be prioritized for early assessments to build momentum in reaching the broader HFA objectives. This also points toward the mitigation efforts that can be the focus of international policy objectives and plans. In fact, treating all mitigation initiatives the same – as they presently are – is a problematic approach to reducing flood impacts. The HFA initiatives are challenging in that they have competing incentives across the five key priority areas. This is not unique to the HFA; flood policy has implementation difficulties when competing incentives are present (Fields and Enia, 2009). Nevertheless, it is beneficial to recognize the relative ease between mitigation efforts within the

HFA priority action plan so that progress can be accurately interpreted. For instance, one may think that the entire HFA has failed, which is a unidimensional assumption due to the progress in some sectors. In this regard, a restructuring of the HFA is needed, not a complete work from scratch. The focus here is the competing incentives in effective mitigation, management, and recovery post-disaster. Incentives are often convoluted and face undesirable consequences and challenges. As the HFA expiration date approaches this year, more exploratory studies of how to measure and implement effective disaster policy are needed.

6.6. Policy is policy's worst nightmare

6.6.1. The cost of cost-benefit analyses and benefits of a multiple-objectives approach

The continued rhetoric surrounding the need of multiscalar integration of both scientific and local knowledge is no longer sufficient. Now more than ever, the multiple scopes of 'scale' need to be translated into policy and action at all levels to reduce flood impacts in the most vulnerable communities. To-date, flood mitigation efforts have largely employed make-shift, cost-benefit analyses (CBA), of which investments are procured based on various cost-benefit ratios. Despite, its obvious utility, CBA in flood mitigation policy reveals the limited number of policy perspectives that affect the multifaceted social construction of flood disasters. Cost-benefit analyses often indoctrinate top-down approaches to flood hazards, such as the dam rush to command-and-control the natural fluvial regime. Alternative-focused thinking approaches flood-related issues by identifying obvious solutions, and in the same instant, begins impact assessments of each alternative. However, an in-depth critique of CBA is beyond the scope of this critique.

This section is dedicated to proposing a new approach to flood-risk reduction; one of multiple objectives (M-O) and value-focused problem formulation through five new priority areas that build on previous HFA progress: the improvement and need for (1) integrating all forms of knowledge in addressing flood-risk; (2) consensual tools that are meaningful and accessible to all groups and appropriate forums for such dialogue and exchange; (3) redefining the current priority areas to develop concrete measures and methods of evaluation for flood mitigation initiatives; (4) practical frameworks that acknowledge the variability in different incentives related to mitigation efforts; and (5) policy implementation constraints in the national context.

6.6.2. New frameworks: multiple-objective approach

A M-O framework sets the foundation for effective flood-related policymaking and practice. The initial step involves uncovering otherwise hidden objectives and identifying appropriate measures that are defined by multiple affected groups. Objectives of flood mitigation vary across spatial and temporal scales and amongst different interest groups. Beyond the inherent difficulties in implementing disaster policy, such as in the case of the HFA, disconnect exists between different forms of knowledge in combatting flood hazards. In the scientific arena, local knowledge is often deemed inferior or secondary to knowledge generated in a methodical and 'scientific' manner (Mercer, 2010). Scientists are often labeled 'experts,' denoting superiority and prestige; while local knowledge is given no such label for its unique contribution in mitigating flood hazards. On the one hand, scientific knowledge is generated, externally 'verified,' and accepted by the international community; while local knowledge related to flood hazards is internalized, contextual, and continually evolving. The gaps in how these forms of knowledge are verified exacerbate the divide between the international scientific community and local knowledge.

Technology-reliant MDCs use top-down approaches to transfer knowledge and solutions to flood hazards; this technological advancement is then translated and imposed on LDCs. Due to rigidities and gaps evident in this approach, community-based DRR (CBDRR) has been cited as a means of reducing risk. CBDRR fosters communal participation and empowers them to deal with flood hazards in interesting ways (Gaillard, 2013). In the globalized space of flood mitigation, scientific and local knowledge often work in isolation of one another without recognizing the beneficial role of its counterpart (Schmuck-Widmann, 2001). With increasingly complex systems, neither scientific nor local knowledge can individually address the equally complex solutions needed for effective flood mitigation. This draws upon the important argument that scientists must collaborate with local communities on equal footing with one not seen as superior to the other. For instance, local communities living in hazard prone areas often develop approaches tailor-made to their specific needs, which may or may not be viable for sustainable flood policy (Shaw et al., 2008). When combined with scientific knowledge, a blend of effective and applicable knowledge emerges that supports sustainable avenues for mitigating flood impacts. This steers the movement away from top-down, technologically-focused solutions to more context specific 'local' solutions.

The dichotomous relationship between different types of knowledge can also turn policymaking obstacles into policymaking opportunities. Reducing vulnerability requires scientific knowledge to adequately quantify flood-risk and local empowerment to reduce individual susceptibility. Importantly, the vast array of stakeholders must be included in multiscalar and multidimensional ways to reduce their overall vulnerability to flood hazards. Local communities should be the centerpiece of flood mitigation, since they are the groups directly affected and the first responders on the scene.

Flood mitigation is challenging in policy and practice due to the inherent mistrust between stakeholders (Gaillard, 2013). They question each other's intentions in part due to the lack of space for direct dialogue. Uneven power dynamics and intangible strategies of flood mitigation on-the-ground also contribute to gaps between policy and action. Thus, a forum is needed for concurrent dialogue between multiple interest groups where mutually accessible and meaningful tools are employed to characterize flood-risk, define objectives, and associated measures. For example, groups can be provided local maps, in which community members and scientists can add details that feature their equally unique knowledge of the area. Local knowledge may provide information on normal levels of seasonal floods and denote extreme thresholds during past flood events. At the same time, scientists can incorporate the various soil nutrient contents pre- and post-disaster. This just scratches the surface of potential dialogue exchange that can be achieved to build trust and mutual objectives of flood mitigation.

Despite these highly contextual and fluid priorities, a common objective in flood mitigation policy can be inferred for the purposes of this critique: to reduce the loss of life and property from high-impact events. This example of a fundamental, mutual objective is used to explicate the remainder of the M-O approach in the context of flood mitigation policy. Since flood hazards are an unavoidable consequence of the Earth's behavior, more focus should be directed towards minimizing deaths and damage associated with severe hydrologic events.

With the common objective of reducing flood-related fatalities and property loss, expert assessments of flood-risk can be generated to establish a M-O evaluation of alternatives. Policy can modify the environment, exposure, effects, mitigate or compensate for the effects, or perform a hybrid of these strategies. Examples of environment modification include river diversions and obstructions, levees, and stormwater management to divert pluvial flooding. Despite the wide utility of these methods in practice, flooding still remains one of the deadliest and widespread disasters. The reduction of exposure to floods may also be combatted through floodplain development policies; regulation of residencies and urban development in the various inundation extents; and proper evacuation plans for potentially affected populations. Although ideal, this strategy has been undermined by the prioritization of economic factors like low-housing and development costs that lure individuals to flood-prone areas. Modifying the effects is another approach in reducing flood impacts; examples include building designs to mitigate seasonal flooding. Finally, the adverse effects related to flooding can be mitigated through emergency response and compensation through forms of insurance. Similar to the shortcomings of the other approaches, insurance practices have also been shown to increase risky behavior in some cases under the guise of monetary compensation for loss. However, insurance can likely be tailor-made to specific needs and rewarded to those that build outside of flood-prone areas, for example.

Measures must be developed and defined to determine to what extent the fundamental objectives have been achieved (i.e. minimizing flood-related fatalities and property damage). In the case of flood mitigation, appropriate measures include reduced fatalities and economic damage compared to those from past events of equal or similar magnitude. More specific, deaths per capita provide a better representation of the severity of a particular event rather than absolute values. Thus, a baseline mortality rate in non-disaster years can be determined; and disaster years can be used as dummy variables to compare changes in mortality within the community to (1) the baseline for non-disaster years and (2) fatalities caused by previous flood events of similar magnitude.

With these measures in mind, it is crucial to evaluate the various alternatives and the associated impacts of M-O. Although economic damage related to disasters can easily be quantified and monetized, assessing the value of a human life saved is a highly problematic (economically and morally speaking) and, ultimately, an insurmountable task. Instead of attempting to monetize an individual life, perhaps it is more useful to set a cap for fatality reduction by a certain year. This can be a goal set by signatory countries at a national level depending on their highly contextual exposure to flood hazards and vulnerability. This only serves as a recommended approach; since caps such as these are not legally binding, implementation is not guaranteed. At the same time, signatory countries can be held responsible through local and political pressure by international bodies. In practice, self-evaluations should not only be available on the national level to meet HFA objectives – but also – local communities and individuals ought to have access to self-evaluations as a form of checks and balances to ensure national and local integration of HFA objectives. This will help identify the gaps between national policy and local practice that are unique to each region and facilitate action tailor-made to the spatial context.

In addition to setting M-Os from various affected groups, appropriate measures, and evaluation criteria, thresholds must also be identified for the best- and worst-case scenarios. The best-case scenario would be to completely eliminate flood-related fatalities and economic damage worldwide. Nations ought to strive to reduce these numbers as much as possible; in regards to economic damage, however, there is a social optimum in which the monetary costs of exposed economic assets equals the marginal benefits. In other words, eliminating all economic activity would reduce associated damages to zero; on the other hand, this would also disregard the benefits associated with economic activity, its opportunities, and provision of employment and growth. These fundamental objectives could ultimately be combined with expert assessments of flood-risk and applied on-the-ground.

6.7. Concluding remarks

This critique addresses the need to reassess flood mitigation among at-risk communities ensuring a truly participatory process in which community members are active decision-makers. In practice, it is important to address different forms of knowledge, their associated power relations, and the manifestation of hierarchies of scale at the detriment of the state. To bridge the gap between local and scientific knowledge and isolated bottom-up and top-down actions, forums for direct dialogue and policy instruments that are meaningful to all affected groups must be employed. Without this level of communication and coordination, local knowledge and action will continue to be intangible and communities may not be able to fully implement scientific recommendations and comply with policy protocol.

Networks of stakeholders should capitalize on both local and scientific knowledge to provide a basis for progressive action and change. Rather than waiting for top-down flood mitigation policy and action to ‘trickle down’ to local actors, it is time for the coalition of experts to step back and consider the breadth of knowledge that has been gleaned by a variety of stakeholders in the last century on flood-related issues. Use of this knowledge is required to develop and integrate new paradigms for reducing flood impacts, which bring the issues between policy and practice under control and ensures concrete outcomes are achieved at international,

national, and local levels. The use of consensus-based, systematic, and mutual measures and instruments, the integration of bottom-up and top-down actions, and co-creation of knowledge born out of local and scientific expertise within and across different scales are crucial in adequately addressing flood-related issues.

The critique developed herein calls for the development of appropriate measures, codes, and standards that are meaningful and accessible to all affected groups. This perspective could greatly contribute to ensuring the integration of local and scientific knowledge in reducing flood impacts and that bottom-up and top-down actions work in tandem with each other. Without such standards and normalization of various policy incentives, there will continue to be resource and capacity gaps at the local level, as well as limited community participation; thereby contributing to an ever-increasing gap between policy and practice at the local level. The issues of scale and especially hierarchies of scale continue to be a hindrance in linking global and local complexities. It is therefore essential that such codes and standards recognize the diversity within and between countries, thereby allowing for flexibility in terms of the transference and implementation of international and national policy at the local level. This assessment calls for the use of existing knowledge and resources to identify appropriate tools, measures, and frameworks for the 2015 HFA renewal; it is a new approach that capitalizes on the integration of local and scientific expertise, bottom-up and top-down actions, as well as encourages appropriate shifts in national policy which enable this collective action to occur. This is necessary in setting a strong foundation for action at international, national, and local levels for flood mitigation.

7. Final Thoughts and Future Directions

Flood hazards are a force to be reckoned with, as evidenced by rising flood-related fatalities, displaced persons, and growing economic impacts across both space and time. Although flood hazards will always threaten communities worldwide, every flood need not become a disaster. Preventative, mitigative, and adaptive action help reduce both environmental and social vulnerabilities that contribute to overall flood-risk. This study provides a baseline for building maps for exposed populations and agriculture and derives a metric for future sensitivity to change in peak flows. Such maps are essential tools for policymakers, especially for the incorporation of local knowledge that may help shape flood exposure through public participation exercises.

Both the GIS-based analyses and discussion of translating science into practice tackle flood-related issues from unique vantage points. The assessment offers a streamlined, comprehensive toolbox for characterizing flood exposure at the local, national, regional, and global scales. In relation to flood exposure, these assessments provide an essential facet of flood-risk. Coupled with flood-hazard studies (e.g. Kleinen and Petschel-Held, 2007; De Wrachien et al., 2008; Ahmad and Simonovic, 2011; Jongman et al., 2012), the breadth of global flood-risk can be realized both today and amidst future climate and environmental changes. Community-based studies (e.g. Adger, 1999; Adams, 2000; Adikari et al., 2010; Bubeck et. al, 2012) can further highlight the unique socioeconomic vulnerabilities that exacerbate natural flood hazards.

As a critical first-step, this study pinpoints exposure hotspots across the globe by producing both absolute and relative (i.e. D_E) estimates of susceptible populations and agricultural lands. Asia's megacities are a significant cause for concern (Balk et al., 2012), especially since urban dwellers exhibit higher proportions of their total population in flood-prone areas. Furthermore, South America was the only case-study that demonstrated higher absolute exposure estimates for their urban population relative to the surrounding rural areas. Parts of urban Africa also produced high estimates of D_E but lower measures of F_S compared to Latin American cities. Additionally, the ratio of urban developments in floodplains (as a percentage of total urban area) seems to be more prevalent compared to the ratio of rural areas that lie within floodplains on a global and regional scale. However, rural areas face their own challenges with higher ratios of cropland exposed in floodplains. In the midst of climate and environmental change, it is uncertain how fluvial systems and their respective floodplains will shift, thus underscoring the importance of characterizing flood exposure across multiple scales and development contexts.

In looking to the future, it is paramount to characterize the sensitivity to change in flooded area in relation to maximum discharge. When all monthly data are available, the F_S metric derived in this study, despite its current uncertainties, can hopefully be translated on a global scale. The end goal is to provide public access to the baseline inventory of globally exposed variables to in-land flooding, i.e. rural and urban populations and land area, cropland, and pastureland. Exposure maps provide versatile tools to end-users and encourage preparedness at all levels where both high exposure and limited adaptive capacity are present.

Identifying hotspots related to flood exposure can inform policy action and relevant stakeholders to the individual exposure of the region, associated impacts, and potential resistance measures. Combined with the policy framework proposed herein, the gap between local and scientific knowledge can be bridged. Emerging paradigms for flood mitigation will better support the goals of reducing the loss of life and property as a result of high-impact events. Assessments of flood exposure provide the foundation for a discourse related to flood-risk to occur, as well as a starting point for a truly participatory management process. Quantifying in-land flood exposure is the first, and arguably, the most critical step in a series of larger strides to characterize overall flood-risk. Future studies, especially at the global scale, demand a baseline of exposed variables that are directly linked to livelihoods and general well-being. This assessment begins to meet that need.

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Appendices

TABLE A-1. Flood assessments reviewed according to region, type, and measures of risk

Region	Flood Assessment Type	Measure(s)	Author(s)
Three rivers (Russia)	Hazard	Flood frequency	Kuchment et al., 1994
Germany	Hazard	Flood frequency	Buchele et al., 2006
Kelantan River basin (Malaysia)	Hazard	Topography, hydro-climate, physical vulnerability	Pradhan, 2009
Red River (Manitoba, Canada)	Hazard	1997 flood event, temporal and spatial variability, physical vulnerability	Ahmad and Simonovic, 2011
United Kingdom	Hazard	Future, urban and rural areas	Wheater and Evans, 2009
River Saar basin (northeastern France/western Germany)	Hazard	Flood frequency	Krahe et al., 2000
Germany	Hazard	Flood frequency	Schumann and Pfutzer, 2000
Red River (southern Manitoba, Canada)	Hazard	Flood frequency	Elawad et al., 2005
Mae Klong River (Thailand)	Hazard	Flood frequency	Sansena, 2006
Europe	Hazard	Flood frequency, climate, water-use change	Lehner et al., 2006
Bagmati River (central Nepal)	Hazard	Flood frequency	Kafle et al., 2007
Hubei Province, China	Hazard	Flood frequency	Zhang et al., 2009
Yom River (Thailand)	Hazard	Flood frequency	Tingsanchali and Karim, 2010
Yangtze River Delta (China)	Hazard	Flood frequency	Li et al., 2013
Mumbai, India	Hazard	Flood frequency, climate change	Ranger et al., 2011
Global	Hazard	Flood frequency, climate change	Kleinen and Petschel-Held, 2007; Hirabayashi and Kanae, 2009; Jongman et al., 2012; Hirabayashi et al., 2013
Global	Exposure	Climate change, populations	Christenson et al., 2014
Asian cities	Exposure	Climate change, urban area, population	Balk et al., 2012
N/A	Exposure	Economic flood damage	Merz et al., 2010
Parrett River catchment/Bridgewater Bay, England	Exposure	Economic, social impacts	Hall et al., 2003
China	Exposure	Population, crops, housing, economy	Li et al., 2012
Wuhan, Yangtze River Basin, China	Exposure	Urban area	Liu et al., 2014

Global	Exposure	Population, GDP, agricultural value, land-use	Ward et al., 2013
Ichinomiya River basin (Japan)	Proxy for Exposure	Agricultural loss	Dutta et al., 2003
N/A	Proxy for Exposure	Agricultural loss/damage	Bremond et al., 2014
Global	Proxy of Exposure	Flood fatalities	Jonkman, 2005
Red River Valley, Manitoba, Canada	Vulnerability	Post-1997 floods	Haque, 2000
Asia	Vulnerability	Vulnerable slums, migration, development, instability	Adikari et al., 2010
Himalaya-Ganga region (Nepal)	Vulnerability	Flood management, social and physical vulnerability, resilience	Dixit, 2003
Asia	Vulnerability	Climate change, perception, adaptive capacity	Manuta and Lebel, 2005
Inner Niger Delta (Mali, Africa)	Vulnerability	Hydro-climatic change, social vulnerability, adaptive capacity	Morand et al., 2012
N/A	Vulnerability	Socioeconomic factors, political power	Blaikie et al., 2014
United States	Vulnerability	Socioeconomic drivers of response to disaster	Elliot and Pais, 2006
N/A	Vulnerability	Perceptions, flood damage mitigation	Bubeck et al., 2012
Africa	Vulnerability	Climate change, perception, adaptation	Douglas et al., 2008
Gangetic West Bengal, India	Vulnerability	Post-2000 flood	Sanyal and Lu, 2005
Munshiganj district (Bangladesh)	Vulnerability	Vulnerability mapping	Prathumchai and Samarakoon, 2006
Dongting Lake Region (China)	Vulnerability	Vulnerability metrics/weights	Gao et al., 2007
Varying spatial scales	Vulnerability	Flood Vulnerability Index	Balica et al., 2009
Abeokuta flood (Nigeria)	Vulnerability	Post-2007 urban flood	Adelekan, 2011
China	Vulnerability	Classification of major rivers	Gao et al., 2004
Upper Citarum River Basin, West Java, Indonesia	Vulnerability	Social vulnerability	Sarminingsih et al., 2014
Yangtze River (China)	Vulnerability	Social and economic impacts	Jiqing et al., 2007
Europe	Hazard/Exposure	Physical vulnerability, land-	Lugeri et al., 2010

		use, stage-damage, economic damage	
Duero River (Portugal/Spain)	Hazard/Exposure	Urban area downstream from dam, potential fatalities, economic damage	Castillo-Rodriquez et al., 2014
China	Hazard/Exposure	Topography, population, GDP	Ma et al., 2010
Kelantan, Malaysia	Hazard/Exposure	Flood hazard, refuges, residential and urban area	Jiang et al., 2009
Pakistan	Hazard/Exposure	Topography, land-use, social economy	Li et al., 2011
N/A	Hazard/Vulnerability	Physical and morale hazards, crop and flood insurance	McLeman and Smit, 2006
Zimbabwe	Hazard/Vulnerability	Resilience, rural, flood frequency	Gwimbi, 2009
Europe	Hazard/Vulnerability	Topography, land-use, preparedness, response, recovery	De Wrachien et al., 2008
Huaihe River Basin (China)	Hazard/Vulnerability	Topography, population, and economic assets	Liu et al., 2008
Balu-Tongikhal River system (Dhaka City, Bangladesh)	Hazard/Vulnerability	Flood frequency, vulnerability mapping	Gain and Hoque, 2013
Africa	Exposure/Vulnerability	Fatalities, damages, urban slums	Di Baldassarre et al., 2010
Elbe and Mulde Rivers (Germany)	Exposure/Vulnerability	Flood frequency and economic assets	Lindenschmidt et al., 2006
Shanghai, China	Exposure/Vulnerability	Nature, social, economic factors	Zhao et al., 2009
Global	Exposure/Vulnerability	Disaster Risk Index	Peduzzi et al., 2009
Wuling Mountain Region (Central China)	Exposure/Vulnerability	Topography, physical exposure, vulnerability	Yin et al., 2013
Jakarta, Indonesia	Risk	Post-2002, 2007, and 2013 floods	Budiyono et al., 2014
Hebei Province (China)	Risk	Hazard, exposure, vulnerability	Liao et al., 2014

TABLE A-2. GIEMS-D15 estimates of exposed urban population compared to DFO confirmed impacted persons

Country	Exposed Urban Population	% of Total Urban Population	DFO confirmed Fatalities (1990 - 2005)	DFO confirmed Displaced Persons (1990-2005)	Total Impacted (1990-2005)
Afghanistan	464,676	26	3,950	259,880	263,830
Algeria	1,795,967	60	909	28,300	29,209
Angola	404,344	39	74	98,140	98,214
Argentina	2,899,865	21	229	1,230,892	1,231,121
Armenia	57,094	5	5	400	405
Australia	2,431,196	32	73	28,616	28,689
Austria	120,533	7	11	10	21
Azerbaijan	7,896	1	10	1,505,200	1,505,210
Bangladesh	10,160,547	98	144,290	112,375,980	112,520,270
Belarus	19,739	1	6	44,000	44,006
Belgium	3,683,862	62	1	400	401
Bolivia	8,942	1	266	584,775	585,041
Brazil	15,651,559	34	1,127	877,850	878,977
Bulgaria	3,453	0	14	12,220	12,234
Cambodia	867,626	100	1,719	8,366,348	8,368,067
Cameroon	615,905	37	31	1,900	1,931
Canada	3,531,987	33	19	44,645	44,664
Chile	64,081	2	190	191,025	191,215
China	50,696,136	56	18,231	77,558,022	77,576,253
Colombia	524,573	5	628	1,547,429	1,548,057
Cote d'Ivoire	908,214	40	2	0	2
Czech Republic	2,483	0	60	40,060	40,120
Democratic Republic of the Congo	13,625	3	80	90,500	90,580
Denmark	455,367	37	**No Events in POR**		
Dominican Republic	1,151,782	55	3,670	28,340	32,010
Ecuador	933,707	32	237	62,000	62,237
Egypt	869,797	29	640	107,850	108,490
Ethiopia	3,531	0	621	956,230	956,851
France	7,700,391	82	231	393,749	393,980
Georgia	40,037	4	16	26,350	26,366
Germany	1,144,332	17	86	349,750	349,836
Ghana	961,463	31	49	144,000	144,049
Guinea	437,960	67	11	43,500	43,511
Haiti	762,904	55	3,525	381,960	385,485
Hungary	84,030	4	0	150	150
India	52,569,126	67	33,085	141,007,890	141,040,975
Indonesia	25,469,552	82	2,083	2,335,397	2,337,480
Iran	1,088,835	9	1,892	633,750	635,642

Iraq	3,082,064	56	0	0	0
Ireland	161,719	17	0	200	200
Italy	1,634,838	21	364	71,631	71,995
Japan	4,662,670	85	689	663,233	663,922
Jordan	118,915	5	41	300	341
Kazakhstan	14,807	1	10	62,000	62,010
Kenya	7,136	0	329	1,441,800	1,442,129
Lebanon	584,667	54	1	2,300	2,301
Libya	509,894	59		**No Events in POR**	
Madagascar	683,502	68	903	1,241,200	1,242,103
Malaysia	1,231,358	31	287	175,535	175,822
Mali	308,841	42		**No Events in POR**	
Mexico	2,923,718	13	1,866	1,465,125	1,466,991
Mozambique	111,439	12	1,200	2,046,900	2,048,100
Myanmar	2,923,811	84	51	277,794	277,845
Nepal	93	0	1,295	369,572	370,867
Nigeria	4,491,405	40	800	1,366,817	1,367,617
North Korea	1,180,784	84	909	1,474,000	1,474,909
Pakistan	5,791,983	28	5,706	7,836,200	7,841,906
Paraguay	78,590	4	105	353,000	353,105
Peru	406,938	8	830	970,450	971,280
Philippines	12,149,580	83	11,330	12,154,164	12,165,494
Poland	126,434	7	110	188,850	188,960
Romania	2,944	0	289	142,314	142,603
Russia	4,427,833	18	404	1,553,588	1,553,992
Saudi Arabia	97,381	3	124	1,450	1,574
Senegal	1,199,939	69	38	90,900	90,938
Serbia	12,939	2	9	600	609
Singapore	1,235,707	36		**No Events in POR**	
Somalia	24,520	4	4,487	647,740	652,227
South Africa	1,753,859	36	207	60,650	60,857
South Korea	4,786,035	61	681	472,723	473,404
Spain	2,151,174	29	146	3,500	3,646
Sweden	310,448	28	0	20	20
Syria	506,043	19	32	8,000	8,032
Tanzania	844,772	60	3,918	4,248,920	4,252,838
Thailand	7,809,437	90	161,378	13,610,656	13,772,034
Turkey	4,192,753	42	568	14,364	14,932
Uganda	222,576	14	68	59,700	59,768
Ukraine	1,314,837	22	21	60,180	60,201
United Arab Emirates	42,158	7	0	4,000	4,000
United Kingdom	5,361,964	58	131	19,042	19,173
United States	7,014,279	41	2,201	3,612,794	3,614,995
Uruguay	288,844	23	1	10,900	10,901

Uzbekistan	223,389	7	0	0	0
Venezuela	222,113	15	20,136	572,610	592,746
Vietnam	6,344,299	98	3,685	8,549,491	8,553,176
Yemen	0	0	199	33,540	33,739
Zimbabwe	244	0	3	18,250	18,253