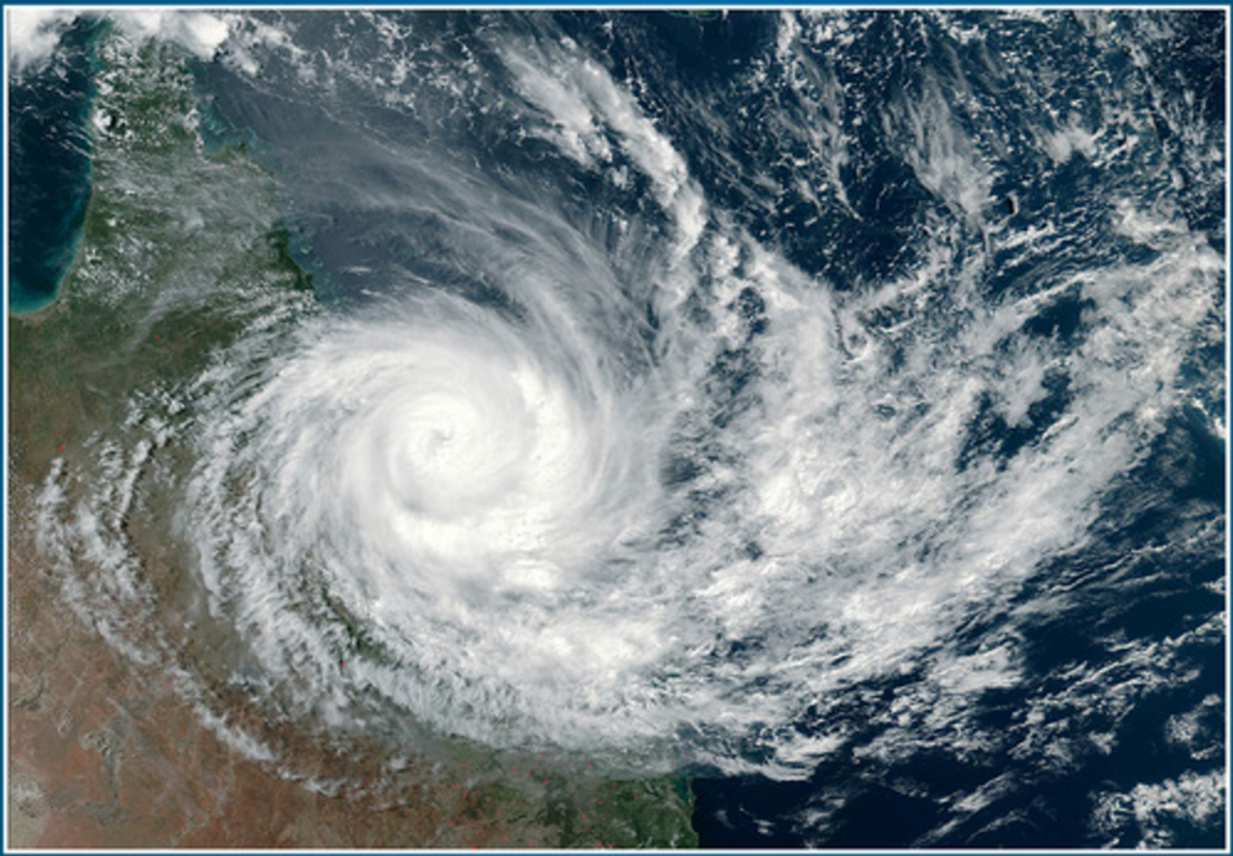
Global Flood Hazard

Applications in Modeling, Mapping, and Forecasting



Guy J-P. Schumann, Paul D. Bates, Heiko Apel, and Giuseppe T. Aronica

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This Work is a co-publication of the American Geophysical Union and John Wiley and Sons, Inc.

AGU 100 ADVANCING EARTH AND SPACE SCIENCE

WILEY

This Work is a co-publication between the American Geophysical Union and John Wiley & Sons, Inc.

This edition first published 2018 by John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA and the American Geophysical Union, 2000 Florida Avenue, N.W., Washington, D.C. 20009

Published under the aegis of the AGU Publications Committee
Brooks Hanson, Executive Vice President, Science
Lisa Tauxe, Chair, Publications Committee
For details about the American Geophysical Union visit us at www.agu.org.

Wiley Global Headquarters
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Library of Congress Cataloguing-in-Publication data is available.

ISBN: 978-1-119-21786-2

Cover image: NASA/NOAA
Cover design by Wiley

Set in 10/12pt Times New Roman by SPi Global, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

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PREFACE

Floods are among the top-ranking natural disasters in terms of annual cost in insured and uninsured losses. Since high-impact events often cover spatial scales that are beyond traditional regional monitoring operations, large-scale flood hazard modeling as well as remote sensing, in particular from satellites, present attractive alternatives. The complementarity of both can help produce better forecasts and better accuracy models, and render remotely sensed flood products and services more credible.

In the last two decades, there have been significant advances in computing architecture, processor speed, and numerical codes for flood inundation models. At the same time, great research efforts have been spent on making boundary data, especially topography at the global scale, fit-for-purpose. This combination has allowed substantial progress in the field of flood hazard modeling at spatial scales that go beyond the traditional reach-scale applications of these types of numerical models. We have recently entered an era of global-scale application of a number of flood hazard models and this now necessitates a lot of work on validation, improving model physics, and overcoming deficiencies in process representation.

In terms of remote sensing of flood hazard, there have been many studies in the scientific literature about mapping and monitoring of floods using satellite imagery since the 1970s. The sensors and data processing techniques that exist to derive information about floods from remotely sensed images are numerous. Instruments that record flood events may operate in the visible-to-infrared and microwave (radar) range of the electromagnetic spectrum. There is now a general consensus among space agencies, numerous organizations, scientists, and end users to strengthen the support that satellite missions can offer, particularly in assisting flood disaster response activities. This has stimulated more research in this area, and significant progress has been achieved in recent years in fostering our understanding of the ways in which remote sensing can support flood monitoring and prediction, and assist emergency response activities.

This book is a collection of chapters that provide state-of-the-art insight on progress, caveats, and limitations in current efforts to map, model, and predict flood hazard at the global scale. Targeted at decision-makers, flood response teams as well as scientists and academics active in the field of flood hazard, the general aim of this book is to report on advances in modeling, mapping, and predicting flood hazard and risk at the global scale. It describes different modeling approaches as well as remotely sensed data sets to predict and map flood risk at different scales, ranging from local to global. Recently, many scientist teams have rolled out models and data sets for flood hazard and risk globally with ever-increasing accuracy and resolution, allowing the research, humanitarian, and development sectors to engage decision-making processes based on better actionable information. This is precisely what this book outlines, and it concludes with a chapter that critically discusses requirements, challenges, and perspectives for improving global flood hazard mapping, modeling, and forecasting.

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1

The Need for Mapping, Modeling, and Predicting Flood Hazard and Risk at the Global Scale

Philip J. Ward[1], Erin Coughlan de Perez[1,2,3], Francesco Dottori[4], Brenden Jongman[1,5], Tianyi Luo[6], Sahar Safaie[7], and Steffi Uhlemann-Elmer[8]

ABSTRACT

The socioeconomic impacts of flooding are huge. Between 1980 and 2013, flood losses exceeded $1 trillion globally, and resulted in approximately 220,000 fatalities. To reduce these negative impacts of floods, effective flood risk management is required. Reducing risk globally is at the heart of two recent international agreements: the Sendai Framework for Disaster Risk Reduction and the Warsaw International Mechanism for Loss and Damage Associated with Climate Change Impacts. Prerequisites for effective risk reduction are accurate methods to assess hazard and risk, based on a thorough understanding of underlying processes. Due to the paucity of local scale hazard and risk data in many regions, several global flood hazard and flood risk models have been developed in recent years. More and more, these global models are being used in practice by an ever-increasing range of users and practitioners. In this chapter, we provide an overview of recent advances in global flood hazard and risk modeling. We then discuss applications of the models in high-level advocacy in disaster risk management activities, international development organizations, the reinsurance industry, and flood forecasting and early warning. The chapter concludes with several remarks on limitations in global flood risk models and the way forward for the future.

1.1. INTRODUCTION

River floods are one of the most damaging forms of natural hazards [*Guha-Sapir et al.*, 2015], causing economic damage, fatalities, and social hardship all around the world. For example, over the period 1980–2013, flood losses exceeded $1 trillion globally, and resulted in approximately 220,000 fatalities [*Munich Re*, 2014]. Moreover, flood losses are increasing. While the reported losses due to floods were about USD 7 billion per year during the 1980s (adjusted for inflation), these increased to USD 24 billion per year during the period 2001–2011 (*Kundzewicz et al.* [2013], based on Munich Re NatCatSERVICE data). These negative impacts of flooding are projected to increase in the future [*UNIDSR*, 2015a] due to climate change [*Arnell and Gosling*, 2016; *Hirabayshi et al.*, 2013; *Winsemius et al.*, 2015], urbanization [*Güneralp et al.*, 2015; *Jongman et al.*, 2012], and land subsidence [*Brown and Nicholls*, 2015; *Syvitski et al.*, 2009].

Flood risk management aims to reduce the negative impacts of floods. The concept of flood risk combines the probability of a flood with its potential consequences. While there are many definitions of risk, it is usually

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Global Flood Hazard: Applications in Modeling, Mapping, and Forecasting, Geophysical Monograph 233, First Edition.
Edited by Guy J-P. Schumann, Paul D. Bates, Heiko Apel, and Giuseppe T. Aronica.

operationalized as being a function of three risk elements, namely: hazard, exposure, and vulnerability [e.g., *Kron*, 2002; *UNISDR*, 2011, 2013, 2015a]. As stated by *UNISDR* [2011], the hazard refers to the hazardous phenomenon itself, such as a flood event, including its characteristics and probability of occurrence; exposure refers to the location of economic assets or people in a hazard-prone area; and vulnerability refers to the susceptibility of those assets or people to suffer damage and loss (e.g., due to unsafe housing and living conditions, or lack of early warning procedures).

Reducing risk, not only to flooding but also to all natural hazards, is high on the global political agenda. For example, it is at the heart of two recent international agreements: the Sendai Framework for Disaster Risk Reduction (Sendai Framework) [*UNISDR*, 2015b]; and the Warsaw International Mechanism for Loss and Damage Associated with Climate Change Impacts (Loss and Damage Mechanism) [*UNFCCC*, 2013]. The Sendai Framework is a 15-year, voluntary, nonbinding agreement that was adopted at the Third UN World Conference in Sendai, Japan, in 2015. The Sendai Framework aims at the following outcome: "The substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries" (*UNISDR*, 2015b; page 12). To do this, the Sendai Framework sets out four so-called priorities for action, one of which (Priority 1) is Understanding Disaster Risk. To achieve this at the global level, the framework points to the need to "enhance the development and dissemination of science-based methodologies and tools to record and share disaster losses and relevant disaggregated data and statistics, as well as to strengthen disaster risk modeling, assessment, mapping, monitoring and multi-hazard early warning systems" [*UNISDR*, 2015b; page 16]. The Loss and Damage Mechanism was adopted at the United Nations Framework Convention on Climate Change (UNFCC) Conference of the Parties (COP19) in Warsaw, Poland, in 2013. It promotes the implementation of approaches to address loss and damage associated with impacts of climate change, including extreme events like floods, in developing countries. One of the ways to do this is by "enhancing knowledge and understanding of comprehensive risk management approaches to address loss and damage associated with the adverse effects of climate change" [*UNFCCC*, 2013; page 6].

To contribute to the aims of the aforementioned agreements, effective risk reduction strategies are required. To achieve this at the global scale requires methods to quantitatively assess global flood risk in a holistic manner [*Mechler et al.*, 2014]. Ideally, this could be achieved by developing detailed, high-resolution local flood models [*Jonkman*, 2013] for all parts of the globe. However, in reality, the data required to develop such fine-scale models do not exist in most locations, and the time required to collect such data and run the models would be prohibitive. Therefore, in the past decade, several global flood risk models have been developed.

In this chapter, a brief overview is given of recent advances in global flood hazard and risk modeling in section 1.2. In section 1.3, we discuss how global flood risk model results are contributing to high-level advocacy in disaster risk management (DRM) activities at the international scale. In sections 1.4–1.6, we demonstrate a number of applications of global flood risk models in international development organizations, the reinsurance industry, and flood forecasting and early warning. An example of how to communicate complex information from global flood risk models to end-users is provided in section 1.7, using the example of the Aqueduct Global Flood Analyzer. Finally, the chapter concludes with several remarks on limitations in global flood risk models, and the way forward in section 1.8.

1.2. BRIEF OVERVIEW OF RECENT ADVANCES IN GLOBAL FLOOD HAZARD AND RISK MODELING

One of the essential inputs to a global flood risk model is global flood hazard maps, or event footprints. One of the earliest attempts at developing a global flood hazard map was the Hotspots project of the World Bank [*Dilley et al.*, 2005]. An objective of this project was the "development of a spatially uniform, first-order, global disaster risk assessment" [*Dilley et al.*, 2005; page 19]. One of the disaster risks included in this project was flooding. Given the lack of availability or global inundation models at the time, the project represented flood hazard using a georeferenced data set of past extreme flood events between 1985 and 2003 from the Dartmouth Flood Observatory. This led to a map showing the extent of floods recorded by Dartmouth Flood Observatory over that time period; no information was available on flood depths or return periods, or for locations that were not flooded during the period 1985–2003.

Advances in global modeling and the availability of more and more global flood loss data sets allowed *UNISDR* [2009] to develop a set of improved flood hazard maps for the Global Assessment Report (GAR) 2009 [*UNISDR*, 2009]. These hazard maps showed flood extent for a limited number of return periods, and were based on the modeling approach of Herold and Mouton [2011]. More recently, UNISDR and CIMA foundation conducted a probabilistic flood hazard and risk assessment for the GAR2015 [*UNISDR*, 2015a]. *Pappenberger et al.* [2012] developed a model to simulate flood hazard maps, showing the fraction of each grid-cell that is inundated for several return periods (2, 5, 10, 20, 50, 75, 100, 200, and 500 years) at a horizontal resolution of 25 km × 25 km resolution. The maps were further reprojected to a higher horizontal resolution of 1 km × 1 km. In 2013, the studies of *Hirabayashi et al.* [2013] and *Ward et al.* [2013] used modeling approaches to develop global flood hazard maps. *Hirabayashi et al.* [2013] took modeled discharge data from 11 Global Climate Models, and used these as input to the Catchment-based Macro-scale Floodplain Model (CaMa-Flood) [*Yamazaki et al.*, 2011] to simulate flood fraction of a cell at a horizontal resolution of 15′ × 15′. These maps were developed for the current climate (1971–2000) for several return periods (10, 30, 50, and 100 years), and also under future climate conditions, namely 2071–2100. At about the same time, *Ward et al.* [2013] developed the global flood risk model GLOFRIS. In GLOFRIS, flood hazard maps were developed showing both inundation extent and depth at a horizontal resolution of 30″x 30″ (about 1 km × 1 km at the equator), using the volume spreading algorithm developed by *Winsemius et al.* [2013]. The model has been used to develop flood hazard maps for several return periods (2, 5, 10, 25, 50, 100, 250, 500, and 1000 years) under current climate conditions [*Ward et al.*, 2013], in the different phases of El Niño Southern Oscillation (ENSO) [*Ward et al.*, 2014], and under future climate conditions in 2030 and 2080 [*Winsemius et al.*, 2016]. Recently, *Sampson et al.* [2015] developed the SSBN-flow global flood hazard model. Unlike previous models, this model simulates inundation by solving hydrodynamic versions of the shallow water equations, resulting in flood hazard maps (inundation extent and depth) at a horizontal resolution of 3″ × 3″ (approximately 90 m × 90 m at the equator). A similar approach has also been used by *Dottori et al.* [2016] to develop global flood maps at 30″ × 30″ horizontal resolution (see section 1.6).

Clearly, then, the capabilities for global flood hazard modeling are developing rapidly, although the field is still in its infancy. Only recently has the community begun examining the potential uses and limitations of the existing models [*Ward et al.*, 2015], as discussed briefly in section 1.8. Efforts are now under way to begin to compare the results of different models, in order to evaluate their reliability and investigate which methods work in which regions, and why. For example, as part of the activities of the Global Flood Partnership (GFP), several researchers are comparing multiprobability flood hazard maps for Africa from six global flood hazard models [*Trigg et al.*, 2016]. GFP is a platform for organizations involved in global flood risk to transfer knowledge between science and users [*De Groeve et al.*, 2015]. Such studies are important for increasing our understanding of modeling global flood hazard.

Fewer models have so far attempted to assess flood risk. The World Bank Hotspots project made a first effort in this regard. The flood maps described previously were combined with gridded population maps at a spatial resolution of approximately 2.5′ × 2.5′ (approxmately 5 km × 5 km at the equator), and these were used to categorize each grid-cell into deciles in terms of their potential flood risk [*Dilley et al.*, 2005]. The biennial Global Assessment Reports (GAR) of the UNISDR have gradually provided more and more flood risk information at the global scale, based on their modeling approach [*UNISDR*, 2009, 2011, 2013, 2015a], and these data are made available through a dedicated data platform on the PreventionWeb website. *Hirabayshi et al.* [2013] combined their flood hazard maps for a 100-year flood with global population data to estimate the change in population living in flood-prone areas between today and the end of the 21st century. Several studies using the GLOFRIS model have estimated flood risk in terms of several indicators (annual expected urban damage, affected population, affected GDP, and affected agricultural value) based on the integration of impacts across a large number of return periods. These studies have been carried out under current climate conditions [*Ward et al.*, 2013], different phases of ENSO [*Ward et al.*, 2014], future climate and socioeconomic conditions [*Winsemius et al.*, 2016], and under future adaptation scenarios [*Jongman et al.*, 2015]. *Arnell and Gosling* [2016] used a more simplified approach to assess changes in flood risk between 1960 and 1990 and two future time periods (2050s and 2080s), using results from 19 global climate models. In this study, the flood hazard is represented by a change in frequency of the current 100-year discharge, and therefore hazard maps are not developed in terms of inundation extents and/or depths. Nevertheless, the approach allowed for first-order estimates in the potential future changes in population and cropland exposed to a potential change in flood frequency, as well as flood loss.

1.3. GLOBAL FLOOD RISK INFORMATION IN HIGH-LEVEL DISASTER RISK MANAGEMENT ADVOCACY

Information on flood hazard and flood risk from global models is having an important impact on disaster risk management advocacy at high level. The Sendai Framework calls for enhancement and increase in access to risk information at all levels for all stakeholders. As mentioned earlier, the importance of risk information as a basis for any policy and investment is outlined clearly in Priority 1, Understanding disaster risk (para 23; page 14 in *UNISDR,* 2015b). Several applications of global risk assessments to date toward this priority include increasing awareness of public, politicians, and practitioners on the risk levels, trends, and spatial characteristics of disaster risk at the global level; developing brief country risk profiles providing a first cut of risk information for the estimation of the fiscal liabilities of national governments; developing an operating picture of hazard intensities, exposure, and disaster risk at global level; risk indexing and rankings for the comparison of hazard and risk levels among countries; and monitoring intensive and extensive disaster risk over time and DRM progress, such as outputs for the Hyogo Framework for Action 2. As part of this process, UNISDR has made the global flood risk assessment created for its Global Assessment Report of 2015 (GAR15) freely available online on the Risk Data Platform CAPRAViewer on its Preventionweb website. For floods, these data are derived from the Global Flood Model of the CIMA Foundation [*CIMA Foundation*, 2015]. Other examples include applications of the GLOFRIS model for major reports of the Global Water Partnership (GWP) / Organisation for Economic Co-operation and Development (OECD) Task Force on Water Security and Sustainable Growth [*Sadoff et al.*, 2015], the OECD on the Economic Consequences of Climate Change [*OECD*, 2015], and a contribution to the forthcoming flagship World Cities Report 2015 of UN-HABITAT [*Ligtvoet et al.*, 2014]. All of these reports and their surrounding advocacy activities serve to place the need for global efforts to reduce disaster risk, including flooding, on the global agenda at the very highest level.

1.4. APPLICATIONS FOR INTERNATIONAL DEVELOPMENT ORGANIZATIONS

International development organizations use flood hazard and flood risk modeling for several purposes. First, quantitative risk assessments are used for the estimation of economic and financial risk of hazards to government clients, and the design of according risk financing instruments. Second, flood modeling is used to bring risk awareness into development portfolios.

1.4.1. Risk Assessment and Financing

Development organizations, such as The World Bank Group and several of the specialized UN agencies, have issued a range of national-level flood risk assessments over the past years. Most of these assessments are conducted in data-scarce developing countries, where input data and modeling capacities are often limited. Global flood risk models are a key asset in such studies, since they rely on global input data for their computations. They can produce quantitative probabilistic risk estimates consistently across different countries, and are much more cost effective to conduct than analyses with new location -specific models.

One example of risk profiling using a global flood model is the set of national level risk profiles produced for the World Bank's Eastern Europe Central Asia Region. In this study, the GLOFRIS model [*Ward et al.*, 2013] was used to produce probabilistic estimates of population and GDP at risk for 32 countries, which were then visualized in easily understandable risk profile documents (Fig. 1.1) [*World Bank*, 2015].

Similarly, a national-scale assessment of the population potentially exposed to flooding has been carried out for the World Bank for Nigeria. In 2012, floods in Nigeria killed hundreds of people and displaced over one million more. Following this disaster, the World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) carried out a Post-Disaster Needs Assessment (PDNA), which recommended an urgent strengthening of the country's resilience to flooding. Consequently, the World Bank Africa Disaster Risk Management team began implementing a National Flood Risk Management Implementation Plan. To support this activity, GLOFRIS was used to rapidly assess the potential extent of flooding and population exposed to flooding per state, for floods of different return periods. Examples of the latter are shown in Figure 1.2. This activity provided "a great first step in providing a national map showing vulnerability to floods for Nigeria, where previously, no such methodologies were in place" (D. Wielinga, Senior Disaster Risk Management Specialist, Africa Region; https://www.gfdrr.org/gfdrr-connects-science-policy-help-address-flood-risk-nigeria).

Global flood models have also been used for national flood hazard mapping in Belize as part of the World Bank–initiated Caribbean Risk Information Program. The program was initiated in 2014 with the objective of building the capacity of government clients in the Caribbean region to generate landslide and flood hazard and risk information and apply this in disaster risk reduction use cases (www.charim.net). The SSBN-flow model [*Sampson et al.*, 2015] was used to produce national flood hazard maps for Belize. The government of Belize will use the nationally consistent indicative fluvial and pluvial flood hazard layers to support decision making in spatial and infrastructure planning, particularly for housing and roads. The availability of these data has enhanced the quality of flood hazard information, which was previously unavailable in this very data scarce area.

Despite the advantages in the use cases described above, global flood risk models have several important limitations (see section 1.8). It is important that these limitations be clearly communicated to potential users. Moreover, global flood risk models are not intended to replace national scale or local models. Where available, these models generally provide much higher quality information, and therefore it is important to ensure global flood risk models are used for the kinds of applications for which they are intended, and to provide complementary

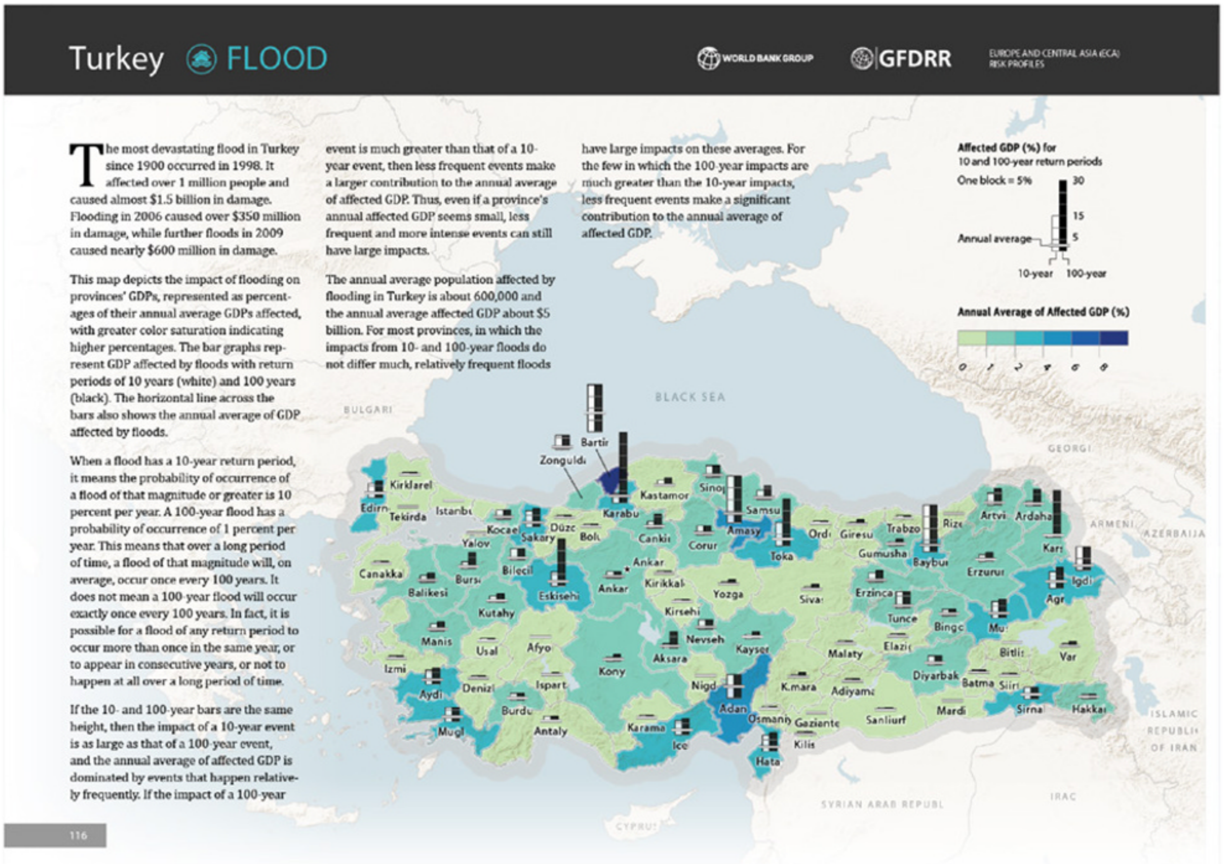

Figure 1.1 National-level flood risk profile for Turkey, produced for the World Bank using the GLOFRIS model [*World Bank*, 2015].

information to local scale models (see also section 1.6). While global flood risk models can be useful for identifying risk hotspots and examining the effectiveness of risk reduction strategies at the large scale, their coarse granularity and high uncertainty means they cannot be used to design individual measures. For example, while global flood risk models can be used to give a first-cut estimate of the damages that could be avoided by protecting a country against a 100-year flood, they cannot be used to design the actual measures that would be needed to achieve this [*Ward et al.*, 2015]. The ThinkHazard! tool, described below, attempts to address this issue by providing users with the highest possible quality hazard information: where national hazard data are available, these are used in the tool, and where these are not available, global data sets are used.

1.4.2. Flood Awareness in Development Projects

Global flood hazard models have the potential to help development professionals understand flood risk in regions where they are undertaking, or planning to undertake, development projects. For example, they could be used to flag potential flood risk to infrastructure construction, agriculture projects, or the construction of new schools, a check that is currently often not conducted.

For this purpose, GFDRR recently launched ThinkHazard! (thinkhazard.org). ThinkHazard! is a web-based tool designed to assist development professionals who are not experts in the field of natural hazards to consider the impacts of disasters on new development projects. It is a flagging tool that highlights the presence of potential natural hazards in a user's project area. Users enter their project location in the browser (national, provincial, or district name) and the tool shows whether they need high, medium, or low awareness of different hazards when planning their project (Fig. 1.3). It also provides the user with recommendations and further resources specific for the region of interest.

As input, ThinkHazard! uses data from existing risk models. Where high-quality national scale risk assessments and data sets are available, these are used as input

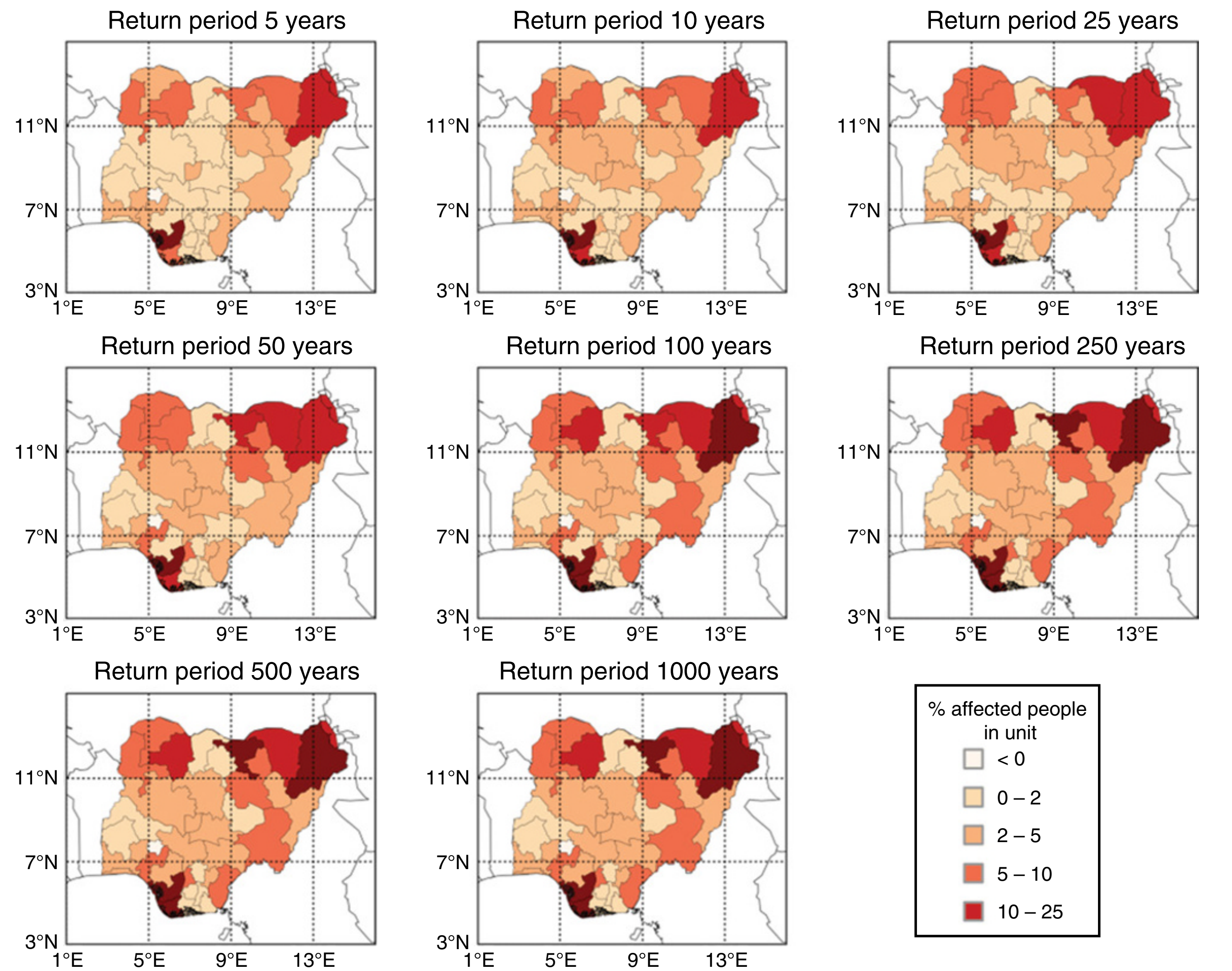

Figure 1.2 GLOFRIS simulations of the number of people affected per state (expressed as a percentage of the total population per state) for floods of different return periods.

to the tool. For regions where such data are not available, global risk data sets are used. By translating global flood model results into understandable hazard categories and actionable information, tools like ThinkHazard! have the potential to make global flood model results directly actionable for nontechnical development professionals, while also allowing for the incorporation of national data sets where available.

1.5. APPLICATIONS FOR THE REINSURANCE INDUSTRY

Within the reinsurance sector, flood risk is mainly assessed for three purposes: (1) for pricing when brokering contracts between reinsurance and insurance companies; (2) for portfolio management to assess risk accumulation across a portfolio; and (3) in calculating solvency and other regulatory or economic capital requirements. The key question that needs to be addressed for each purpose is that of the frequency and magnitude at which flood losses occur simultaneously (or within a time window) to a given set of locations. While for the first purpose the annual expected loss is a key metric, for the other two purposes the tail risk or probable maximum loss is important. Typically, regional to national (individual contracts) to continental (the entire portfolio) sets of exposure need to be assessed for their risk of flooding, explicitly accounting for the correlation of losses between the large numbers of locations (in the order of several thousand to hundred thousands). This requires an event-based probabilistic large-scale flood risk assessment.

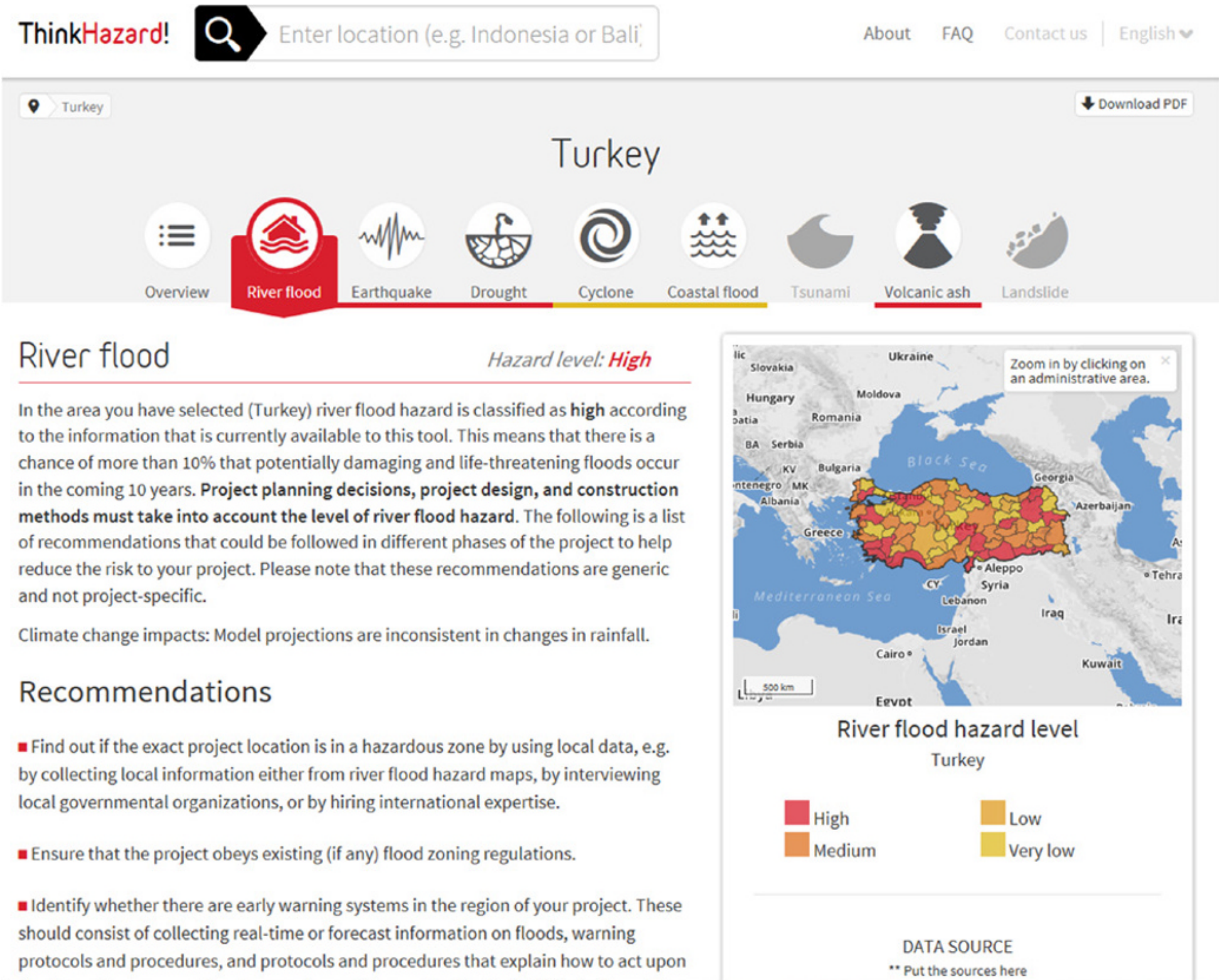

Figure 1.3 Screenshot of an early beta version of ThinkHazard!, a tool developed by the World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR). The tool utilizes global flood hazard models and gives the development professional easy access to hazard information as well as practical recommendations for risk reduction.

A whole industry has evolved offering tailor-made modeling solutions, that is, probabilistic models, for reinsurance applications (e.g., AIR: http://www.air-worldwide.com; CoreLogic: http://www.corelogic.com/solutions/catastrophe-risk-management.aspx; Impact Forecasting: http://www.aon.com/impactforecasting/impact-forecasting.jsp; JBA: http://www.jbarisk.com/; RMS: http://www.rms.com/). These models are commonly referred to as catastrophe models (or cat models) and their principle design is identical for the different hazards. A cat model generates a set of stochastic events, which includes all physically plausible hazard scenarios, that is, also ones that have not yet been observed, and estimates the resulting loss to the portfolio for each event. From this, the exceedance probability curve of loss to the portfolio and the expected annual loss are computed and the tail risk can be assessed.

Since floods are a complex and computationally very expensive hazard to model, fully probabilistic catastrophe models came to the market relatively late. While catastrophe models for hazards such as wind or earthquakes were already available in the 1980s, flood models were available only since the early 2000s for some selected countries. It is only recently that flood risk models have been developed for the continental scale like Europe or the United States and for countries of emerging markets like Asia and Latin America. Beside commercial models, in-house model development has received increasing attention. These are used either complementary to commercial models for the sake of an independent second point of view of the risk, or in order to fill regional gaps, or to avoid very substantial licensing fees.

Depending on regional practice or the specific wording of a contract, either a defined selection or all types of flooding that cause damage to the structure of a building or its content, or an interruption of the business are being covered. For a complete risk assessment, this requires the modeling of all those flood types that may cause an insured loss and, in particular, it requires the joint modeling of correlating flood types. This ranges from flood losses due to cloud bursts in an urban environments, to large river floods due to heavy rainfall, to coastal flooding from storm surges, or tsunamis. Considering the scale-range and differences in the driving physical processes, there is (currently) no one-fits-all modeling solution.

The main type of flooding that is explicitly modeled in probabilistic flood risk models is river flooding. Losses are largely caused by property located in floodplains and a wide array of scientific methods have been developed to model floodplain inundation (see Chapters 5, 6, 8, 10, and 11). To date, the accuracy of the modeling has been constrained by the availability of good quality data and the simplifications required to model key physical processes, rather than the computational resources at hand. The important role of Digital Elevation Models is discussed in Chapters 5, 8, 13, and 14. Further, knowledge about structural flood protection measures is indispensable for flood risk assessment at any scale, also the global scale [*Ward et al.*, 2013]. Only recently have efforts begun to develop a database of flood protection standards at this global scale [*Scussolini et al.*, 2015]. Such a database is essential for improving large scale estimates of flood risk [*Hall*, 2014], both for the reinsurance industry and for other applications.

As mentioned earlier, for reinsurance purposes, it is also important to model all flood types that can cause an insured loss, as well as correlated flood types. Tsunamis are modeled based on their seismic origin in the framework of a probabilistic earthquake model, or independently. Since weather induced and tsunami flood risk can be considered uncorrelated, they can be treated as a simple additive of the two model results (if required). Storm surges are being modeled almost exclusively in the framework of probabilistic wind models. For extratropical storm systems, storm surge is the main cause of flooding and flooding from heavy precipitation is of less concern. However, the residual risk of coinciding river flooding and storm surge remains unaddressed in many cases. Tropical cyclones (TC) instead, besides causing storm surges, often carry a lot of precipitation, which can lead to inundation also far inland. Some TC models include a flood model component; however, often flood losses are only assessed statistically and at coarse spatial resolutions. So far, no model has been presented that jointly assesses the risk of flooding from both river flooding and coastal flooding at adequate resolution. This is seen as a research priority, since several studies in Europe, Australia, the United States, and China have demonstrated that statistical dependence exists between the frequency or magnitude of coastal floods and inland flood processes [e.g., *Hawkes*, 2008; *Kew et al.*, 2013; *Klerk et al.*, 2015; *Lian et al.*, 2013; *Van den Brink et al.*, 2005; *Van den Hurk et al.*, 2015; *Wahl et al.*, 2015; *Zheng et al.*, 2014].

When assessing flood risk due to large river floods, for reinsurance, another phenomenon needs to be considered. Claims data and damage surveys after events have repeatedly highlighted that a substantial amount of losses originates from inundation processes that are difficult to model on the large scale and that are commonly summarized as "off-floodplain" losses. These processes act on mesoscales to microscales (a few km^2 down to several m^2) and include direct runoff and flash floods in the areas of heavy precipitation, sewerage overflow, and groundwater flooding. The pluvial flood component requires a higher spatial and temporal resolution in the modeling of the precipitation field than what is input into large-scale river flood models. So far, in most cat models off-floodplain processes are treated statistically only and improvements to this are a research priority in the reinsurance flood modeling community. To date, off-floodplain processes are not explicitly accounted for in global flood risk models, and it will be important to investigate the importance of this fraction of risk for other international risk applications.

When considering the overall uncertainties of a large-scale flood risk model, in the reinsurance context, the uncertainties introduced by the exposure data and the modeling of the loss often outweigh the uncertainties in the hazard component. Increasingly, exposure data are being submitted to a reinsurer at high quality, that is, at coordinate or street address level and with attributes that define the insured property's vulnerability. In evolving markets in particular, it is, however, not untypical to receive a share or all of the exposure as sums of total insured value per some administrative unit, for example, postcode. In these cases, algorithms for disaggregating or distributing values within the administrative unit need to be employed making assumptions about both the spatial distribution and the building characteristics. Often industry exposure databases that capture these characteristics are being developed (or employed from different sources) in the flood model and used for disaggregation or sampling. Vulnerability functions are used when estimating the damage ratio of a building given a hydraulic load (mostly inundation depth). Often many different engineering based functions are used for certain types of buildings and their characteristics. Where possible, these functions are calibrated using empirical data. However, the few data available are characterized by a great variance and often little statistical coherence. Strong regional differences in building types and standards further complicate the transfer of functions across regions.

Flood contracts are in most cases renewed every year, and when pricing the key metric used is the expected annual loss for the year to come. For reinsurance flood risk modeling, the expectation and assumption is that the flood model provides a correct representation of the current risk. That is, it represents aspects such as the current climate, river training and flood management information, and land use. This requires that a flood model accounts for any trends or step changes in the underlying data, like hydrometeorological time series. For long-term strategic planning, drivers of flood risk change are being assessed (e.g., climate change, land subsidence especially in delta regions, changes in protection standards). Shorter-scale changes in flood risk, such as seasonal, annual, and decadal variations caused by climate variability and climate oscillations, are being investigated. These processes are less standardized and cat models are only just starting to account for temporal clustering in events. To date, the only study to have examined the influence of these shorter-term fluctuations on risk in the global scale scientific flood risk literature is an assessment of the influence of ENSO on flood risk [*Ward et al.*, 2014].

1.6. APPLICATIONS FOR GLOBAL FLOOD FORECASTING AND EARLY WARNING

Next to global scale assessments of flood risk, global flood models are essential for developing early warning systems. The Sendai Framework for Disaster Risk Reduction 2015–2030 [*UNISDR*, 2015b] clearly emphasizes the importance of early warning systems in DRM. This requires global flood forecasting, and (near) real-time monitoring systems. Examples of such systems are GloFAS (Global Flood Awareness System) [*Alfieri et al.*, 2013], GFMS (Global Flood Monitoring System) [*Wu et al.*, 2014], and Dartmouth Flood Observatory (http://floodobservatory.colorado.edu/).

A potential use of these systems is for triggering DRM actions before flood events occur, rather than and/or complementary to carrying out ex-post-disaster recovery in the aftermath of disasters [*Coughlan de Perez et al.*, 2014a]. The novel concept of forecast-based financing is being developed to facilitate this. As described by *Coughlan de Perez et al.* [2014b], a forecast-based financing system automatically triggers action based on modeled climate forecasts or observations. Such a system matches threshold forecast probabilities with appropriate actions, disburses required funding when threshold forecasts are issued, and develops standard operating procedures containing the mandate to act when these threshold forecasts are issued.

Several pilot projects are being implemented to test such a system, including a project in northern Uganda by the Uganda Red Cross, together with the German Red Cross, and the Red Cross Red Crescent Climate Centre. The project region was the site of decades of regional conflict that subsided in the mid-2000s [*Kandel*, 2014]; many resettled communities are vulnerable to floods and waterlogging. However, high resolution local models for the rivers and lakes in this region are not available, and there is little historical monitoring data from the area.

Therefore, the team worked with national and international hydrologists to develop a set of thresholds to trigger ex-ante actions based on GloFAS forecasts. GloFAS [*Alfieri et al.*, 2013] is a probabilistic flood early warning system running at global scale, jointly developed by the Joint Research Centre (JRC) and the European Centre for Medium Range Forecasts (ECMWF). The system has been running preoperationally since 2011, producing daily flood forecasts. Since May 2015, the forecasts have been accessible for registered users in real time on a dedicated web platform (http://globalfloods.jrc.ec.europa.eu/).

In the pilot project in Uganda, specific high-discharge GloFAS forecasts were linked to specific humanitarian preparedness actions in the region. For example, the team indicated that a GloFAS forecast of 50% chance of flooding in the district of Kapelebyong should trigger the disbursement of chlorine tablets to the target high-risk villages in that district. The forecasts were specifically linked to large-scale actions that are appropriate for the high false alarm rates and low spatial resolution inherent in global flood models; actions such as evacuation of specific households would not be possible.

National and international teams of humanitarians and scientists monitored the GloFAS forecasts, and this trigger was indeed reached in Kapelebyong in November 2015. With 4 days of advance notice to the highest-forecasted water levels, Uganda Red Cross worked with local government to distribute two jerrycans, two bars of soap, and a month's supply of water purification tablets to 370 households. They also gave shovels and instructions for digging drainage trenches, and bags for storing harvested food to protect it from waterlogging. Anecdotal feedback from the affected area indicated that the model captured the flood peak relatively well in this case, and Uganda Red Cross anticipated a reduced disease burden in the area, even though the water levels had risen to impactful levels.

As such global flood models are becoming increasingly available, the humanitarian sector is increasingly setting up such standard operating procedures to ensure that the risk information is used to automatically trigger action. The German Red Cross maintains a preparedness fund, which can be disbursed based on a forecast, and the implementing agencies acknowledge the fact that they will often act "in vain" because the forecasts are not perfect. However, global flood models can provide useful information in areas with little other information on dynamic flood risk, and allow for targeted and effective action before impacts are realized.

Next to this application, GloFAS is also being used by national and regional authorities before and during large flood crisis as an information tool complementary to local early warning systems and flood hazard information. For example, it is being used by the European Commission's Emergency Response Coordination Centre, the Brazilian National Center for Monitoring and Warning of Natural Disasters, the National Meteorological and Hydrological Service of Peru, as well as other such organizations. It is important to note that, to avoid conflicts with national legislative frameworks, access to GloFAS forecasts is currently restricted to registered users, and information is provided with the disclaimer that users should complement, and not replace, national-scale flood warning systems, where available.

Several end-users are calling for further developments of global flood forecasting and early warning systems to also give forecasts or warnings in terms of the potential impacts of an impending flood event. Currently, forecasts are given in terms of hydrological parameters such as river discharge, but there is a demand from users for risk-based forecasts, for example in terms of affected areas, assets, and population. Several global flood forecasting and warning systems are now being developed towards this goal.

In GloFAS, a first step has been developed for integrating flood hazard mapping within the hydrological database and structure [*Dottori et al.*, 2016]. Streamflow data available from long-term GloFAS simulations are statistically analyzed to derive peak discharges for return periods from 10 to 500 years, and then downscaled on a high resolution river network (30″ × 30″) to provide the input for the flood simulations. For each river basin considered, the drainage network is divided in river sections where local simulations are run in parallel. Simulations are performed with a two-dimensional hydrodynamic model, designed to ensure an accurate representation of flow processes in the river network and flood-prone areas. Finally, local flood maps produced for each return period are merged to produce continental inundation maps at horizontal resolution of 30″ × 30″. All the global flood hazard maps are freely available for download and reuse at the JRC Data Catalogue (http://data.jrc.ec.europa.eu/collection/floods). A visualization for Africa is shown in Figure 1.4. A further project is ongoing to develop a near-real-time, event-based procedure for rapid flood mapping and impact assessment, based on GloFAS flood forecasts. The methodology will use the catalogue of local flood maps to link GloFAS discharge forecasts and hazard maps, based on the predicted flow magnitude and the forecast lead time. Such an application will greatly improve the early warning system of GloFAS by providing a quick evaluation of expected flood-prone areas and flood impacts, and thus allowing for timely preparation in areas at risk. An application at European scale is already in operational use within the European Flood Awareness System (EFAS) [*Dottori et al.*, 2017], while an experimental global version is planned by the end of 2018.

1.7. COMMUNICATING GLOBAL FLOOD RISK: THE AQUEDUCT GLOBAL FLOOD ANALYZER

As demonstrated in the previous sections, a growing number of global flood hazard and flood risk models are now generating growing amounts of data on global flood risk. However, in order to increase the effectiveness of this data in supporting DRM, it is important to make sure that the complex flood risk data are converted into actionable information [*Ward et al.*, 2015]. Information must be communicated effectively and in an understandable way, and be easily available in a timely manner. A way to facilitate this is through the development of tools that clearly and effectively communicate risk. One example of such a tool for communicating global flood hazard information is GFDRR's ThinkHazard! tool, which has been described in section 1.4. An example of a tool developed to communicate actionable information on both flood hazard and risk is the Aqueduct Global Flood Analyzer (www.wri.org/floods).

The Aqueduct Global Flood Analyzer is a free to use, web-based interactive platform that displays global flood hazard and risk maps, and allows any users to carry out their own flood risk analysis on the fly. The analyzer aims to help the public and decision makers better understand and quantify flood risks, and to raise the awareness around disaster risk reduction and climate change impacts and adaptation opportunities, by making advanced scientific data and models accessible and actionable to the public. It allows users to estimate flood risk in terms of urban damage, affected GDP, and affected population at the country, state, river basin, and city scale. The tool was developed by the World Resources Institute, together with the Institute for Environmental Studies of the Vrije Universiteit Amsterdam, Deltares, PBL Netherlands Environmental Assessment Agency, and Utrecht University. The analyzer uses flood risk data from the GLOFRIS model [*Ward et al.*, 2013; *Winsemius et al.*, 2015], and makes these data available in the form of actionable information. Using the analyzer, users can assess present-day risk, and also how that risk will change in the future due to climate change and socioeconomic development. Uniquely, the analyzer also provides interactive analytical

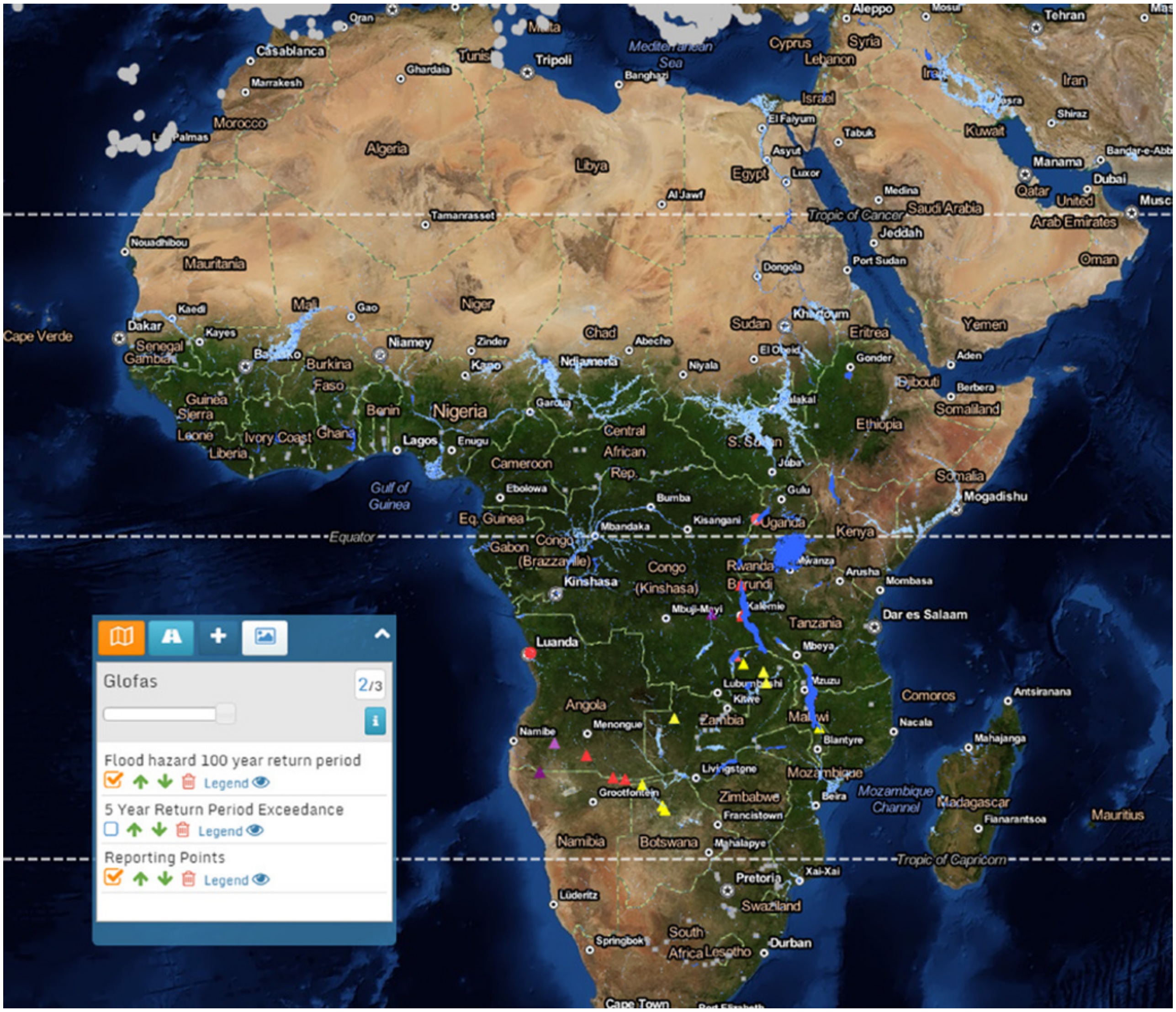

Figure 1.4 Pan-African flood hazard map for the reference return period of 100 years, as displayed on the GloFAS website (http://globalfloods.jrc.ec.europa.eu/).

capabilities. It is possible to quantitatively assess how flood risk could be reduced by increasing flood protection standards at the scale of countries, states, river basins, and cities. These estimates can help decision makers quantify and monetize flood damages in cost-benefit analyses when evaluating and financing DRM projects. A screenshot of the tool can be found in Figure 1.5, showing a flood risk assessment at the country level for India.

For the past 15 months since the analyzer's debut in March 2015, the tool has been visited and used by more than 12,000 unique users from almost every country, including many users from the World Bank, Pacific Disaster Center, Red Cross Climate Centre, as well as many journalists from major international news outlets. For example, analysts from the World Bank have used flood risk estimates from the analyzer in their country level disaster profile reporting. They have also modeled the correlations between environmental factors and health issues in Zimbabwe, using subnational flood risk estimates from the analyzer as one of variables. Senior economists from the World Bank have been using visualizations from Aqueduct in the negotiations on investment in water security with country officials from 21 Middle East and North African countries. All of these made possible because of the easy access to flood risk data the Aqueduct Global Flood Analyzer provides.

Besides understanding how users are using the tool, it is also very important to collect and distill user feedback

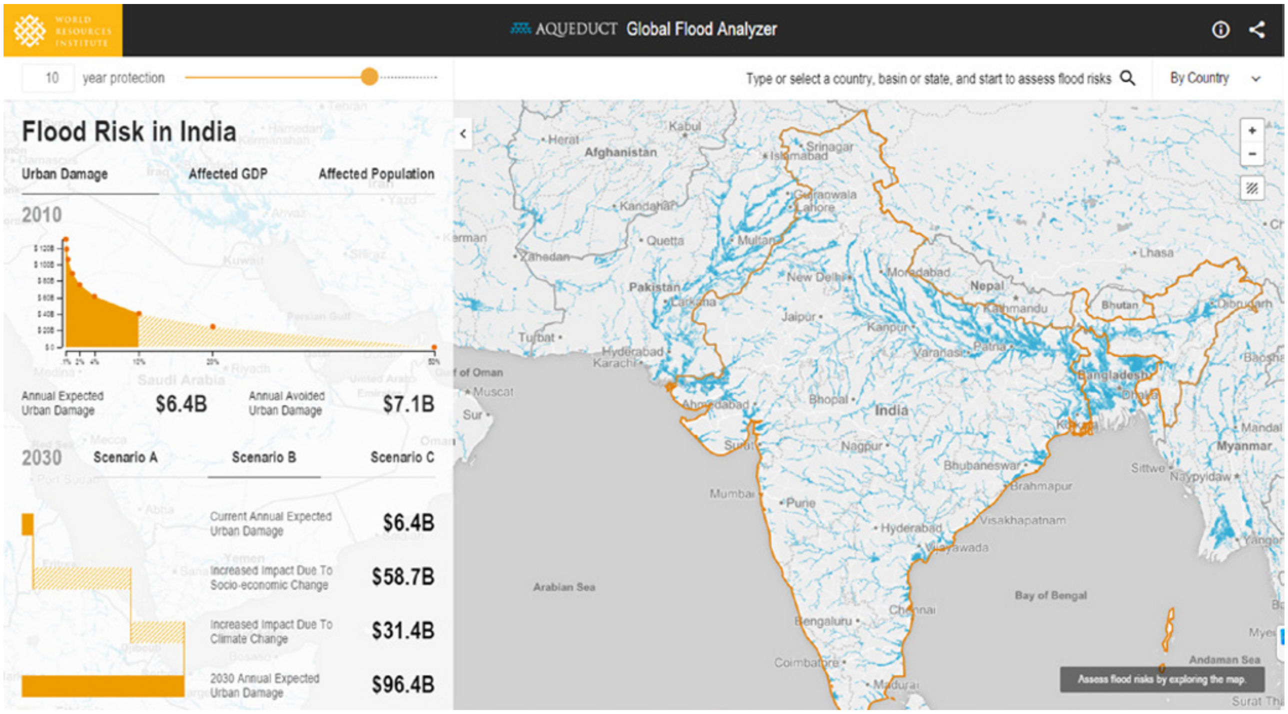

Figure 1.5 Screenshot of the Aqueduct Global Flood Analyzer, showing a flood risk assessment at the country level for India. The analyzers displays a flood hazard map, as well as estimates of flood risk under current conditions and under future conditions due to climate change and socioeconomic development.

to improve the product, making it more relevant and helpful to its target audiences. Product managers of the analyzer are constantly monitoring the user behavior and flow using Google Analytics, addressing and documenting questions and comments shared by users, and actively engaging with user communities via user testing workshops and webinars.

The second version of the analyzer will include many capabilities not yet present in the first version. For example, coastal flood hazard and risk will be included, thereby allowing a more complete assessment of flood risk. The influence of land subsidence on global flood risk will also be included in the next version; land subsidence is one of the key drivers of increasing risk in many of the world's rapidly developing delta regions [*Brown and Nicholls*, 2015; *Syvitski et al.*, 2009]. Moreover, the tool will allow users to carry out a first-order cost-benefit assessment of certain adaptation strategies on the fly. However, of course there are limitations to what a user can do with these tools. While they can be used to gain a first-cut estimate of flood risk in large spatial regions (e.g., countries, river basins), they cannot be used to produce local scale risk assessments. Moreover, while they can be useful for assessing the potential effectiveness of DRM strategies at the large scale, the granularity of the input data means that they cannot be used to design individual DRM measures.

1.8. THE WAY FORWARD

As shown in the preceding sections, global flood hazard modeling has made huge scientific advances in recent years, and the results of those models are being used in all kinds of applications, projects, and tools related to global-scale flood risk assessment, flood forecasting, and early warning. Of course, global models have their limitations. A discussion of some of these key limitations was presented in a recent commentary by *Ward et al.* [2015], and limitations of current flood hazard models are discussed extensively in Chapters 5, 6, 8, 10, and 11. Below, we point briefly to a few of these limitations, as well as possible ways to overcome these in the years to come.

Improvements are still needed in the representation of fundamental physical processes in global-scale flood hazard models. For example, most of the current generation of global flood hazard models use simple volume spreading algorithms to simulate inundation on the floodplain [*Ward et al.*, 2015]. However, the SSBN-flow model [*Sampson et al.*, 2015] now simulates inundation by solving hydrodynamic versions of the shallow water equations. Another key aspect is the need for improved elevation data, not only in terms of horizontal resolution, but also in terms of vertical accuracy [*Schumann et al.*, 2014]. Improved data sets are needed on key geomorphological variables at global scale, building on recent advances by Yamazaki *et al.* [2014] to develop a global river-width database. Another exciting recent development has been the launch of the first global database of flood protection standards at the global scale, FLOPROS [*Scussolini et al.*, 2016]. However, moving forward, this database would benefit from continual updates and additions from the flood community. A challenge is how to set up and maintain an interactive database that can effectively gather and house the knowledge of experts. Moreover, a valuable extension would be a global database showing where specific flood risk reduction measures are taken, both in terms of structural and nonstructural measures.

Next to an improved understanding and modeling of flood hazard, improved flood risk estimates are by definition dependent on improved methods to assess and represent exposure and vulnerability at the global scale [*Ward et al.*, 2015]. While exposure data sets have improved, most global-scale flood risk models still use highly aggregated gridded data sets of variables such as population and GDP to represent exposure. A wealth of object-based exposure data, in which these individual exposed elements are shown, is now available through volunteered geographic information (VGI) initiatives such as OpenStreetMap (OSM) [Haklay and Weber, 2008]. VGI data sets have been used in local-scale risk projects [*Haklay et al.*, 2014], and hydrological modeling [*Schellekens et al.*, 2014], but so far remain unused in global flood risk modeling. The representation of vulnerability in global flood risk models is even more limited. Either it is not represented at all, or it is represented by one (or a handful of) so-called depth-damage function for the entire world [*Ward et al.*, 2015]. Such an effort could be facilitated by a closer interaction between the global flood risk community and reinsurance flood risk modeling. Even where vulnerability is considered, it is assumed to be constant over time, even though new research in Bangladesh [*Mechler and Bouwer*, 2014] and globally [*Jongman et al.*, 2015] has shown that vulnerability to flooding has decreased strongly over time.

Next to improvements in the modeling of hazard, exposure, and vulnerability, more attention must be given to the validation of models. Some efforts have been made in this direction, with several groups "benchmarking" their hazard maps against hazard maps from high-resolution local models [e.g., *Sampson et al.*, 2015; *Winsemius et al.*, 2016; *Ward et al*., 2017] and satellite-derived flood extent maps [*Dottori et al.*, 2016], and efforts have been made to compare simulated damages with reported damages in international loss databases [e.g., *Ward et al.*, 2013]. Moving forward, we need more observed hazard extent and depth observations, and geographically constrained disaster loss databases, in order to facilitate a more thorough validation of models. Validation of global flood models is discussed further in Chapters 5, 6, 8, 10 and 11.

Novel methods are needed to effectively quantify and communicate model uncertainty, and more tools are needed to translate complex flood risk data into actionable information, such as the Think Hazard! and Aqueduct Global Flood Analyzer. To achieve these goals, close collaboration is required between physical and social scientists, as well as between scientists and users of risk information. Networks like the Global Flood Partnership provide excellent opportunities to bring together these different communities, and can play an important role in developing improved flood hazard and risk models that can continue to contribute to DRM in the coming years.

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