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Flood Risk Assessment and Forecasting for the Ganges-Brahmaputra-Meghna River Basins

Satya Priya, William Young, Thomas Hopson, and Ankit Avasthi

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Cover photo caption: June 2013: Torrential rains and flash floods along the Alaknanda River, Uttarakhand (India).

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Foreword

Water issues are at the heart of economic and social development and are thus critical for reducing poverty. Emerging economies, including those in South Asia, require improved water management in order to overcome key water challenges. Recurrent flooding is one of those challenges.

The Ganges-Brahmaputra-Meghna river basins in South Asia are prone to tremendous flood-related human suffering and economic loss. Their transboundary character further complicates efforts to protect people and their livelihoods. In recognition of these challenges, many groups are actively and cooperatively engaged in reducing South Asia's vulnerability to flooding. As a contribution to these efforts, the World Bank recently commissioned specialist teams to assess and map flood risk across the Ganges River basin and to design and evaluate flood forecasting tools for the greater Ganges-Brahmaputra-Meghna basin. These teams detailed their findings in over 500 pages of technical reports plus several new online resources.

To make the technical findings and advances more accessible to a wider audience, a World Bank team led by Satya Priya and William Young distilled the original reports into the present summary document, "Flood Risk Assessment and Forecasting for the Ganges-Brahmaputra-Meghna River Basins." This distillation includes technical highlights of the work, plus links to the full technical reports and new interactive online resources, as well as references to related work and resources for context.

On behalf of the World Bank, I would like to express my gratitude to the many experts who contributed to the preparation of this important publication and in particular to contributors from across the region. Many of these people are affiliated with organizations working to encourage and facilitate the cross-border sharing of hydrometeorological data, technologies, learning opportunities, and capacity building. Examples include not only the World Bank but also the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP), the International Centre for Integrated Mountain Development (ICIMOD), the International Water Management Institute (IWMI), the Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES), and the national meteorological and hydrometeorological services of the riparian countries. Their combined accomplishments and members' contributions all helped to improve this document. We look forward to continued regional collaboration toward cooperative flood management in South Asia.

Meike van Ginneken
Practice Manager, Water Global Practice, South Asia Region

Acknowledgments

The Flood Risk Assessment and Forecasting for the Ganges-Brahmaputra-Meghna River Basins Project has been a collaborative effort among transboundary partners within and between the countries coping with floods across these basins. The publication of results was supported by the South Asia Water Initiative (SAWI)—a partnership between the World Bank and the governments of the United Kingdom, Australia, and Norway—which works to improve management of the major Himalayan river systems of South Asia for sustainable, fair, and inclusive development, as well as climate resilience.

The work was conceptualized and led by Satya Priya[1] and William Young[1] of the Water Global Practice of the World Bank and Thomas Hopson[2] of the National Center for Atmospheric Research (NCAR).

RMSI Private Ltd., India, developed a calibrated flood risk assessment for the Ganges River basin and created an online flood risk atlas under the leadership of the World Bank team. The RMSI work was led by Pratul Srivastava, Ankit Avasthi[3], Deshraj Singh, and Pushpendra Johri. The team thanks the Indian Central Water Commission for their willingness to host the interactive *Ganges Basin - Flood Risk Atlas* on their website and for their enthusiasm for improving the underlying modeling with classified government hydrological data that were not available to RMSI. We would like to convey special thanks to Chairman G. S. Jha, Member Narendra Kumar, and Chief Engineer M. P. Singh of India's Central Water Commission, for their all-round support and guidance in the preparation and implementation of the *Ganges Basin - Flood Risk Atlas*. Special appreciation is due to Directors N. K. Manglik, Y. Paithankar, and V. Roy for their continuous technical support and guidance in implementing and hosting the online atlas.

The NCAR team, led by Thomas Hopson, investigated innovations in the flood forecasting continuum. This effort included important contributions from Emily Riddle, Daniel Broman, Jennifer Boehnert, Arnaud Dumont, Kevin Sampson, Joseph Grim, William Cheng, Lara Ziady, and Cindy Halley Gotway. The work also included essential contributions from Robert Brakenridge of the Dartmouth Flood Observatory (DFO) at the University of Colorado, related to river-width measurements and inundation mapping, and Charon Birkett of the Earth System Science Interdisciplinary Center of the University of Maryland, related to satellite altimetry measurements. The DFO effort included, in turn, significant contributions from Albert Kettner of the University of Colorado and Tom De Groeve of the Joint Research Council. Jeff Lazo provided helpful perspectives on socioeconomic context, ensemble forecasting, and the communication of uncertainty.

[1] *Water Global Practice, World Bank Group*
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[3] *RMSI Pvt. Ltd, India*

The Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES), supported by the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP), has consistently provided a neutral venue and mechanism for the South Asian countries to discuss priorities, pertinent information, and possible innovations that could be applied in the region. In particular, the team would like to thank A. R. Subbiah, Director of the RIMES Program Unit, and Sanjay Srivastava, Chief of the ESCAP Disaster Risk Reduction Section, not only for their support but also for their contributions to ESCAP's transboundary flood forecasting initiative and efforts toward the establishment of an intergovernmental platform in the region.

This summary report relied on the editorial and intellectual support of Tonya Clayton (Aqueous Media, LLC) and the administrative support of World Bank colleagues Priyanka Chaturvedi, Jai Mansukhani, and Minerva S. Espinosa-Apurada. The team also thanks World Bank colleagues Joop Stoutjesdijk, Xiaokai Li, and Ximing Zhang for their technical reviews and suggestions; Muthukumara Mani, Thomas Mosier, Xiaokai Li, Deepak Singh, and Megha Phansalkar for their excellent peer review inputs and suggestions; Poonam Pillai and Arati Belle for their helpful input on earlier versions; and Meike van Ginneken (Practice Manager, Water Global Practice, South Asia Region) for her guidance and support for this work and her encouragement to prepare this synthesis document. The project team also gratefully acknowledges the assistance of Erin Ann Barrett and the World Bank's communication team, as well as Bruno Bonansea and the Bank's map design/cartography unit.

Finally we thank the many additional people, too numerous to name, who provided extremely useful insights at consultation meetings with a variety of government and donor partner agencies, as well as with research, policy, and academic institutions in Bangladesh, India, and Nepal.

Executive Summary

This report summarizes recent analytical work on flood risk management in South Asia through the implementation of transboundary knowledge generation and sharing. The work included two distinct but linked activities, conducted with the support of the South Asia Water Initiative (SAWI; http://www.worldbank.org/en/programs/sawi)

- A transboundary flood risk assessment for the Ganges River basin
- An improved transboundary flood forecasting system for the Ganges-Brahmaputra-Meghna basins

These activities are more fully described in the original technical publications:

- *Flood Risk Assessment for the Ganges Basin in South Asia: Final Report,* Volume I (technical report) and Volume II (risk atlas) (RMSI 2016a, 2016b)
- *Evaluation of Flood Forecasting Predictability: Technical Report* (Hopson and Priya 2017)

The reports and tools from these studies are available to guide flood planning and the development of operational platforms for flood forecasting, decision support, and early warning systems. For more information, including the original technical documents, see http://documents.worldbank.org/curated/en/docsearch?query=P153299.

South Asia is one of the world's most disaster-prone regions, with floods posing a severe threat. In 2015, South Asia accounted for nearly two-thirds of the global fatalities attributed to natural disasters. Floods were the most frequent cause, and economic impacts were severe and widespread. The people most affected by flood impacts are the poor and vulnerable, especially women and children.

Two new contributions to reducing flood risk in South Asia are now available: a flood risk assessment for the Ganges River basin and an improved flood forecasting system for the Ganges-Brahmaputra-Meghna basins. Both projects provide information directly to decision makers and other stakeholders through interactive online displays, and both have developed methods that could be applied to other river basins. Flood risk assessment and flood forecasting are essential elements of managing flood risks in order to save lives, livelihoods, and assets.

Integrated flood management and people-focused, end-to-end early warning systems are key to reducing flood losses. In transboundary river basins, some elements require international cooperation. Integrated flood management simultaneously considers water resources, land use, and risk management in order to minimize flood losses while also allowing for flood benefits. Operational end-to-end warning systems include the building of risk knowledge and response capabilities, real-time monitoring and forecasting of rainfall and river conditions, expert translation of forecasts into targeted warning messages, dissemination and communication of warnings to community members, and people's responses to the warnings. Both approaches are adaptive, with formal monitoring of outcomes (including user feedback) and the charting of course corrections as needed.

Flood risk assessments are an essential first step in managing flood risks. These assessments help decision makers to identify vulnerability hotspots and establish mitigation priorities. The overall objective of a risk assessment is to understand the geographical impacts of floods on people and economic sectors. The key steps are to map the populations and assets at risk and to develop a flood simulation model and asset-specific vulnerability descriptions (damage functions). These tools are then used to map estimated losses due to model floods of various magnitudes.

The new transboundary flood risk assessment for the Ganges basin provides, for the first time, a quantitative basin-wide view of affected populations, major assets, flooding hazards, and damage estimates by sector for floods of various magnitudes. The findings are also available in the form of easy-to-use maps. Major physical assets considered include buildings, infrastructure (roads and railways), and crops. The methods and major findings are published in a technical report and accompanying atlas. For the portion of the risk assessment relating to India, maps and findings are also available in an interactive online atlas that provides basin-level to block-level information directly to users. The assessment findings can be used to identify priority areas for targeted risk management—for example, risk mitigation, flood forecasting, and resilience building.

The most severely affected subbasin was found to be the densely populated Lower Ganges. At the country level, average annual losses due to flooding were estimated to be highest for India (approximately US$609 million), followed by Bangladesh (approximately US$19 million) and Nepal (approximately US$4 million). For a relatively minor flood (two-year return period), the Indian states of Bihar and Uttar Pradesh have the highest numbers of people exposed to flood impacts (approximately 35 million people combined). In Bangladesh, the Rajshahi Division has the highest number (0.99 million) and in Nepal, the Eastern Province has the highest number (0.15 million). The Lower Ganges subbasin was identified as a priority candidate for future mitigation work.

Flood forecasting and warning together provide a proven, cost-effective option for reducing flood losses. Longer forecasting and warning lead times go beyond saving lives to ensuring livelihood support. For small farmers in Bangladesh, a flood-warning lead time of one day results in asset-specific damage reductions of up to 33 percent (reduced losses of aquacultured fish). A lead time of seven days yields estimated damage reductions of up to 90 percent (in household settings). For the moderate 2007 floods of Bangladesh, a forecasting and early warning system could have reportedly reduced damages by an estimated US$208 million. Estimated benefits over a decade of typical flooding would be about US$1,700 million—more than 500 times the cost of the hypothetical forecasting and warning system.

Significantly for decision makers, the new long-lead flood forecasting scheme for the Ganges-Brahmaputra-Meghna basins provides forecasts that inherently express not only a prediction of future water levels but also the appropriate level of confidence regarding each forecast. Such forecasts do not answer the question, "Is the river predicted to flood above the danger level, yes or no?" but rather, "What is the *probability* that the river will flood above the danger level?" Knowing whether the probability is 10 percent or 90 percent helps people decide what actions to take (if any). The forecasting scheme described in this report was developed by the National Center for Atmospheric Research (NCAR).

Evaluation of the NCAR forecasting scheme indicates that a "blending" approach—incorporating multiple data sets and multiple computational models—significantly improves flood forecasting skill. The NCAR evaluations indicate benefit in incorporating rainfall predictions from multiple weather centers, as well as rainfall and river observations from multiple platforms and institutions. Satellite data are useful where on-the-ground measurements are sparse. Forecasts are generally most skillful for locations with larger upriver catchments. Using locally optimized combinations of rainfall forecasts yields roughly two additional days of flood warning time. For some stations, skillful forecast lead times are as long as 16 days. This blending approach could also incorporate other forecasting models. A pilot project has commenced in Bihar to develop an operational flood forecasting platform. Forecasting skill will be assessed in terms of reduced flood risk and losses.

The operational NCAR system delivers up-to-date transboundary flood-related information directly to online users: rainfall, river conditions, and 16-day flood outlooks. Near-real-time maps show predicted and observed rainfall for individual catchments, as well as observed water levels at selected river locations. Operational 16-day water-level forecasts are provided for 87 locations across the Ganges and Brahmaputra basins. An important next step will be to incorporate these tools and outputs into accessible and usable platforms that include mechanisms for user feedback and upgrades.

A cooperative regional platform for flood forecasting and warning would help to prevent deaths, reduce property losses, build technical and management capacity, and strengthen participatory processes in the region. Such a platform would provide multiple benefits that would ultimately contribute to the reduction of flood-related deaths and other losses: for example, the identification and filling of data and knowledge gaps; a greater understanding of regional, basin, and subbasin-level hydrological processes and conditions; greater capacity of water resources organizations in areas related to transboundary cooperation; greater trust and confidence in regional and basin water management; more timely delivery of information to decision makers and other stakeholders; and stronger stakeholder input to government decision making through participatory processes.

In recognition of the need for greater transboundary cooperation, the United Nations Economic and Social Commission for Asia (ESCAP), in association with the Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES), is carrying forward a new regional program on end-to-end flood forecasting and warning in South Asia. The framework for this program was designed by participants at the 2015 Regional Flood Early Warning System Workshop. The cooperative program will use existing regional mechanisms to build capacity and share information, integrate flash flood and riverine flood concerns at the basin level, and incorporate new forecasting technologies into user-oriented flood-risk information systems, thereby enhancing early flood warning capacity. ESCAP will begin the stepwise process by convening an intergovernmental panel of meteorologists, hydrologists, and disaster risk management professionals from the operational organizations of the Ganges-Brahmaputra-Meghna riparian countries.

Abbreviations

AAL	average annual loss
CFAB	Climate Forecasting Applications for Bangladesh
CWC	Central Water Commission (India)
DFO	Dartmouth Flood Observatory
ECMWF	European Centre for Medium-Range Weather Forecasts
ESCAP	Economic and Social Commission for Asia and the Pacific (United Nations)
FMIS	Flood Management Information System (of the state of Bihar, India)
GBM	Ganges-Brahmaputra-Meghna
GDP	gross domestic product
GFDS	Global Flood Detection System
GNI	gross national income
HVR	hazard, vulnerability, and risk
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
LEC	loss exceedance curve
NCAR	National Center for Atmospheric Research (United States)
NOAA	National Oceanic and Atmospheric Administration (United States)
RIMES	Regional Integrated Multi-Hazard Early Warning System for Africa and Asia
RP	return period
SAWI	South Asia Water Initiative
U.S.	United States
US$	United States dollars

June 2013 - Floods in Uttarkashi (India). Hundreds of villages across the Uttarkashi, Rudraprayag, Chamoli, and Tehri regions were washed away, submerged, or otherwise affected during the floods.

Section 1 Introduction

Across South Asia, iconic large rivers—the Ganges and the Brahmaputra—flow down from the Himalayas, across country borders, and into the Bay of Bengal. Along the way, nearly 650 million people depend on these waterways for their life-supporting services—providing drinking water, agricultural irrigation, electricity, inland transport, and the many goods and other benefits that accrue from healthy river ecosystems.

These great rivers and their tributaries and distributaries play a central role in South Asia's vulnerability to flood disasters. Each year, monsoon-driven floods cause disruption and loss of life, livelihoods, property, infrastructure, and other assets. Many of the floods are transboundary in nature. High population densities, rapid population growth, widespread poverty, and ongoing cross-border tensions, in combination with frequent flooding, act to undermine development and well-being in the region.

The people most severely affected by flooding are the poor and vulnerable, especially women and children. Poverty constrains people's choices of where to live while also limiting their ability to protect homes and belongings. The socioeconomic consequences of floodwater inundation are severe, especially for those without adequate resources for recovery. Women and children are generally more vulnerable than men to the impacts of floods and have more limited coping options. Poverty is therefore a key consideration in managing flood risks. This is especially true for South Asia where an estimated 40 percent of the world's poor live on or near major transboundary river systems. The United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) notes that managing transboundary river basin floods is essential for achieving sustainable development.

Greater regional cooperation would greatly benefit the millions of people at risk from river flooding. Throughout the region, a number of groups are working to encourage and facilitate cross-border sharing of hydrometeorological data, technologies, learning opportunities, and capacity building. Examples include ESCAP (http://www.unescap.org/), the International Centre for Integrated Mountain Development (ICIMOD; http://icimod.org/), the International Water Management Institute (IWMI; http://www.iwmi.cgiar.org/), the Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES; http://www.rimes.int/), and the World Bank Group (http://www.worldbank.org/), all working in collaboration with the national meteorological and hydrometeorological services of the riparian countries.

These collaborative efforts and the implementation of their recommendations would bring significant accompanying benefits, including:

- Enhanced technological contributions toward filling data and knowledge gaps
- Greater understanding of regional, basin, and subbasin-level hydrological processes and conditions
- Greater capacity of water resources organizations in areas related to transboundary cooperation
- Greater trust and confidence in regional and basin water management
- Adoption of new technologies to deliver convenient and accessible information to decision makers and other stakeholders
- Stronger stakeholder input to government decision making through participatory processes

This summary report describes two recent transboundary contributions to the development of end-to-end flood early warning systems in the Ganges-Brahmaputra-Meghna (GBM) river basins. The overall intent of these efforts was to advance the operationalization of flood forecasting methods and technologies. The first step was a robust spatial assessment of flood risk—considering hazard, exposure, and vulnerability—in order to guide flood forecasting priorities. This work led to an evaluation of forecasting services and options for improving flood forecasting skill, with a focus on capitalizing on recent advances in weather prediction.

These efforts are detailed in the following publications:

- *Flood Risk Assessment for the Ganges Basin in South Asia: Final Report,* Volume I (technical report) and Volume II (risk atlas) (RMSI 2016a, 2016b)
- *Evaluation of Flood Forecasting Predictability: Technical Report* (Hopson and Priya 2017)

The accompanying interactive online resources include the following:

- *Ganges Basin - Flood Risk Atlas*
  http://www.cwc.nic.in/ (then follow link to "Ganges Basin Flood Risk Atlas")
- *World Bank – South Asia Water Initiative: Ganges and Brahmaputra Meteorologic Predictability. Development of Flood Forecasting for the Ganges and the Brahmaputra*

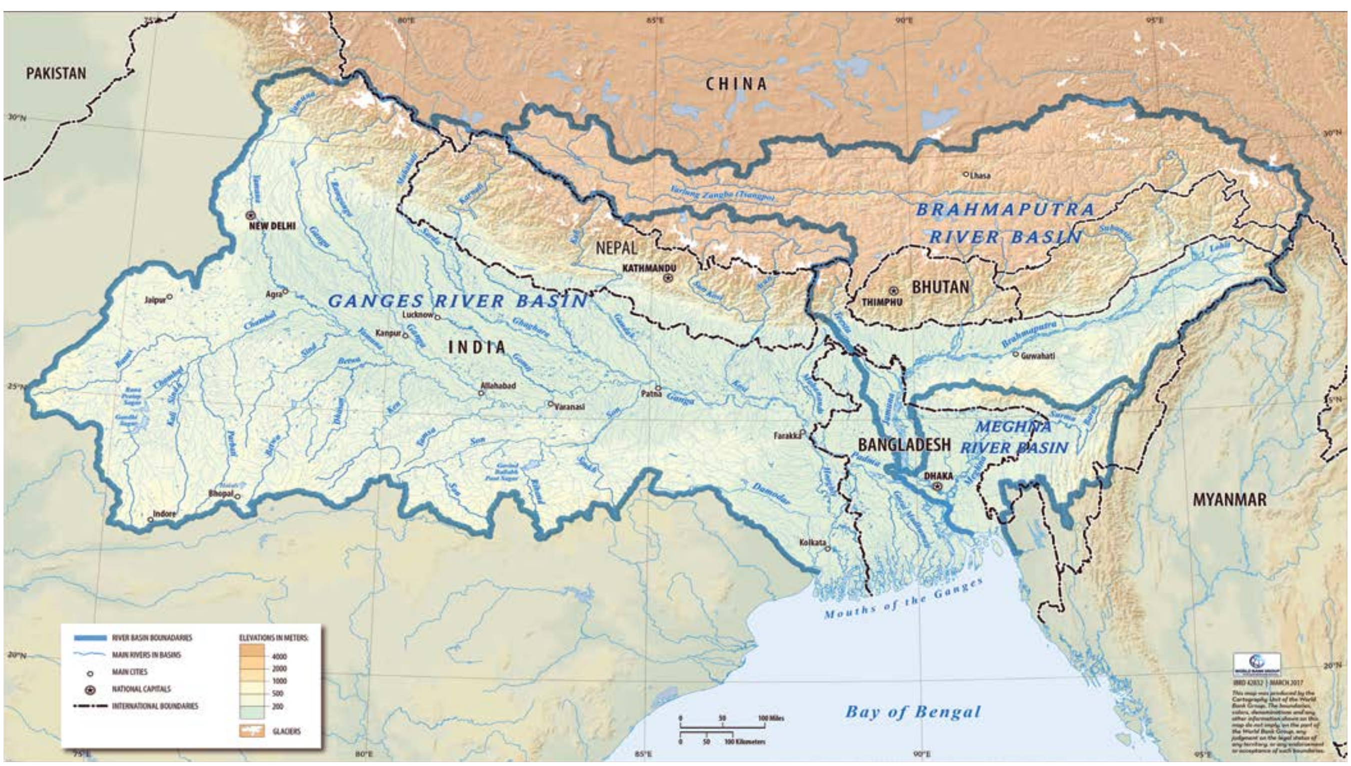
Basins: Using Satellite-Based Precipitation, Ensemble Weather Forecasts, and Remotely Sensed River Widths and Height.
http://indiawbg.rap.ucar.edu/

Section 1 of this summary report introduces the GBM river basin, the concepts of integrated flood management and end-to-end early warning systems, and selected aspects of current forecasting activities. A new regional program for transboundary flood forecasting and warning, designed at the 2015 Regional Flood Early Warning System Workshop, is also described. Sections 2-3 share selected highlights from the risk assessment and forecasting efforts mentioned above. Section 4 provides concluding thoughts and recommendations.

The Ganges-Brahmaputra-Meghna River System

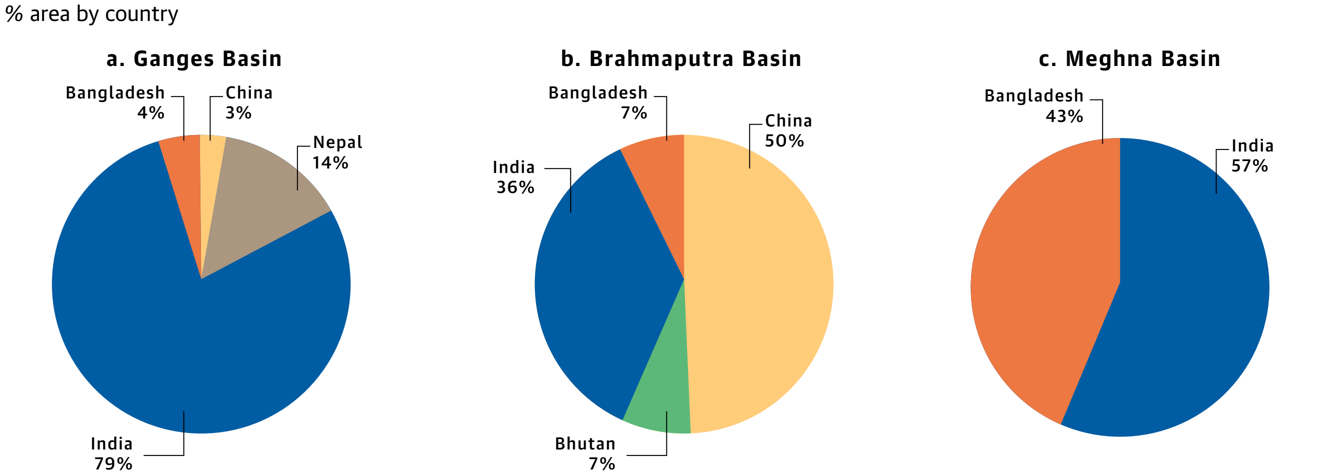
The GBM river system defines a vast transboundary basin that encompasses portions of six countries and almost 2 million square kilometers of varied terrain, reaching from the high Himalayas to the Bay of Bengal (map 1.1; figure 1.1; tables 1.1-1.2). All three rivers converge in the low delta country of Bangladesh. By the time the conjoined waters discharge into the Bay of Bengal, they constitute the world's third largest source of freshwater flow to the ocean. All three rivers are prone to flooding (table 1.3), especially during the monsoon season. The GBM delta is the world's most populous river delta.

Map 1.1: The Ganges-Brahmaputra-Meghna River Basins



Source: World Bank, 2017

FIGURE 1.1. Countries of the Ganges, Brahmaputra, and Meghna River Basins



Source: Data from FAO 2011.

Note: The Ganges, Brahmaputra, and Meghna river basins encompass portions of six countries. Myanmar, not shown, includes approximately 100 km^2 of the upper Meghna basin.

TABLE 1.1. Basin Statistics

Basin	Basin area (km^2)	River length, headwaters to sea (km)	Annual basin flow at entry to Bangladesh (km^3)
Ganges	1,087,300	2,515	525
Brahmaputra	543,400	2,840	537
Meghna	82,000	930	48

Source: Data from FAO 2011; original data from Joint Rivers Commission Bangladesh.

TABLE 1.2. Area and Demographic Statistics for the Major Riparian Countries

Basin	Area (km^2)	Population (no.)	Population density (no./km^2)	GDP, 2015 (current US$, trillions)	Poverty headcount ratio, 2015 (% of population)	GNI per capita (current US$)
China	320,600	1,692,700	5	10.866	—	7,820
Nepal	147,100	29,339,900	199	0.021	25	730
Bhutan	39,800	2,421,700	61	0.002	12	2,370
India	1,015,000	475,986,000	469	2.074	22	1,590
Bangladesh	106,900	122,379,000	1,145	0.195	32	1,190

Sources: Data regarding area, population, and population density are from De Stefano et al. 2010. Data regarding GDP, poverty head count ratio, and GNI per capita are from the World Bank DataBank, http://databank.worldbank.org/data/home.aspx (accessed 17 August 2016).

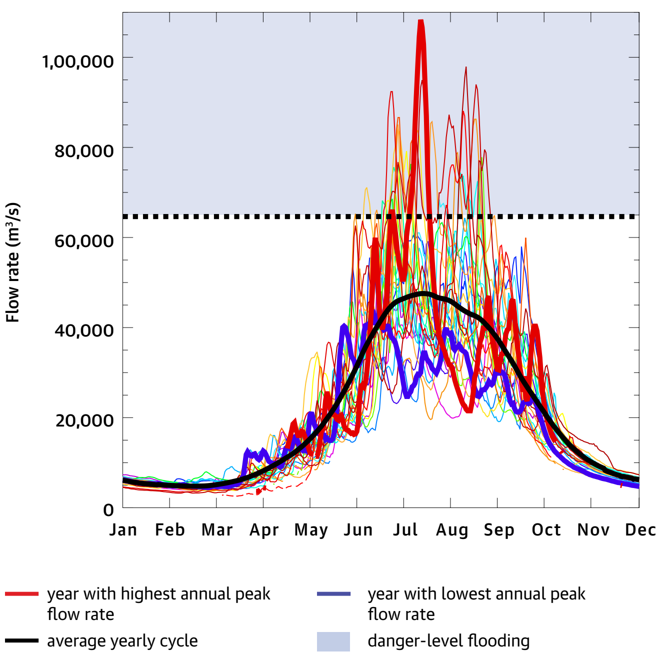
Note: Myanmar, not listed here, encompasses about 100 km^2 of the GBM basin area, with approximately 300 residents. GBM = Ganges-Brahmaputra-Meghna; GDP = gross domestic product; GNI = gross national income; — = not available

TABLE 1.3. Impact of Large Floods, 2000–10

Basin	No. of floods reported	No. of days flooded	No. of people dead	No. of people displaced (millions)	Economic damage (US$, billions)
Ganges	35	789	8,307	82.77	8.22
Brahmaputra-Meghna	32	821	8,392	120.2	11.22
Total	67	1,610	16,699	202.97	19.44

Source: Data from ESCAP and RIMES 2016; original data from Brakenridge 2016.

FIGURE 1.2. Seasonal Changes in River Flow for the Brahmaputra River



Sources: T. Hopson, NCAR. Based on data from the Flood Forecasting & Warning Centre of Bangladesh (http://www.ffwc.gov.bd).
Note: River flows and flood hazards change greatly through the seasons and year to year. This example shows river flow rates by month for the Brahmaputra River at Bahadurabad, near the India/Bangladesh border (1987–2016). The annual surge in summertime flow is due to the monsoon rains.

The GBM basin is diverse in terrain, climate, and flood risk. Most of the basin's 1.7 million square kilometers is strongly influenced by annual monsoons, with most rainfall arriving during just a few months of the year. River flows and flood hazards also change greatly through the seasons (figure 1.2).

Against this shared backdrop, geographic differences in basin characteristics, precipitation, and development practices result in significant differences in river behavior, flood types, and flood risks (box 1.1, figure 1.3).

China encompasses portions of both the Ganges and Brahmaputra basins. Major flood hazards in the mountainous headwater regions include heavy rainfall, flash floods, and outburst floods from glacial lakes and landslide dams. The Chinese Himalayan region is one of the world's hotspots for disasters related to glacial lake outburst floods.

Nepal lies entirely within the Ganges basin. The major hazards in this steep countryside include heavy rains, flash floods, glacial lake outburst floods, and landslides. According to the World Resources Institute, Nepal ranks tenth in the world in terms of percentage of country gross domestic product (GDP) regularly exposed to inland flooding (more than 1 percent on average per year).

Bhutan lies entirely within the Brahmaputra basin. Major hazards include flash floods, glacial lake outburst floods, landslide dam outburst floods, and riverine floods. According to the Royal Government of Bhutan and the World Bank, much of the country's infrastructure, agricultural lands, and settlements are at high risk of flooding. With more than 70 percent of settlements located along main drainage basins, nearly 2 percent of the total population is exposed to flood risks.

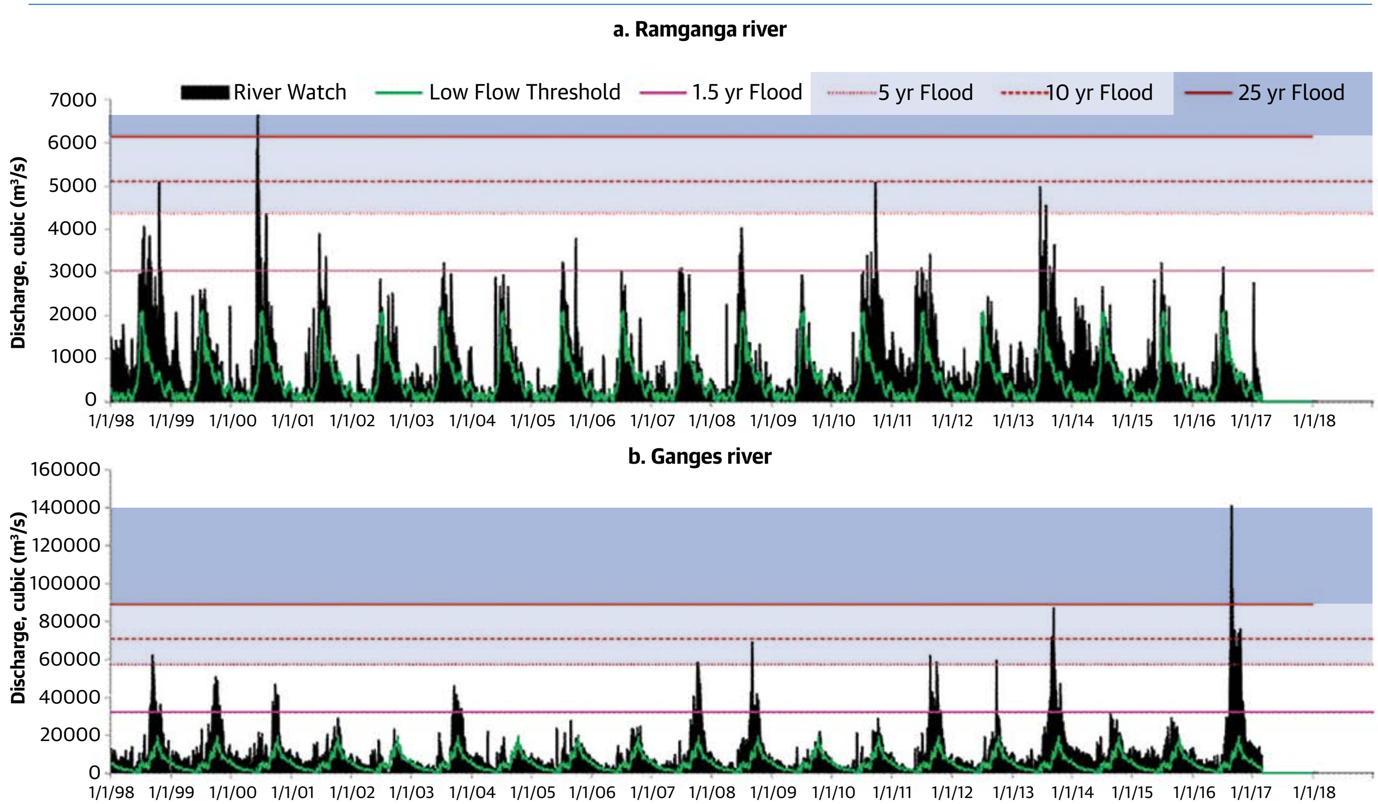
India encompasses large fractions of all three drainage basins. Flooding hazards include flash floods, locally heavy rainfall, and inadequate drainage, as well as inundation of river

BOX 1.1. Flood Hazards

The diverse terrain of the Ganges-Brahmaputra-Meghna basin is subject to several types of flood hazard:

- *Flash floods.* Heavy rainfall or rapid snow/ice melt in steep terrain leads to rapid increases in water level and fast, intense river flows; may also result from catastrophic dam failure.
- *Glacial lake outburst floods.* The naturally formed dam of a glacial lake fails, leading to sudden lake drainage and torrential outflow and flooding; a type of flash flood.
- *Landslide dam outburst floods.* A dam formed by an earlier landslide fails, leading to sudden lake drainage and torrential outflow and flooding; a type of flash flood.
- *Riverine floods.* Rising river waters, fed by upstream and local rainfall, spill over riverbanks to inundate surrounding lands; often associated with seasonal monsoons.
- *Rain floods.* Sustained heavy rainfall outpaces drainage, leading to local flooding; often associated with monsoons or tropical cyclones.
- *Coastal (marine) floods.* Seawater inundates low-lying coastal areas; can be due to high tides or storm surges.

FIGURE 1.3. River Flow and Flood Risk in Ramganga and Ganges Rivers, 1998–2017



Source: Adapted from Brakenridge et al. 2016; for details see http://floodobservatory.colorado.edu/SiteDisplays/208.htm and http://floodobservatory.colorado.edu/SiteDisplays/195.htm.

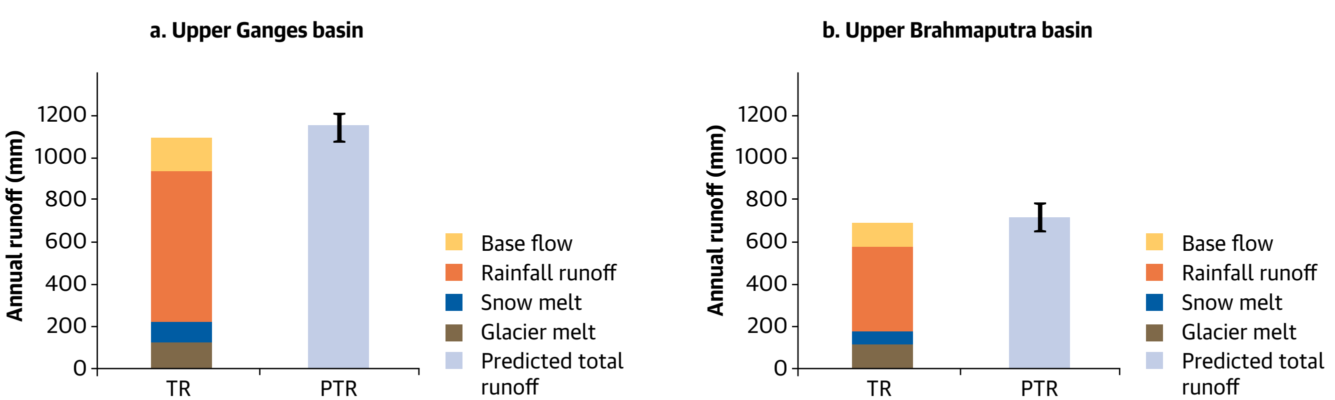
Note: The Ramganga River (GFDS/DFO site #208) is a springfed tributary of the Ganges River. Note the difference in vertical scale—much more water flows in the Ganges than the Ramganga. The black area indicates river flow, as estimated by River Watch (using information from satellites). The peaks that occur every year are due to the monsoon rains. The blue shading indicates major flood levels. The Ramganga station has experienced four major floods since 1998, with catastrophic flooding in 2000. The Ganges station (GFDS/DFO site #195) experienced catastrophic flooding most recently in 2016. GFDS = Global Flood Detection System.

floodplains. According to the World Resources Institute, India has the world's highest absolute value of GDP regularly exposed to inland flooding (US$14.3 billion on average per year) and the highest number of people exposed (4.84 million).

Bangladesh encompasses the confluence of the Ganges, Brahmaputra, and Meghna rivers as they approach the Bay of Bengal. Situated on the great delta plain formed by their sediments, this low-lying country is especially prone to riverine flooding. During monsoon season, nearly a fifth of the country can be inundated. During severe floods, more than a third can be inundated. In the catastrophic flood of 1998, about two-thirds of the land was affected. According to the World Resources Institute, Bangladesh ranks first in the world in terms of percentage of country GDP regularly exposed to inland flooding (nearly 5 percent on average per year) and second in terms of population exposed (3.48 million).

Climate change introduces an element of uncertainty into the region's water outlook. Current trends include warming air temperatures and rising sea levels. Future projections include changes in the timing of the South Asian monsoon and increased monsoon strength. For the upper basins of High Asia, increased precipitation and runoff are projected for mid-century (figure 1.4). An increase in extreme precipitation events would exacerbate flooding hazards of all sorts (box 1.1). Changes in the timing of the monsoon floods could increase the chance that river floods may coincide with cyclone-driven coastal floods, with potentially catastrophic effects. Even with the uncertainty regarding future rainfall and runoff, it is likely that today's water challenges—including drought and flood—will be even greater challenges tomorrow.

FIGURE 1.4. Current and Projected Annual Runoff in Upper Ganges and Upper Brahmaputra Basins



Sources: Lutz et al. 2014, © Nature Publishing Group. Redrawn by the World Bank from data provided by A. F. Lutz, with permission from Nature Publishing Group; further permission required for reuse.

Note: The bar plots show the current total average annual runoff (TR; 1998–2007) and projected future average annual runoff (PTR; 2041–2050) for the Upper Ganges and the Upper Brahmaputra basins. Both upper basins are rainfall-dominated (orange) due to monsoon influence. Both are projected to experience greater runoff in the future (light blue), primarily due to an increase in precipitation.

Integrated Flood Management

The concept of "integrated flood management" provides a useful framework for considering flood protection in South Asia. This approach considers both land and water resources, both the benefits and damages that floods can bring, and both structural ("hard") and nonstructural ("soft") options for flood mitigation. Dams and embankments are examples of structural options (box 1.2). Floodplain zoning and early warning systems are examples of nonstructural options. Among nonstructural interventions, flood forecasting and early warning systems are particularly efficient and cost-effective, with proven benefits. These measures are especially important where the relocation of vulnerable communities is impractical.

Integrated flood management recognizes that floods have beneficial impacts and that floods can never be completely eliminated or controlled. The overall goal is to act proactively to minimize loss of life and maximize the efficient use of floodplains. The Associated Programme on Flood Management (http://apfm.info) promotes the concept and its implementation.

BOX 1.2. Embankments

Embankments are a widely used type of flood-control structure, now lining thousands of kilometers of tributary and river banks within the Lower Ganges and Brahmaputra basins. Embankments are designed to prevent floodwater spilling over from river channels onto adjacent floodplains. The structures are relatively inexpensive and can be quickly built.

The practice of confining river flow, however, can force flowing waters to rise to higher levels, with higher peak discharges. Embankments also deprive floodplains of sediment and may encourage development in vulnerable areas. Through time, embankments may become incrementally less effective due to sedimentation within the channels. Embankment erosion and failure can be major problems, in terms of both the costs of ongoing maintenance and the potential for catastrophic failure. When embankments are overtopped, they then prevent floodwaters from draining back to the channel when river levels fall—especially if sedimentation has led to the channel being "perched" above the level of the floodplain. In these situations, the duration of flooding is extended and thus the prolonged waterlogging causes additional damage.

The dual, mixed-blessing nature of embankments has been the subject of thoughtful discourse in the region. Some governments, nongovernmental organizations, and other groups now encourage a blend of flood-management approaches, including a greater emphasis on nonstructural measures. The toolbox of complementary measures includes floodplain zoning and flood forecasting and warning.

A robust and responsive plan for integrated flood management aims to:

- Manage the water cycle as a whole
- Integrate land and water management
- Manage risk and uncertainty
- Adopt a best mix of strategies
- Adopt integrated hazard management approaches
- Promote a participatory approach

Integrated flood management incorporates a holistic view of river basins, from headwaters to deltas. Ideally, flood management is part of a broader program of integrated water resource management, wherein managers and policy makers consider the many complex connections between sometimes competing interests within a river basin. The goal is to find a cooperative, healthy balance that manages a variety of risks and improves overall community and ecological resilience (box 1.3).

From an economic point of view, the success of integrated flood management depends to some extent on how the costs of flood risks are shared between those who directly benefit from occupying the floodplains and those who do not occupy the floodplains but do indirectly benefit from floodplain services and the economic activities conducted there. Economic instruments for sharing flood risks include taxes, subsidies, and insurance. IWMI is currently piloting an index-based flood insurance project in selected flood-prone districts in India and Bangladesh.

Integrated flood management is adaptive. Managers and other decision makers continually assess program outcomes in a structured, formal way. The aim is to incorporate, in a timely manner, the benefits of new findings and lessons learned.

Integrated flood management is consistent with recent regional support for basin-based knowledge sharing and cooperation in South Asia. For example:

- A recent comprehensive strategic assessment of the Ganges River basin (World Bank 2014) supports a shift in emphasis from flood control to flood management. This adjustment would entail the use of structural and nonstructural measures, with a greater emphasis on regional forecasting and warning systems, management of river embankments, and drainage. More locally focused "soft" responses would also be included. Examples include disaster preparedness, land use zoning, safe havens, flood insurance, and training and communications campaigns.
- Participants at a recent international workshop on early warning systems (World Bank 2016a) likewise noted the value of a basin-oriented approach. They highlighted, in particular, the value of sharing flood monitoring, forecasting, and warning information.

End-to-End Flood Forecasting and Early Warning Systems

An essential aspect of flood risk management is the development of people-focused, end-to-end flood forecasting and warning systems. The chain of events (figure 1.5) incorporates both technical and societal considerations.

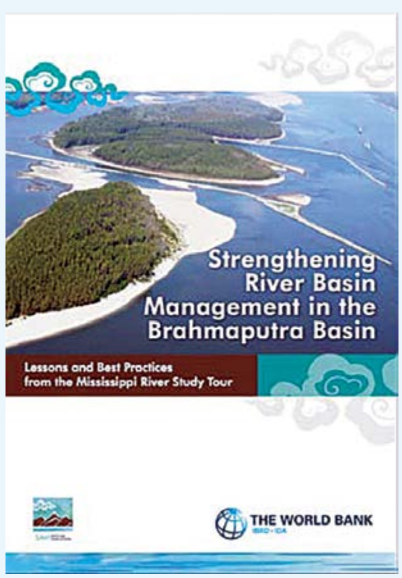
BOX 1.3. Cross-Country Capacity Building: Lessons from the Mississippi River Basin

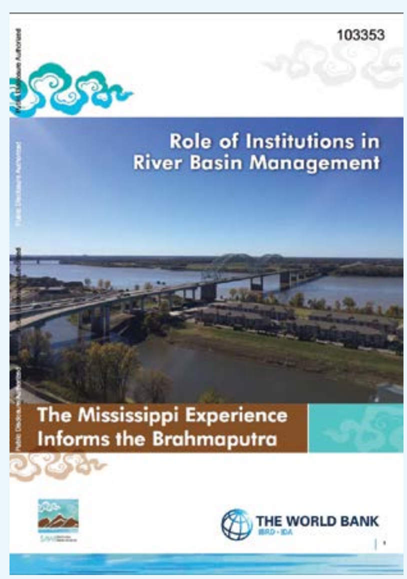
Cross-country exchanges are one way to build capacity in integrated flood management. In 2014 and 2015, senior officials and technical specialists from China, Bhutan, India, and Bangladesh visited the United States on study tours to the Mississippi River basin. These tours included field visits and technical discussions. Topics included analytical tools for modern flood management and institutional frameworks for managing large river basins. The study tours sought to assess good practices that could be applied to the Brahmaputra basin.

In both the Mississippi and Brahmaputra basins, many factors drive change and adaptation in flood management—for example, major flood events, new technologies, and changing societal values. The tours provided a platform for multi-country dialogue and knowledge sharing, thus improving diplomacy and providing opportunities to build toward the cooperation needed for holistic solutions to basin challenges.

Key lessons from the study tours include:

- Successful flood management relies on robust institutions and supportive laws and policies.
- Effective flood risk management requires not only structural interventions but also softer measures such as river flood and cyclone forecasting, strategic communications, and well-planned evacuations.
- A suite of decision support tools is required to make informed decisions and plans at a basin scale.
- Adaptive management requires resilience and coordination at all levels at all times.



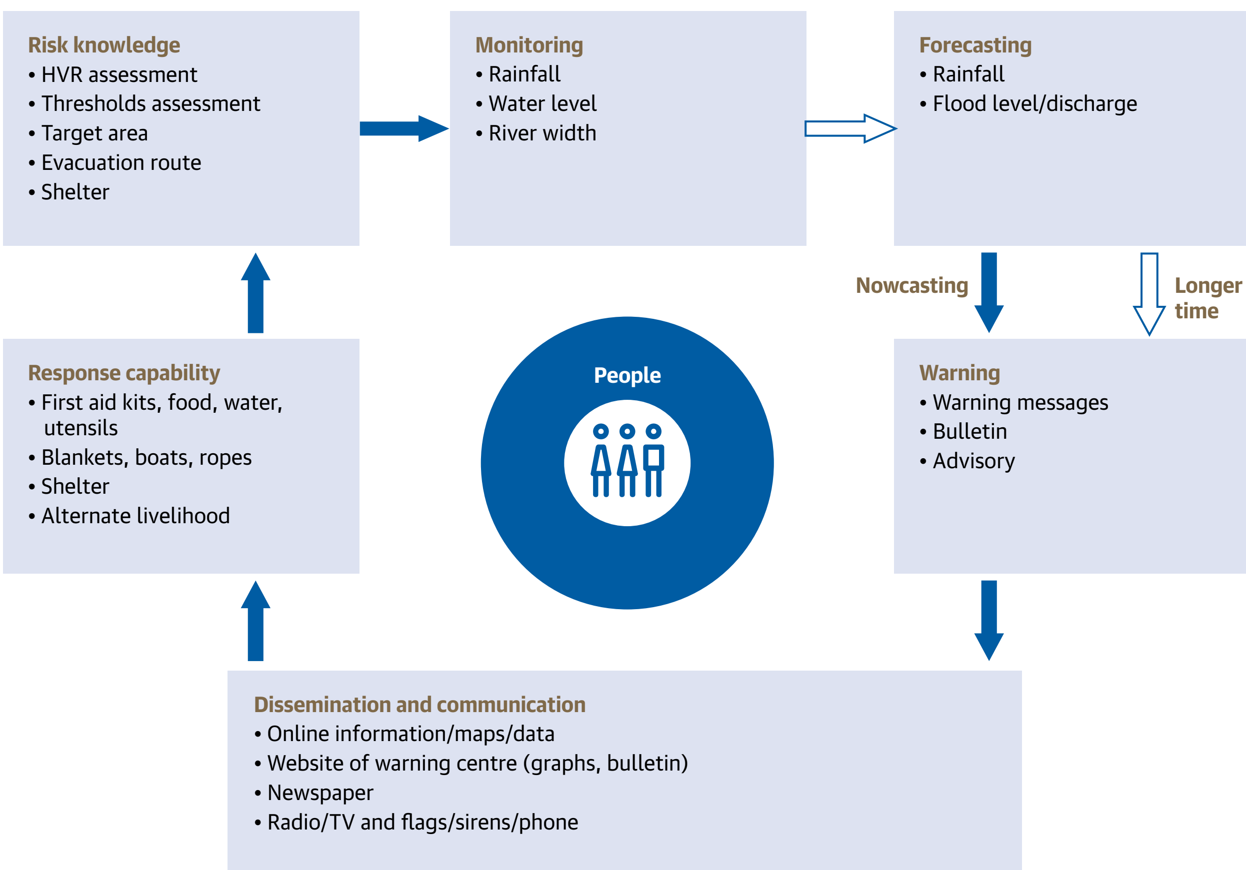


- Actively engaging with communities and enrolling them into the planning process is integral to flood risk management and the building of resilient systems.
- Water resource management requires a multidisciplinary approach that incorporates engineering, technological, social, economic, and legal expertise.

These publications describe more fully the Mississippi River study tours and lessons learned:

- *Strengthening River Basin Management in the Brahmaputra Basin: Lessons and Best Practices from the Mississippi River Study Tour* (World Bank 2015b)
- *Role of Institutions in River Basin Management: The Mississippi Experience Informs the Brahmaputra* (World Bank 2016b)

FIGURE 1.5. End-to-End Warning Systems: Chain of Events



Sources: Modified from Gautam 2016, © D. Gautam and RIMES, 2016, with permission. Further permission required for reuse.
Note: The technical efforts highlighted in this report contributed primarily in the areas of *risk knowledge* and *flood forecasting*. Both efforts also made new contributions to the dissemination of flood-related information. HVR = hazard, vulnerability, and risk.

The key elements of an end-to-end flood forecasting and early warning system include:

- *Risk assessment.* To quantify and map where people and material assets are at risk from flooding.
- *Real-time monitoring.* To continuously measure precipitation and water levels and then share that information.
- *Flood forecasting.* To predict future water levels and inundation extent and duration, based on weather forecasts and monitoring data.
- *Warning.* To interpret flood forecasts, assess potential impacts, and generate advisories.
- *Dissemination and communication.* To issue clear, authoritative, targeted messages that enable well-informed individual decisions.
- *Preparation and response.* To help people minimize and recover from flood damage.
- *Feedback.* To assess how well the end-to-end system worked; includes stakeholder input, identification of good practices and lessons learned, and recommendations for improvement.

Transboundary cooperation, both national and international, would greatly facilitate some of these essential activities.

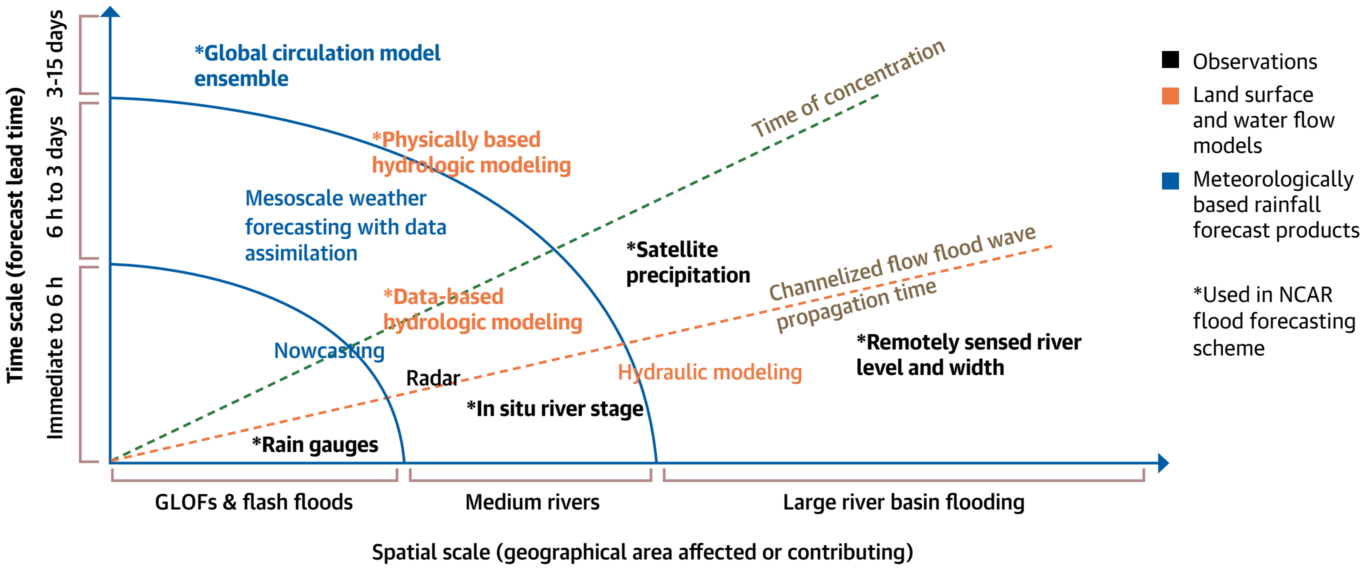
Flood Forecasting in the Ganges-Brahmaputra-Meghna Basins

Forecasting different types of flood requires different tools and approaches (figure 1.6). Flash floods are relatively small and brief, but intense. Large river basin floods are widespread and longer lasting. The different tools used to forecast water levels (for example, rain gauges, weather forecasts) also operate over a range of spatial scales (geographic extent) and time scales. Each tool makes its own distinct contribution to the goal of increasing forecast lead times and usefulness for the different types of flood.

Observations of river conditions, for example, are essential for flood forecasting but can never directly provide lead times longer than the time required for a flood wave to make its way downstream through the basin (figure 1.6 and map 1.2). Rainfall measurements can improve lead times but never directly beyond the time required for upper-basin rainfall to make its way into the river and then downstream to the river outlet (called "time of concentration"). For longer lead times, weather forecasts should be incorporated into a flood-forecasting methodology. The "global circulation models" mentioned in figure 1.6 are one source for these forecasts of future precipitation.

The countries of the GBM basin have varying capacities for flood forecasting and warning. Flood forecasting has proven effective in reducing human and economic losses due to flooding, but gaps remain in forecasting capabilities within the region. Areas for improvement include the enhancement of flood monitoring systems, data exchanges, technical cooperation, and institutional and capacity development (boxes 1.4 and 1.5).

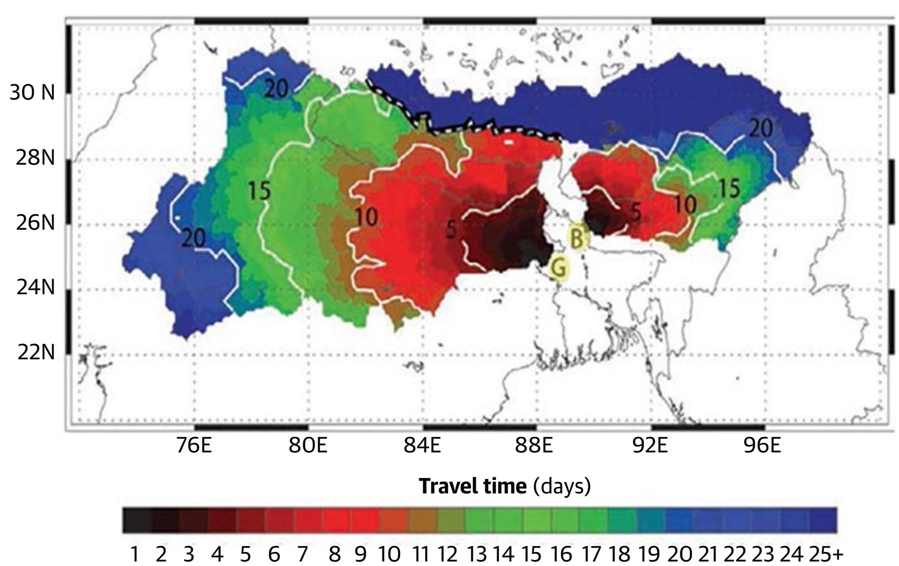
FIGURE 1.6. Forecasting Tools and Methods for Different Types of Floods



Sources: Modified from Hopson et al. 2015b; axis annotations adopted from ESCAP 2016b.

Note: Various forecasting tools provide information at different scales, thereby providing different lead-time contributions. The NCAR model, which focuses on large river basin flooding, relies on weather forecasts (blue), simulation models (orange), and measurements (black). The specific NCAR tools are highlighted with asterisks. GLOFs = glacial lake outburst floods.

MAP 1.2. Water Travel Times within Ganges and Brahmaputra Basins



Source: Modified from Webster et al. 2010, © American Meteorological Society. Used with permission from American Meteorological Society; further permission required for reuse.

Note: Knowing about upstream rainfall and river flow helps forecasters to predict floods at downstream locations. The map colors show the average number of days that water takes to travel from upstream areas down to the Ganges (G) and Brahmaputra (B) outflow points into Bangladesh. For example, water takes about three weeks or more to travel from the blue areas down to the outflow points. Water from the red areas takes about a week or so. Forecasters can use these travel times to improve flood predictions, especially when combined with forecasts and measurements of upstream rainfall and river flow.

BOX 1.4. Hydrometeorological Modernization, Disaster Risk Management, and Climate Resilience for South Asia

Through its South Asia Regional Program on Hydromet Modernization, Disaster Risk Management and Climate Resilience, the World Bank supports the modernization of hydromet services and early warning systems. The program is strengthening national capacities for weather forecasting and disaster risk management to build climate resilience and enhance regional collaboration in these areas. The program sees improved national systems and capacity as necessary for subregional and regional collaboration.

By working with providers and users of hydromet services, the program supports country capacity to develop and share tailored weather, water, and climate information tools for planning and decision making. Users span multiple sectors, including agriculture, water resources, and disaster risk management. Support for flood forecasting and early warning systems is an integral part of this broader support for the modernization of hydromet services across the region. The program currently includes investments in Nepal, Bhutan, and Bangladesh, and investments in other countries are being prepared.

BOX 1.5. Two Types of Forecast: Deterministic and Probabilistic

***Deterministic* forecasting models provide a single forecast of expected future conditions.** A deterministic forecast might say something like, "The water level at station X is expected to crest at 22 meters elevation between noon and midnight on August 22, one meter above the danger level." This forecast will turn out to be either accurate or inaccurate.

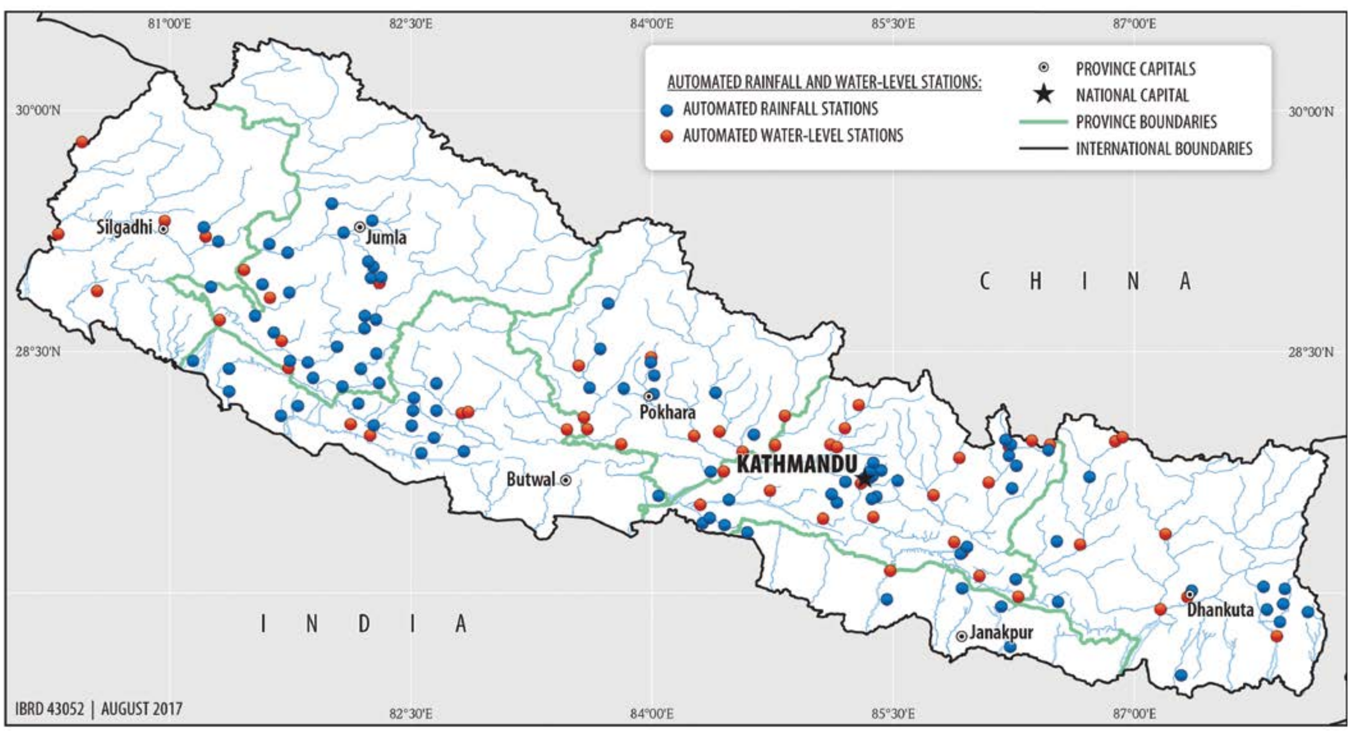
***Probabilistic* (ensemble-type) forecasting models provide multiple forecasts of expected future conditions, each with a quantitative estimate of likelihood.** A probabilistic forecast might say something like, "There is an 80 percent probability that the water level at station X will exceed the danger level of 21 meters elevation between noon and midnight on August 22." If the probabilistic model is well calibrated, this statement is accurate.

Agencies that issue weather forecasts or flood forecasts are increasingly shifting from deterministic to probabilistic models. The additional "likelihood" information included in a probability-based forecast is useful for decision making. Probabilistic models are also well suited for adjusting forecast schemes to accommodate climate change and other drivers of changes in flood patterns. Section 3 further discusses the advantages and implications of using probabilistic models.

In China, flood-control departments and meteorological administrations maintain a storm-monitoring network that includes ground observations, a meteorological radar network, and satellite capabilities. The hydrological monitoring and flood forecasting system includes rain gauges, water-level gauges, and hydrological stations that measure rainfall, water level, and discharge. Flood forecasts and warnings are issued by Flood Control and Drought Relief Headquarters. In 2006, the Honorable President of the People's Republic of China visited India, and it was agreed to establish an expert-level mechanism for discussion, interaction, and cooperation regarding flood season hydrological data, emergency management, and other issues regarding transboundary rivers.

In Nepal, the Department of Hydrology and Meteorology (http://www.dhm.gov.np/) monitors 286 hydrometeorological stations. Most are manually operated, but some have been automated to continuously monitor rainfall and water levels, with data transmitted to the department every five minutes. Nepal's Flood Forecasting Section (http://hydrology.gov.np/new/bull3/index.php/hydrology/home/main) provides web-based public access to real-time water-level and rainfall data (figure 1.7). Flood warning bulletins are also available online.

FIGURE 1.7. Automated Rainfall and Water-Level Stations in Nepal



Source: Redrawn from screenshot of the website of the Government of Nepal Department of Hydrology and Meteorology, http://hydrology.gov.np/new/bull3/index.php/hydrology/home/main.

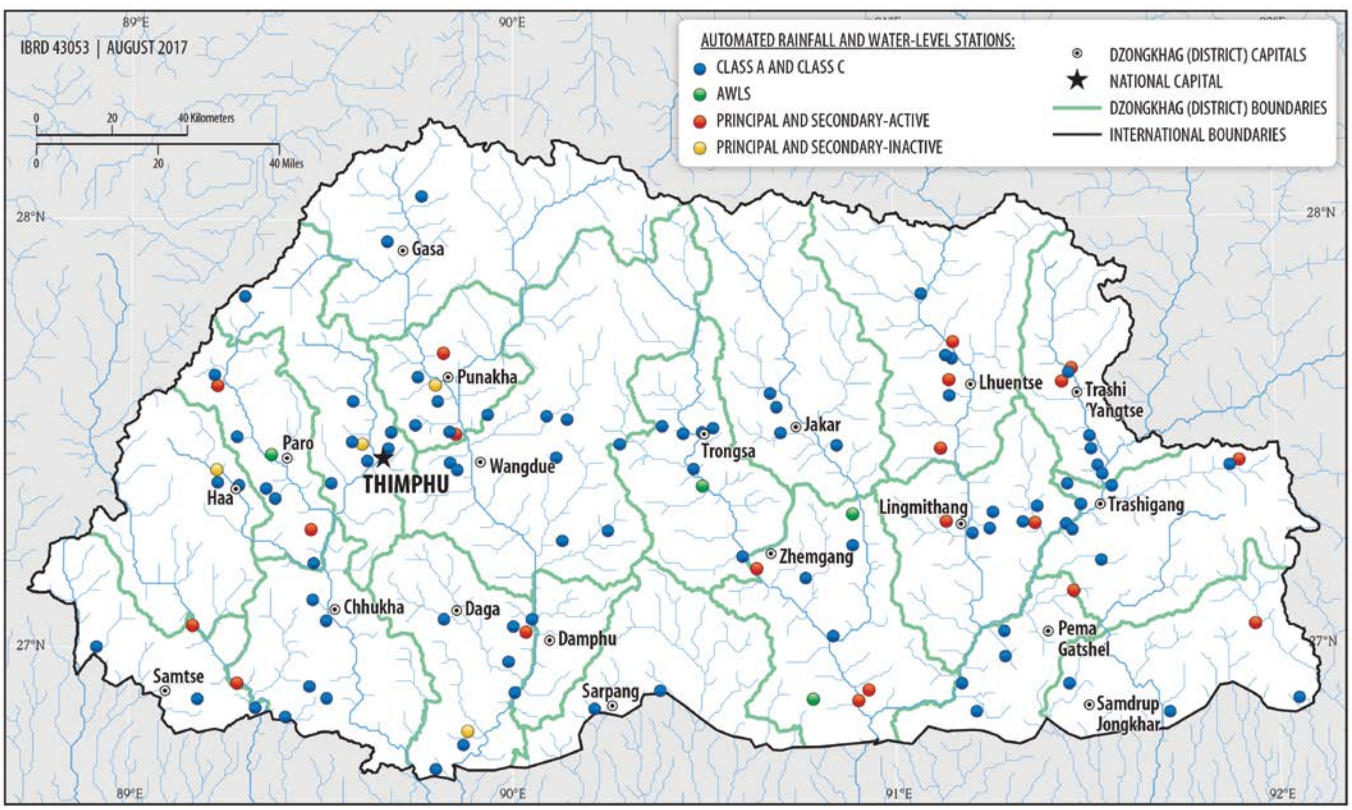
Along rivers that flow from Nepal to India, 46 hydrometeorological stations have been cooperatively established within Nepal under a 1988 bilateral agreement. Real-time data transmitted from these stations to India's Central Water Commission (CWC) is shared with the flood-prone Indian states of Bihar and Uttar Pradesh.

In Bhutan, the Department of Hydro Met Services (http://www.hydromet.gov.bt/) maintains 92 meteorological stations, 26 hydrological stations, and 15 flood warning stations. Some of these stations have been recently upgraded to include telemetry systems. The department also provides online, interactive, real-time data maps (figure 1.8) and operates satellite-based warning systems for glacial lake outburst floods in three basins. Two hydrological models have been tested for flood forecasting but have not yet been made operational.

Along rivers that flow from Bhutan to India, 32 hydrometeorological stations are maintained by the Royal Government of Bhutan with funding from India. India's CWC uses the data to formulate flood forecasts. A joint expert team of officials from the governments of Bhutan and India continuously review the cooperative scheme.

In India, the CWC (http://www.cwc.nic.in/) provides 12-, 24-, and 36-hour deterministic flood forecasts for 175 sites, including 28 inflow-forecasting sites. For some sites, simple statistical correlations of gauge-to-gauge, gauge, and discharge data are used. For other

FIGURE 1.8. Automated Rainfall and Water-Level Stations in Bhutan



Source: Redrawn from screenshot of the website of the Department of Hydro Met Services, Bhutan, http://www.hydromet.gov.bt/.

sites, rainfall data, soil moisture data, and stream-gauge data are used. These measurement-based approaches lend skill to short-range forecasts (figure 1.6). The water level and inflow forecasts are assessed in terms of their accuracy relative to later observations.

For several major rivers that flow from India to Bangladesh, flood forecasting data is transmitted to Bangladesh during the monsoon season. These data sites are located on the Ganges (two sites), Teesta (one site), Brahmaputra (four sites), and Barak rivers (one site). This data transmission has enabled civil and military authorities in Bangladesh to evacuate threatened populations to safer locations.

In Bangladesh, the Flood Forecasting & Warning Centre (http://www.ffwc.gov.bd/) provides online, interactive, real-time data maps (figure 1.9). The center also provides 24-, 48-, 72-, 96-, and 120-hour deterministic river-level forecasts for 54 locations. A one-dimensional fully hydrodynamic model provides these forecasts across all major rivers and floodplains. The forecasts are based on rain-gauge data and runoff estimates, stream-gauge data, and upstream-to-downstream travel times (figure 1.6 and map 1.2).

Bangladesh is unique in that roughly 90 percent of the catchment area supplying water to its rivers lies upstream of its country borders; forecasts with 5-day lead times can therefore be generated by observing river flows at the border-crossing sites, coupled with simple time-series forecasting. In 2006, experimental Climate Forecasting Applications for Bangladesh (CFAB) river discharge forecasts were coupled to the in-country MIKE 11–based forecasts at the Ganges and Brahmaputra border crossings (Hardinge Bridge and Bahadurabad, respectively). The CFAB forecasts provide 1- to 10-day probabilistic flow forecasts based on probabilistic rainfall forecasts from the European Centre for Medium-Range Weather Forecasting (ECMWF; 1 to 10 days lead time) and rainfall observations from satellites and rain gauges. The coupled MIKE 11 and CFAB forecasts provide 12 to 13 days of skillful lead-time flood warning to lower reaches of the country. Recently, ICIMOD has been providing experimental 8-day lead-time forecasts for Bangladesh based on river-gauge data, upriver satellite water-level observations, and new techniques in hydraulic modeling (http://www.icimod.org/?q=20075).

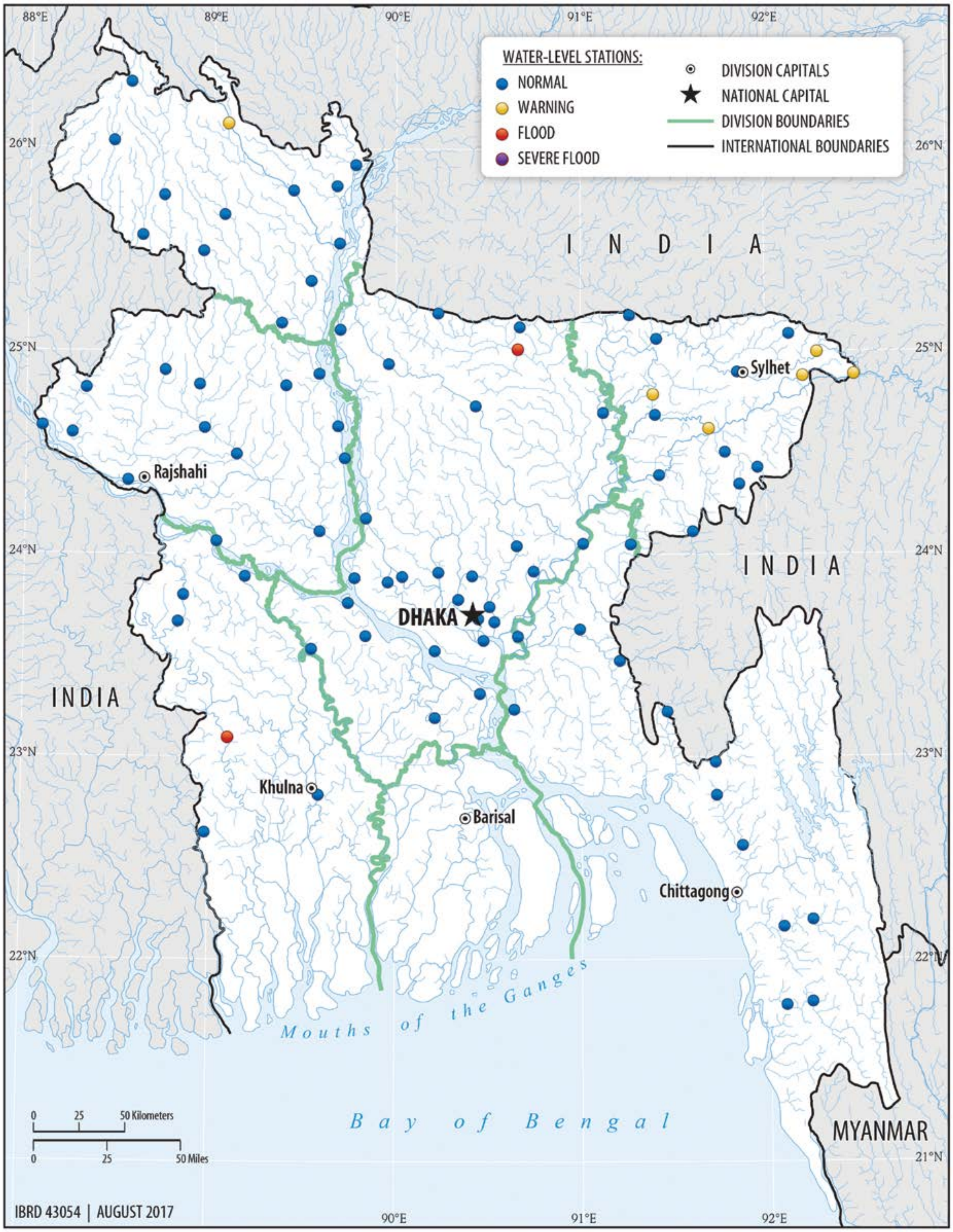
Table 1.4 lists country priorities for further improvements in flood forecasting.

Several efforts are under way to help facilitate international collaboration on transboundary flood issues. For example, ICIMOD's Hindu-Kush-Himalayan Hydrological Cycle Observing System (HKH-HYCOS) has provided a venue for Pakistan, Nepal, Bhutan, and Bangladesh to work together to establish a flood-observing network in selected basins and also flood information systems to facilitate real-time data exchange and increase flood forecasting and warning lead times. The establishment of a new ESCAP-facilitated effort for the South Asia region (box 1.6) is a welcome step in this endeavor.

For a more comprehensive overview of recent efforts toward managing flood risks in the region, see the following reports published in 2016:

- *Proceedings of the Regional Flood Early Warning System Workshop* (World Bank 2016a)
- *Flood Forecasting and Early Warning in Transboundary River Basins: A Toolkit* (ESCAP and RIMES 2016)
- *Disasters in Asia and the Pacific: 2015 Year in Review* (ESCAP 2016b)

FIGURE 1.9. Water-Level Stations in Bangladesh



Source: Redrawn from screenshot of the website of the Bangladesh Water Development Board, http://www.ffwc.gov.bd/.

TABLE 1.4. Priorities for Improving National Flood Forecasting and Early Warning Systems

Nepal	• Identification of flood zones and development of flood inundation maps • Re-evaluation of danger and warning levels for most rivers • Training and capacity building for the Department of Hydrology and Meteorology
Bhutan	• Greater density of sensors within the hydrometeorological observing network, with real-time telemetry • Access to global data assimilation into numerical weather prediction models • Reliable high-bandwidth Internet connectivity • High-speed computing • Training and capacity building • Strengthening of community-based early warning systems
India	• Two-dimensional modeling for major flood-prone basins • Updating of water-level thresholds based on location, time, and season • Real-time flood warning system • Floodplain zoning • Consideration of cloud-burst floods plus glacial-lake and landslide-dam outburst floods • Inventory of all glacial lakes and water bodies • Move from deterministic to probabilistic forecasting • International cooperation on access to upstream data • Engagement with users, recognizing their interest in water-level trends and flood onset, extent, and duration • Improved coordination with user agencies
Bangladesh	• Expansion of the existing flood forecasting and warning system to cover a greater area • Monthly and seasonal outlooks for water level • Hydrological drought prediction system • Regional cooperation on data sharing for transboundary rivers • Basin-wide flood forecasting

Source: Based on presentations at the 2015 Regional Flood Early Warning System Workshop, Bangkok, Thailand (Kumar 2016; Miah and Hossain 2016; Rajkarnikar and Sharma 2016; Tsering and Dupchu 2016), as reported in World Bank 2016a.

BOX 1.6. A New Regional Program on End-to-End Flood Forecasting and Early Warning

Participants in the 2015 Regional Flood Early Warning System Workshop in Bangkok designed and adopted a framework for a regional program on end-to-end flood forecasting and warning in South Asia. Workshop attendees came from Bangladesh, Bhutan, India, and Nepal, as well as from regional and international organizations. Discussions considered the risk assessment and flood forecasting advances described in this summary report, as well as other important work in the region. The workshop was organized by the World Bank and RIMES.

The overall objective of the proposed regional program is to reduce human and economic losses from flooding in the Ganges, Brahmaputra, and Meghna basins. The action plan includes three intermediate aims:

- Improve user responses to flash flood warnings.
- Improve user responses to riverine flood warnings.
- Improve regional coordination and information- and data-sharing between the national hydrological services.

In its implementation, the program will:

- Integrate flash flood and riverine flood concerns.

box continues next page

- Build early flood warning capacities.
- Use existing regional mechanisms for capacity building and knowledge sharing.

Participants noted that a basin-oriented collaborative approach to the sharing of monitoring, forecasting, and warning information would be cost-effective and of high socioeconomic value. Table B1.6.1 provides a summary of the final framework as formulated by the workshop participants, plus a recent update from ESCAP.

TABLE B1.6.1. Regional Program Framework

Objective: Reduce human and economic losses due to flash floods and riverine floods in the Ganges-Brahmaputra-Meghna basins		
Intermediate result 1: Improved user responses in Nepal, Bhutan, India, and Bangladesh to flash flood warnings	*Intermediate result 2:* Improved user responses in India and Bangladesh to riverine flood warnings	*Intermediate result 3:* Improved regional coordination and information- and data-sharing between the national hydrological services of Nepal, Bhutan, India, and Bangladesh
Early activities: 1.1 Landscaping of institutions involved in the generation and application of flash flood forecasts and warnings *Final program design may include these activities:* 1.2 Develop flash flood forecasting and early warning system: Nepal, Bhutan, India 1.3 Engage with users for risk awareness and communication to guide response decisions 1.4 Establish telemetered observing and monitoring systems in support of flash flood warning 1.5 Integrate flash flood forecasting and decision support into operations of the national hydrological services	*Early activities:* 2.1 Landscaping of institutions involved in the generation and application of riverine flood forecasts and warnings *Final program design may include these activities:* 2.2 Develop riverine flood forecasting and early warning system with lead times that meet user requirements (India and Bangladesh) 2.3 Engage with users for risk awareness and communication to guide planning and decision making 2.4 Integrate riverine flood forecasting and decision support into operations of the national hydrological services	*Activities:* 3.1 Establish a portal for sharing transboundary data and forecast products 3.2 Establish a forum for the region's national meteorological and hydrological services to share products, experiences, and technical information 3.3 Conduct collaborative research on priority areas identified through assessments of user needs
Implementation (Oct. 2016 update): Resolution 71/12 mandates ESCAP to establish an intergovernmental platform of meteorologists, hydrologists, and disaster risk management professionals from the operational organizations of the riparian countries of the Ganges-Brahmaputra-Meghna basins initially and then to scale up to other transboundary river basins, including the Indus basin. ESCAP is moving forward with a stepwise strategy toward the fulfillment of this mandate.		

Source: Modified from World Bank 2016a

Note: This framework reflects the formulation of Regional Flood Early Warning System Workshop participants, plus ESCAP updates.

ESCAP will carry forward the new regional program. This leadership role is consistent with ESCAP's mandate to strengthen regional cooperation for flood forecasting in transboundary river basins and with its commitment to the promotion of intergovernmental, multistakeholder cooperation. Activities within this mandate include the facilitation of data exchanges, the integration of recent scientific advances into operational systems, and the sharing of best practices. For more information, see Resolution 71/12, adopted in 2015: "Strengthening Regional Mechanisms for the Implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030 in Asia and the Pacific" (United Nations Economic and Social Council 2015).

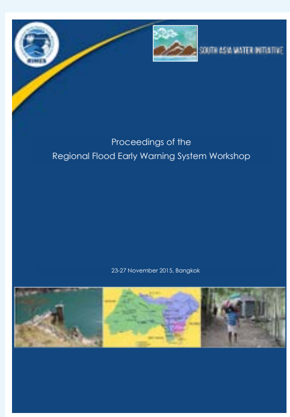
RIMES will serve as technical secretariat. This leadership role is consistent with RIMES's support for building national capacities for enhanced flood warning systems and for the pilot testing of new-generation forecast technologies for community-level applications.

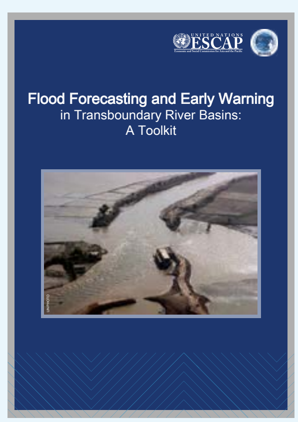
For more information about the workshop and the ongoing contributions of the various countries, groups, and agencies represented there, see the published proceedings:

- *Proceedings of the Regional Flood Early Warning System Workshop*, November 23–27, 2015, Bangkok, Thailand (World Bank 2016a)

These publications also include material presented at the workshop:

- *Flood Forecasting and Early Warning in Transboundary River Basins: A Toolkit* (ESCAP and RIMES 2016)
- *Disasters in Asia and the Pacific: 2015 Year in Review* (ESCAP 2016b)





June 2013 - Buildings stand on flood-ravaged land alongside the Alaknanda River in Chamoli district, Uttarakhand (India).

Section 2 Flood Risk Assessment for the Ganges Basin

Introduction

In any flood risk management or adaptation strategy, risk assessment is a critical first step. Making wise choices about how to reduce flood losses requires a quantitative understanding of where people and material assets are at risk. A formal risk assessment therefore uses a variety of tools to estimate the impacts of flooding on people and on assets such as buildings, roads, and agricultural crops. These findings can then be used to identify priority areas for targeted risk management—for example, risk mitigation and flood forecasting.

A comprehensive flood risk assessment was recently completed for the Ganges River basin. The Ganges basin was chosen for the first such assessment in the region because of its history of major economic losses and loss of lives as a consequence of flooding, together with relatively good data availability compared with other basins.

The overall aim of this risk analysis was to help planners, decision makers, and other stakeholders in their efforts to reduce losses due to frequent flooding. The objective was twofold:

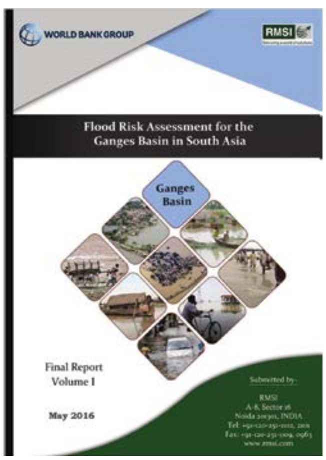
- Estimate and map flood risks for the entire Ganges basin, across a variety of socioeconomic sectors and at a scale that would be useful to local planners.
- Support a river basin approach for developing a shared knowledge base and an analytical framework for flood risk assessment.

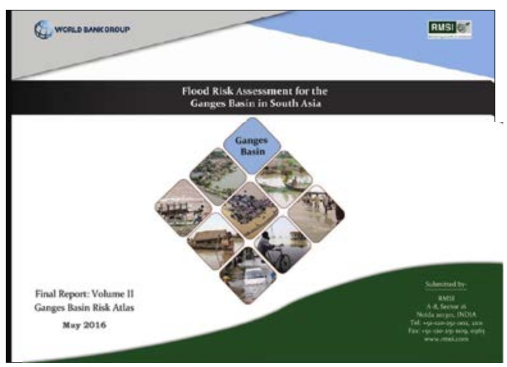
The results of this assessment include a series of maps and tables that identify areas and assets that are most at risk from river flooding. This type of information is useful to a wide variety of users in the private and public sectors—for example:

- Decision makers and policy makers
- Government agencies and departments
- Nongovernmental organizations
- Engineers and disaster managers
- Insurers and reinsurers
- Farmers
- Residents of flood-prone areas
- Researchers

Similar risk assessment studies would be beneficial for other basins of the South Asia region.

The following pages describe the methods and selected major findings of the Ganges basin risk assessment.





More information is provided in the original flood risk assessment report: *Flood Risk Assessment for the Ganges Basin in South Asia: Final Report, Volume I* (RMSI 2016a).

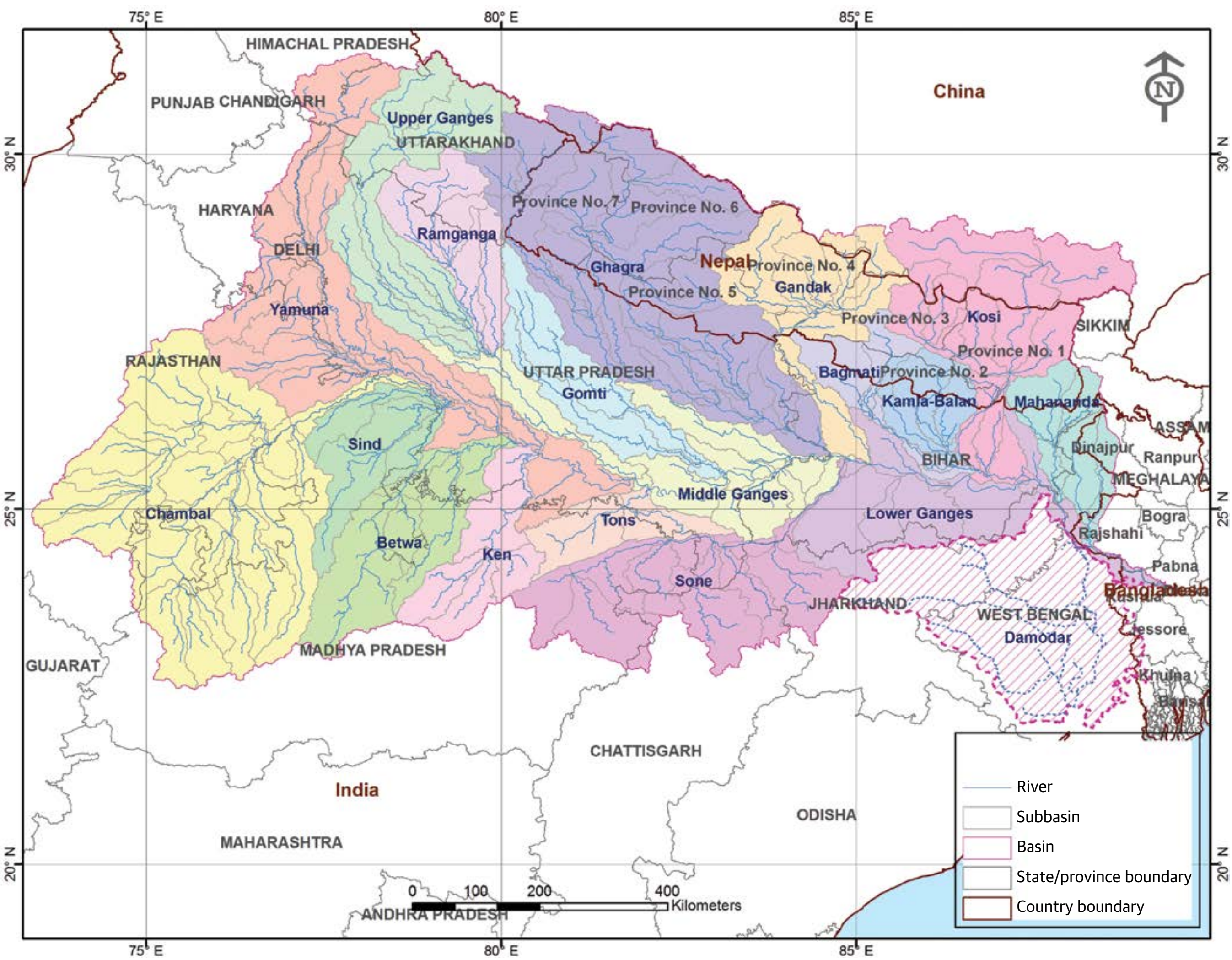
An accompanying atlas with basin and subbasin maps is also available: *Flood Risk Assessment for the Ganges Basin in South Asia: Final Report, Volume II* (RMSI 2016b)

The Government of India recently revised the Indian portion of the original risk assessment, using classified data. The updated information is available in the online, interactive *Ganges Basin - Flood Risk Atlas,* available through the website of the Central Water Commission (CWC) of India (CWC and RMSI 2016).

Millions of people suffer from flooding in the Ganges basin. Most flooding is due to heavy rains that fall during the monsoon season—July through September for most of the basin (figure 1.2). The western portion of the basin experiences the shortest monsoon season and the least rainfall. The eastern portion experiences a longer monsoon season and the greatest rainfall. Tropical cyclones also bring heavy rains and damaging floods.

The Ganges River basin sprawls across four countries: China, Nepal, India, and Bangladesh (map 2.1). The Ganges basin is one of the world's largest, most fertile, and most densely populated river basins.

MAP 2.1. The Ganges River Drainage Basin: Administrative Divisions and Transboundary Subbasins



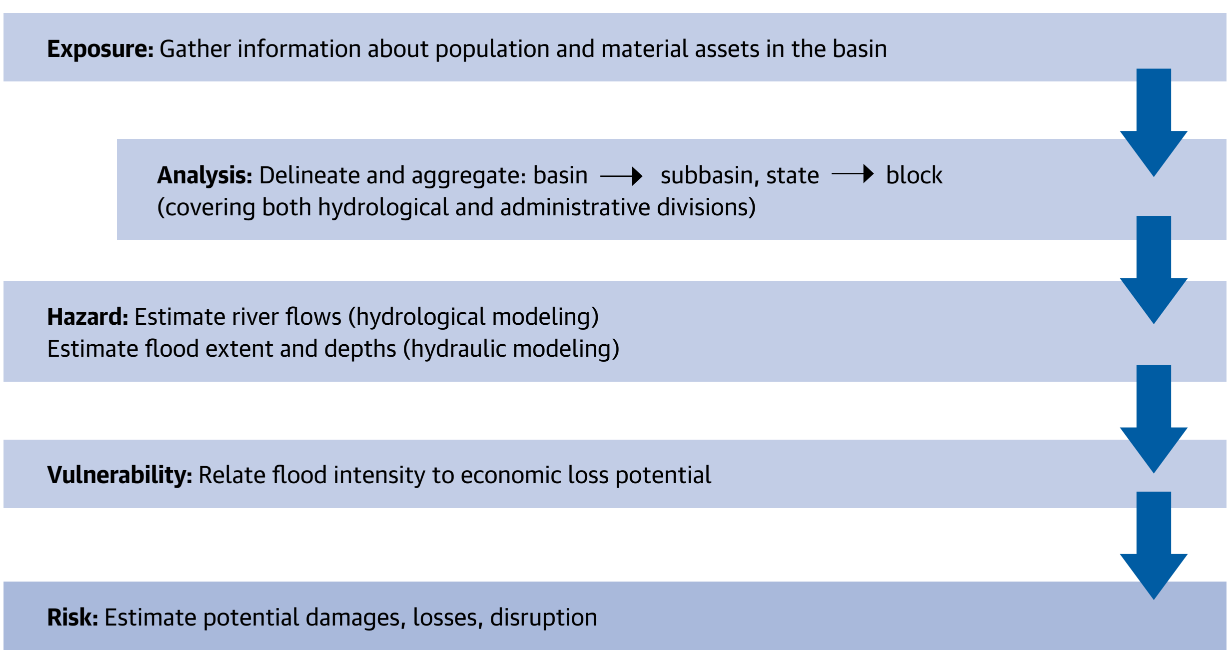
Source: RMSI 2016a.
Note: Names of administrative divisions are shown in gray. Names of drainage divisions are shown in blue.

The information base for the risk assessment (figure 2.1) covers all of the Nepalese, most of the Indian, and some of the Bangladeshi parts of the basin. China was included for the hydrological modeling, but no exposure data were available. The analysis considered the Ganges River catchment area from the upper basin to the river's confluence with the Brahmaputra River in Bangladesh. The Damodar River basin in India (the hatched area on map 2.1) was excluded because this river has a separate source and flows to a separate outlet. Much of Bangladesh was excluded because modeling floods across the Bangladesh delta would require incorporation of the entire Brahmaputra (and Meghna) river basins. Importantly, the government of India has recently updated the underlying modeling for the Ganges risk assessment, using classified government hydrological data that were unavailable for the original analysis.

Exposure: People and Property in the River Basin

The first step of the risk assessment was to determine the number of people and the value of properties or assets within the Ganges basin (figure 2.1). These data were compiled and mapped for Nepal, India, and Bangladesh. China was not included because there was insufficient data.

FIGURE 2.1. Flood Risk Assessment



Source: Modified from Priya 2016, with contributions from RMSI.

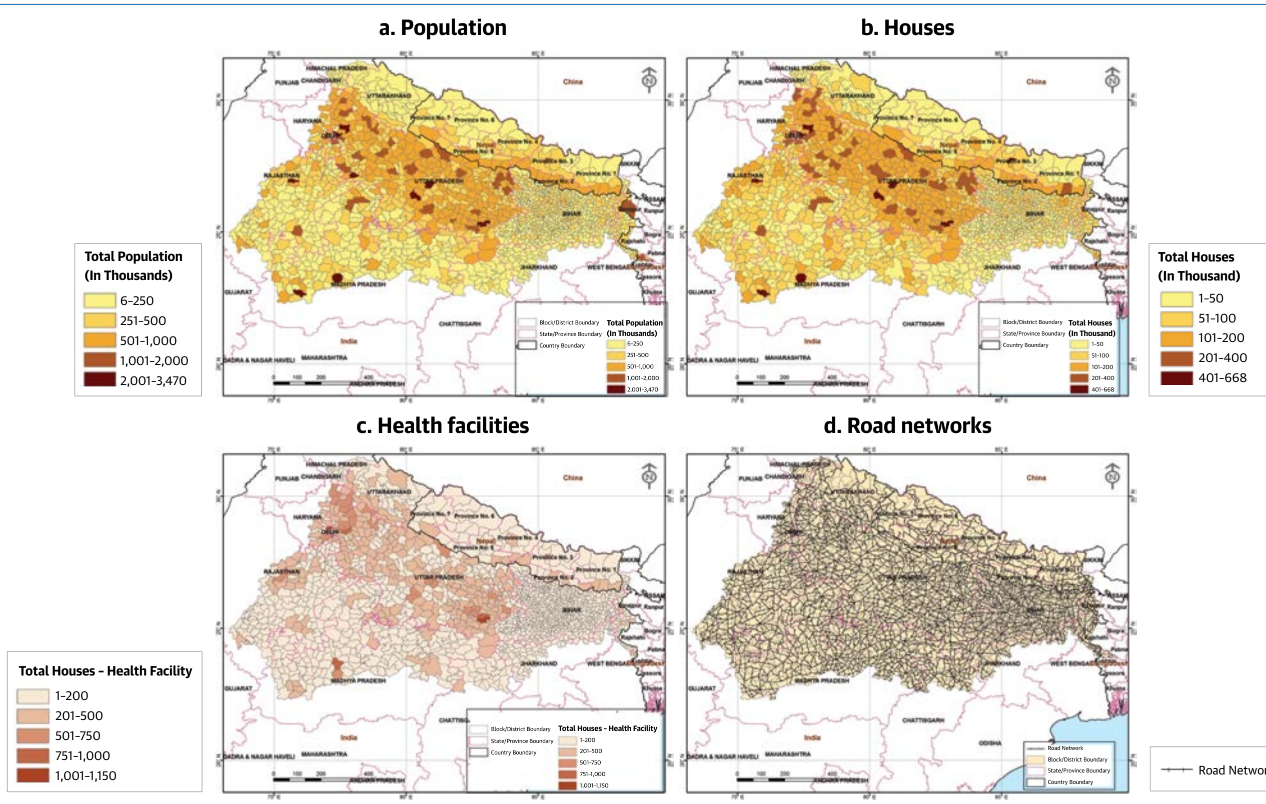
Note: Flood risk assessment is an essential first step in flood risk management. Risk assessment is also a key element of an end-to-end, people-focused early warning system (see figure 1.5). This flow chart outlines the steps of the Ganges Basin risk assessment.

The exposure analysis and maps include demographic and asset information:

- *People*—including gender, children, scheduled castes, scheduled tribes, and literacy rates
- *Buildings*—residential, commercial, industrial, educational, medical, and other (for example, places of worship), including occupancy and construction type (for example, grass, brick, reinforced concrete)
- *Infrastructure*—roads and railways
- *Agricultural crops*—rice, maize, and wheat

Finding: The total population within the basin is about 474 million, based on 2011 census data. India encompasses the largest share of the basin area (about 80 percent) and population (more than 90 percent). (The population estimate for the Ganges Basin in *Ganges Strategic Basin Assessment: A Discussion of Regional Opportunities and Risks* is 655 million (World Bank 2014). This higher number reflects the strategic assessment's inclusion of a much larger portion of Bangladesh, inclusion of the Damodar basin in India, and extrapolation of 2001 census data to obtain a population estimate.) Map 2.2 shows the distributions of people and selected assets within the basin.

MAP 2.2. Ganges Flood Risk Assessment: Populations and Asset Classes



Source: RMSI 2016b.

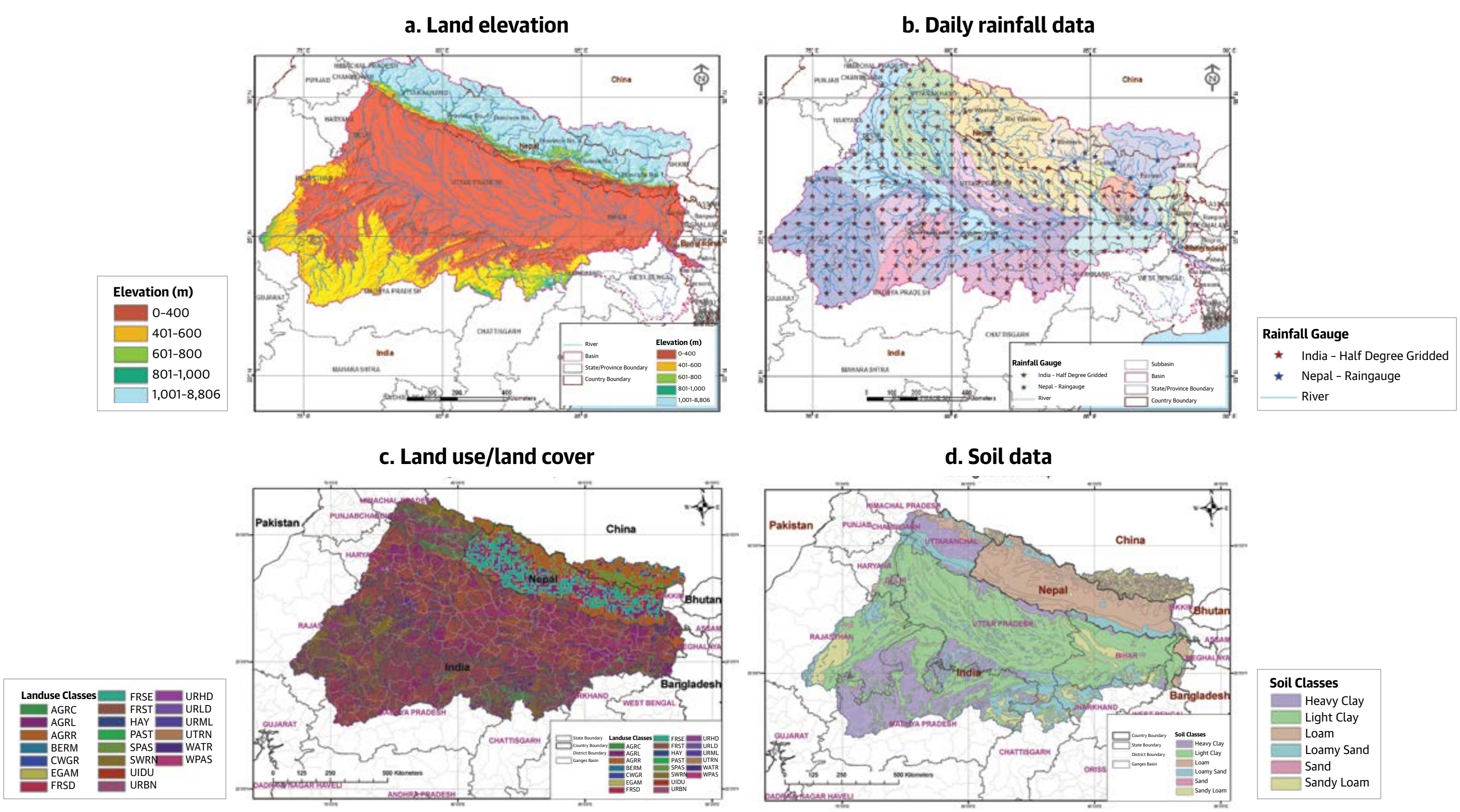
Note: The Ganges flood risk assessment mapped populations and asset classes within the basin. The examples shown here are population, houses, health facilities, and road networks. The risk assessment also characterized the basin-wide distribution of railroads, major crops, and other types of buildings. On panels a–c, the darker the color, the greater the number of people or buildings. The most populous states, divisions, or districts (panel a) in each country are Uttar Pradesh (India), Province No. 2 and Province No. 3 (Nepal), and Nawabganj (Bangladesh). House numbers (panel b) follow the same pattern. Health facilities (panel c) are of particular interest because of the critical role they play in disaster mitigation and recovery. The greatest number of health facilities is in Uttar Pradesh.

Finding: The total estimated value of material assets in the basin is approximately US$1 billion. Most of these assets are located in India (96 percent), where the greatest land area and highest populations occur. Basin-wide, almost all of the total value is in buildings (95 percent). The most expensive buildings to replace, per square meter, are those made of reinforced cement concrete.

Hazard: Extent and Depth of Flooding

The second step of the risk assessment was to determine which areas of the basin are susceptible to flooding. This analysis starts with basic information about the basin itself, including terrain, soils, land use, and flood protection structures (map 2.3). Much of the study area is cropland (approximately 62 percent), open/grassland areas (approximately 24 percent), or forest (approximately 7 percent). Other inputs include historical river flow

MAP 2.3. Ganges Risk Assessment: Basic Data

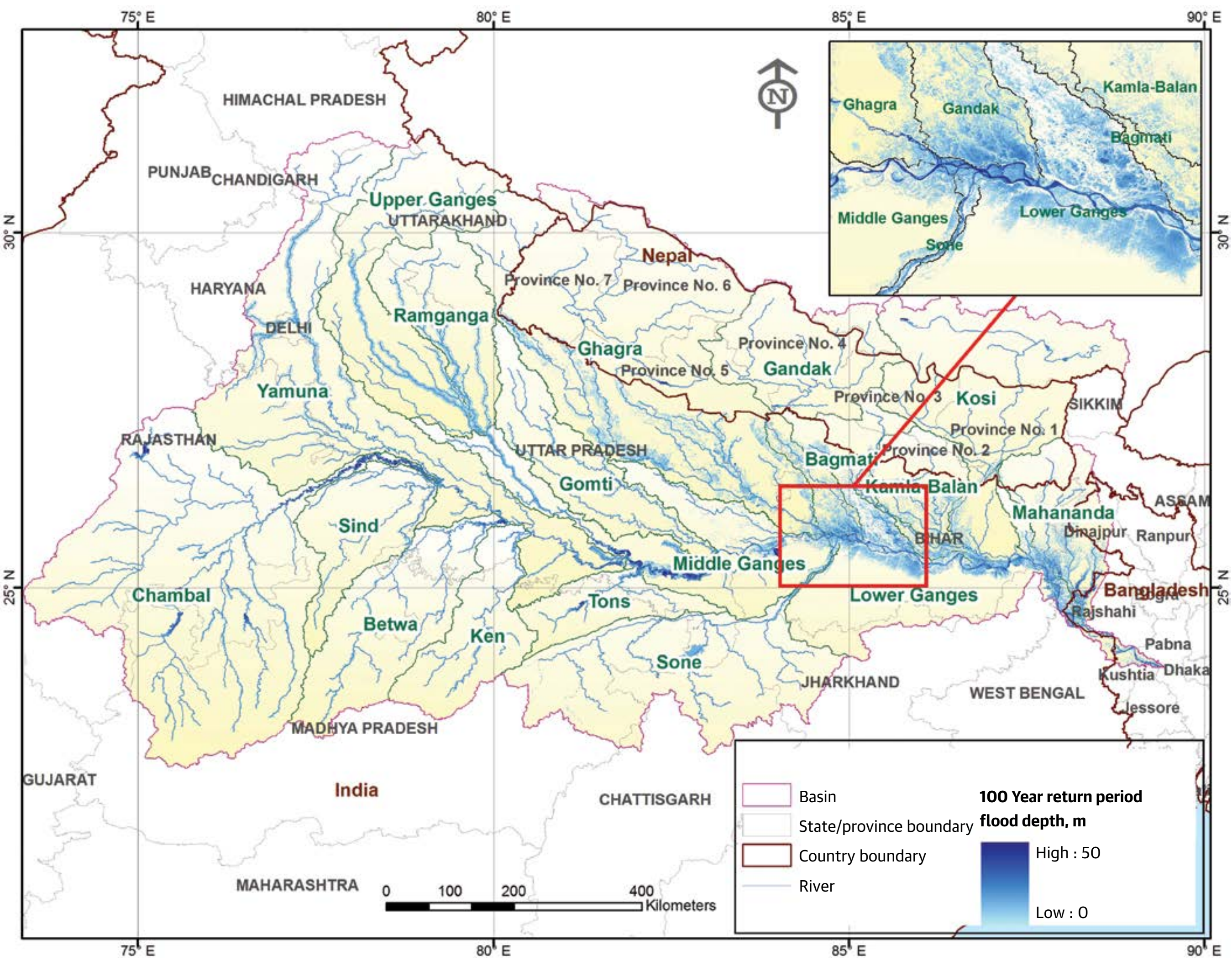


Source: Modified from Priya 2016a, with contributions from RMSI. Maps are from RMSI.
Note: The Ganges risk assessment used many types of basin data to delineate flood hazards. Examples shown here are land elevation, rainfall data, land use and land cover information, and soils data.

and flood data. The flow data exhibited some quality issues, and details about historical flood damage were generally sparse.

Analyses were performed for Ganges River discharges with return periods of 2, 5, 10, 25, 50, and 100 years. The longer the return period, the more severe the flood. A flood with a 100-year return period has a 1 percent probability of occurring in any given year. A flood with a return period (RP) of 2 years has a 50 percent chance of occurring in any given year. A flood with a return period of 100 years is less common—with a 1 percent probability of occurring in any given year—but more severe.

MAP 2.4. Ganges Hazard Analysis for a 100-Year Flood



Source: RMSI (reanalysis of results from RMSI 2016a).
Note: Flooded areas along the river are shaded blue. The darker the blue, the deeper the floodwaters.

The Hydrologic Engineering Center's River Analysis System (HEC-RAS; United States Army Corps of Engineers) was used for the hydraulic modeling. The model output is expressed in a series of flood hazard maps that depict inundation extent and water depth for simulated small to large floods (as in map 2.4, for example).

Finding: A Ganges basin flood with a 100-year return period inundates an estimated 75,000 square kilometers of land. A Ganges basin flood with a two-year return period inundates an estimated 47,000 square kilometers of land. This extent is approximately 60 percent of the estimated inundation area of a 100-year flood. The majority of the inundated area is in the low-lying plains of the Lower Ganges River (that is, the Lower Ganges subbasin).

Modeling floods across a large floodplain like that of the Ganges River requires calibration and validation to ensure that the models accurately reproduce observed flooding behavior. This analysis used an iterative approach. The flood models were initially calibrated and validated by using hydrological data mainly from open-source data websites such as the Dartmouth Flood Observatory. Some data were also used from the CWC of India and the Department of Hydrology and Meteorology of Nepal. During the later stages of this analytical work, the CWC made available classified daily gauge discharge data and corresponding water surface elevations for 179 stations across the basin.

Information was provided for seven flood events: 1978, 1981, 1988, 1996, 1998, 2004, and 2008. The selection of events was based on historical flood records. Five events were used for calibration, and two were used for validation. The use of high-quality hydrological data significantly improved the calibration and validation of the models and therefore also the quality of the results and the level of confidence regarding the findings. Comparison of the simulated and observed flood events showed general agreement.

The flood hazard maps were also compared to maps provided by the *Flood Risk Mapping: South Asia* online application of the International Water Management Institute (IWMI 2016). A comprehensive comparison of flood-inundated areas on the two sets of maps (for example, figure 2.2) showed a reasonable match.

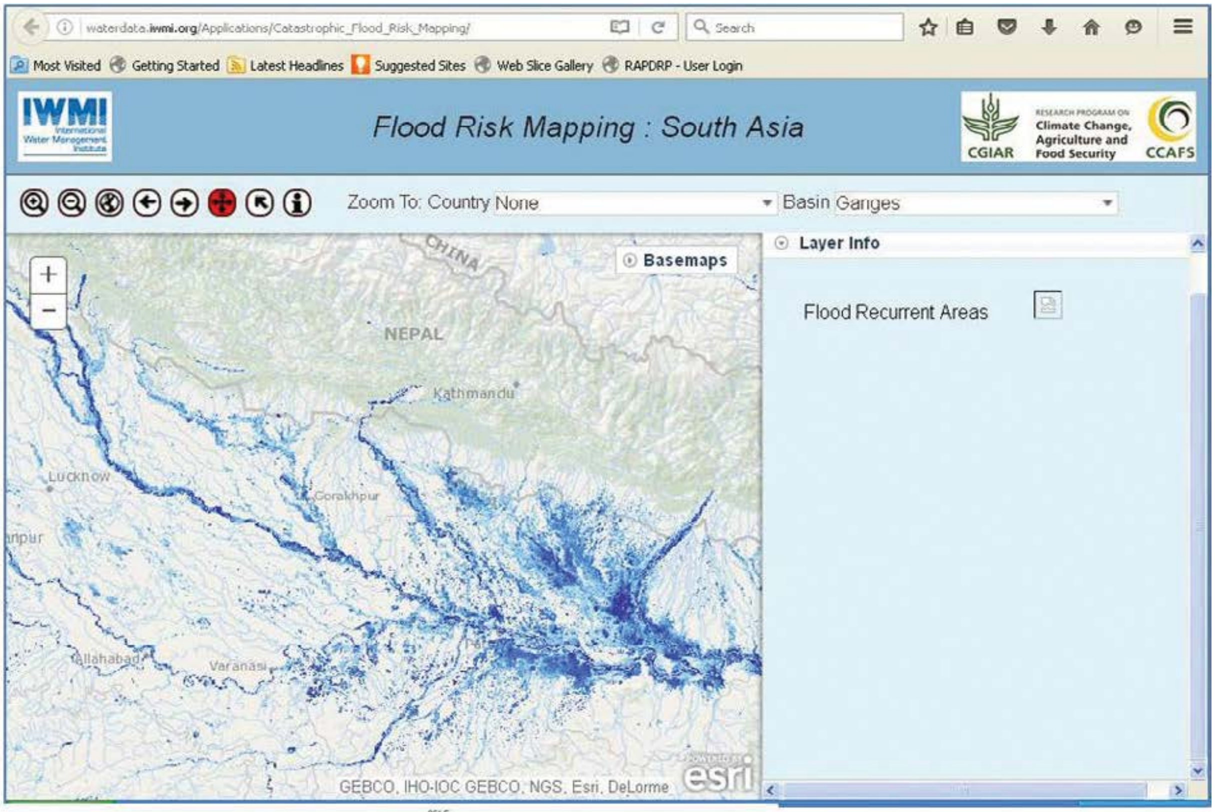
Vulnerability: Susceptibility to Damage or Loss

The vulnerability module links information about exposure (step 1) and flood hazard (step 2) in order to deduce the probability of specific loss scenarios. Damage or vulnerability functions (quantitative expressions of damage as a function of hazard severity) are used to relate flood intensity (flood extent and depth) to the economic loss potential. Damage functions are often based on engineering knowledge combined with information about insurance claims. Such data, however, are very difficult to obtain.

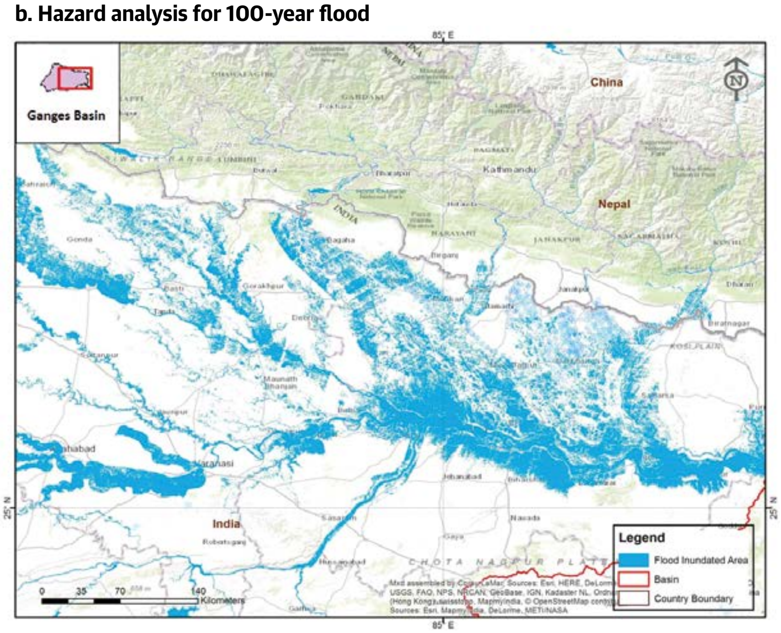
For buildings, for example, seven different types of structure were considered, based on their vulnerability to flood damage. Some construction materials are more robust than others. For each building type, damage loss was expressed in terms of a building damage

FIGURE 2.2. **Comparison of Flood Hazard Maps with Flood-Recurrent Areas**

a. Flood-recurrent areas (IWMI)



b. Hazard analysis for 100-year flood



Source: RMSI. Screenshots are from IWMI 2016 and RMSI.

Note: A comprehensive comparison of the Ganges flood hazard maps with the flood-recurrent areas mapped by the International Water Management Institute (IWMI) showed reasonable agreement. This example shows maps for flood-recurrent areas, as mapped by IWMI (panel a), and areas flooded by a 100-year return period flood, as modeled by this study (panel b).

ratio—the event-related repair or replacement cost divided by the total replacement cost. Similar damage functions were formulated for infrastructure and agricultural elements.

The resulting loss estimates are conservative (low-end); actual losses are likely much higher. In estimating vulnerability, this study considered flood extent and depth. For certain types of flood damages and losses, flood duration is also important. However, inadequate data prevented assessment of flood duration. Floodwaters also disrupt commerce and business productivity and interrupt critical services, such as water supply, power supply, telecommunications, and medical services. These impacts were not assessed (again, because of a lack of data), but an indication of these types of losses is provided by the maps and loss estimates for buildings (including commercial and residential buildings), roads, and railroads.

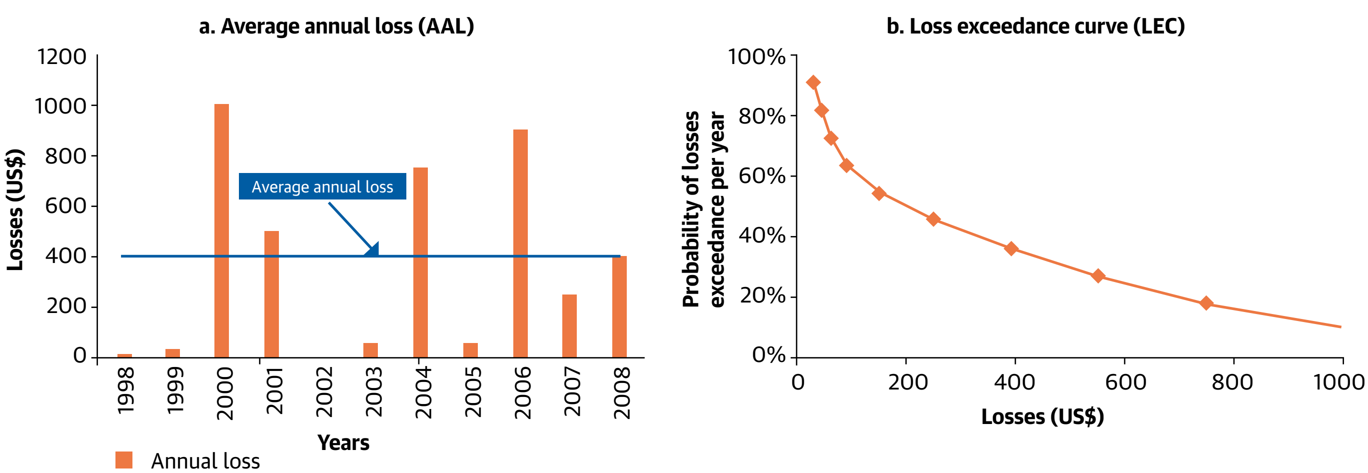
Risk: Probability and Impact

The final step of the analysis was to estimate the number of people and the value of assets likely to be affected or damaged by floodwater inundation. Risk refers to the possibility, not the certainty, of future losses. (If a future loss is perfectly known, then it is a cost—not a risk.)

Estimated losses associated with the simulated flood events are expressed in two ways (figure 2.3):

- Average annual loss (AAL)—the average of yearly losses through time
- Loss exceedance curve (LEC)—a graphical representation of the probability that a given monetary loss amount will be exceeded in a single year

FIGURE 2.3. Representations of Flood Damage



Source: RMSI.

Note: In panel a, the bars represent yearly losses associated with a random sequence of flood events. The blue horizontal line represents the AAL over that time period. That information feeds into the generation of the LEC information shown in panel b—that is, the probability of exceeding a certain level of loss in a year. The risk assessment atlas (RMSI 2016b) provides AAL tables for the entire Ganges basin and for individual subbasins—by country and by asset class—for floods ranging from a 2-year return period to a 100-year return period. An LEC is also provided for each subbasin. AAL = average annual loss; LEC = loss exceedance curve.

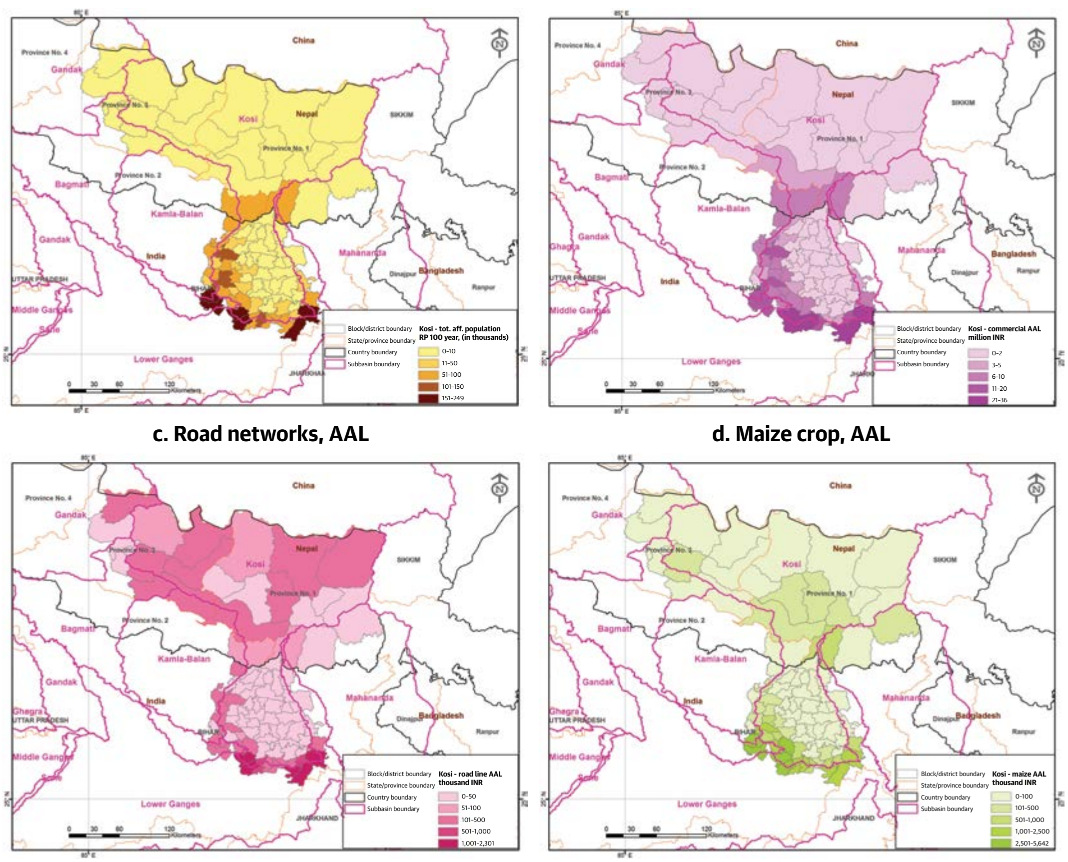
AAL (figure 2.3, panel a) is particularly important to the insurance industry for risk pricing. LECs (figure 2.3, panel b) are useful for understanding whether the risk is driven by large or small events. Panel b of figure 2.3 shows, for example, that the probability of incurring a loss of US$200 million within a single year at this location is about 50 percent (a 2-year return period event). In other words, the probability of at least some flood-related losses over the course of a year is quite high. For higher levels of loss, the probability is lower. This type of information is useful for public policy making and for insurance applications.

For the Ganges flood risk assessment, an LEC was fitted to the modeled flood events using standard regression techniques. The return period of any loss could therefore be estimated, and the AAL could be calculated. Based on the flood hazard maps, direct losses were calculated for each flood scenario (2- to 100-year return periods) for all at-risk exposures. Hazard-related financial losses are different for different types of structure or asset.

MAP 2.5. Example: Flood Risk Maps for Kosi Subbasin

a. Population affected **b. Commercial buildings, AAL**

c. Road networks, AAL **d. Maize crop, AAL**



Source: RMSI (modified from RMSI 2016b).

Note: The Ganges flood risk assessment produced a comprehensive set of flood risk maps for a variety of asset classes. These examples of flood risk maps are from the Kosi subbasin, for a flood with a 100-year return period, showing number of people affected (panel a); commercial buildings, AAL (panel b); road networks, AAL (panel c); and maize crop, AAL (panel d). On each map, the darker the color, the greater the disruption or loss. The risk assessment atlas provides similar maps for all subbasins and asset classes. AAL = average annual loss.

Finally, a comprehensive set of risk maps was generated for selected return periods, showing the geographic distribution of affected populations and assets. Map 2.5, for example, shows selected risk assessment maps for the Kosi subbasin. Maps are often the simplest and most powerful way to convey crucial hazard and risk information.

Findings: A complete set of loss tables, LECs, and risk maps is provided in the risk assessment atlas. The atlas includes risk maps for a dozen different attributes (populations and various asset classes) for 18 Ganges subbasins (map 2.5). This type of information is useful to a wide range of people—from policy makers to individual farmers and residents.

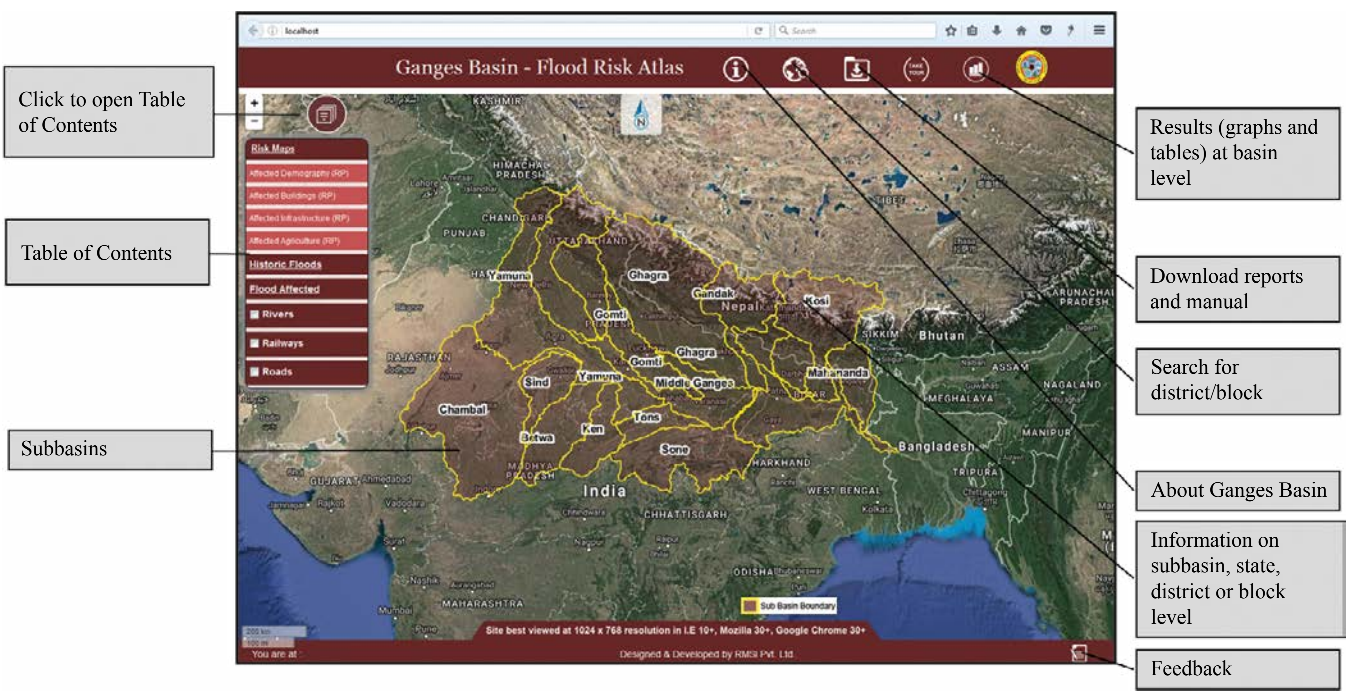
Interactive Online Flood Risk Atlas

An augmented, updated version of the risk assessment maps for India is available online as the interactive *Ganges Basin - Flood Risk Atlas* (figure 2.4), which is hosted by India's CWC (CWC and RMSI 2016b).

The online atlas provides easy-to-use access to the flood risk assessment data and results. This information is available for a wide range of spatial scales—from the basin level down to individual blocks. Anyone with Internet access can use the interactive atlas to visualize flood impacts, analyze base exposure and risk data, and also generate reports.

Examples are shown in figures 2.5-2.6.

FIGURE 2.4. Ganges Basin Interactive Flood Risk Atlas for India



Source: Modified from Priya 2016, with contributions from RMSI. Screenshot is from the Ganges Basin - Flood Risk Atlas, accessed through the home page of the Central Water Commission (India) (CWC and RMSI 2016).

FIGURE 2.5. User-Generated Risk Maps at Different Scales

a. Entire Ganges basin

b. Subbasin level

c. State level

d. District level

e. Block level: before flood

f. Block level: after flood

Source: Priya 2017, with contributions from RMSI.
Note: The interactive online risk atlas for India allows users to access risk information and generate risk maps at their scale of interest—from basin level to block level. This information is useful to a wide range of end users in the public and private sectors.

Major Findings

Flood frequency. The Ganges basin has a very high flood frequency. Some states and provinces experience very high losses due to floods every year or nearly every year. These areas would benefit from immediate attention to flood risk reduction. Possible measures might include the construction of protective walls, elevation or realignment of roads, improvements to drainage systems, migration of assets and people from high-risk zones to safer areas, and changes in cropping patterns and other land use practices.

Affected populations. For a Ganges River flood with a two-year return period (a relatively minor flood), the number of people affected is approximately 47 million (10 percent of the total basin population). About 45 percent of this affected population lives in India. The Indian states of Bihar and Uttar Pradesh have the highest numbers—about 18 million and 17 million people, respectively. In Bangladesh, the Rajshahi Division has the highest number—0.99 million. In Nepal, Province No. 2 (defined by the latest constitution to be completely within the Tarai region) would be hardest hit, with about 0.16 million people affected. Figure 2.7 shows the various populations affected by a modeled two-year flood,

FIGURE 2.6. **User-Generated Risk Reports at Different Levels**

a. Bihar state

Basin → Subbasin → **State** → District → Block

Affected population (millions)

2-year	10-year	100-year
18.12	23.27	28.13

Building loss (Rs millions)

2-year	10-year	100-year	AAL
24,058	34,412	47,030	14,057

Infrastructure loss (Rs millions)

2-year	10-year	100-year	AAL
210	339	524	131

Agriculture loss (Rs millions)

2-year	10-year	100-year	AAL
1,085	1,496	1,935	623

b. Patna Rural district

Basin → Subbasin → State → District → **Block**

Affected population (millions)

2-year	10-year	100-year
1.18	1.42	1.51

Building loss (Rs millions)

2-year	10-year	100-year	AAL
1,847	2,699	4,040	1,099

Infrastructure loss (Rs millions)

2-year	10-year	100-year	AAL
0.84	1.34	1.83	0.51

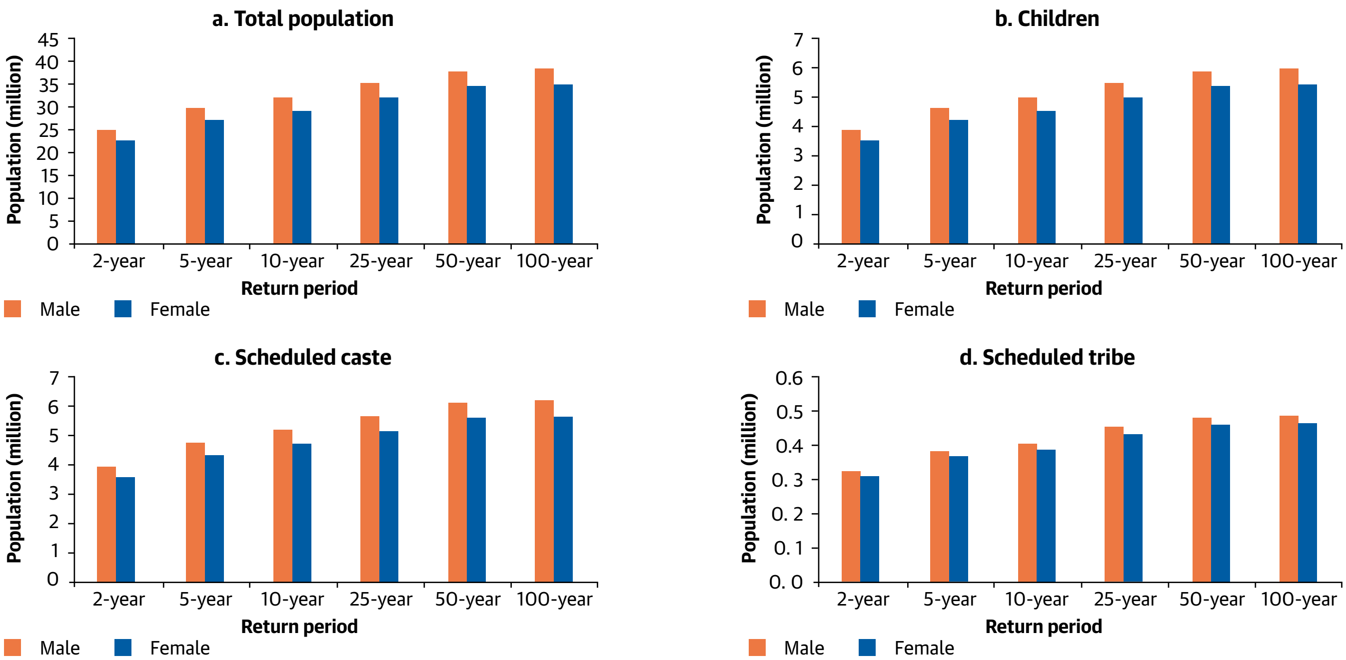
Agriculture loss (Rs millions)

2-year	10-year	100-year	AAL
3.29	4.66	5.69	1.90

Source: Priya 2017, with contributions from RMSI.

Note: The interactive online risk atlas for India allows users to generate risk reports at their scale of interest—from basin level to block level. These examples show the estimated impacts of flood events with 2-year, 10-year, and 100-year return periods in the state of Bihar and the Patna Rural district. AAL = average annual loss.

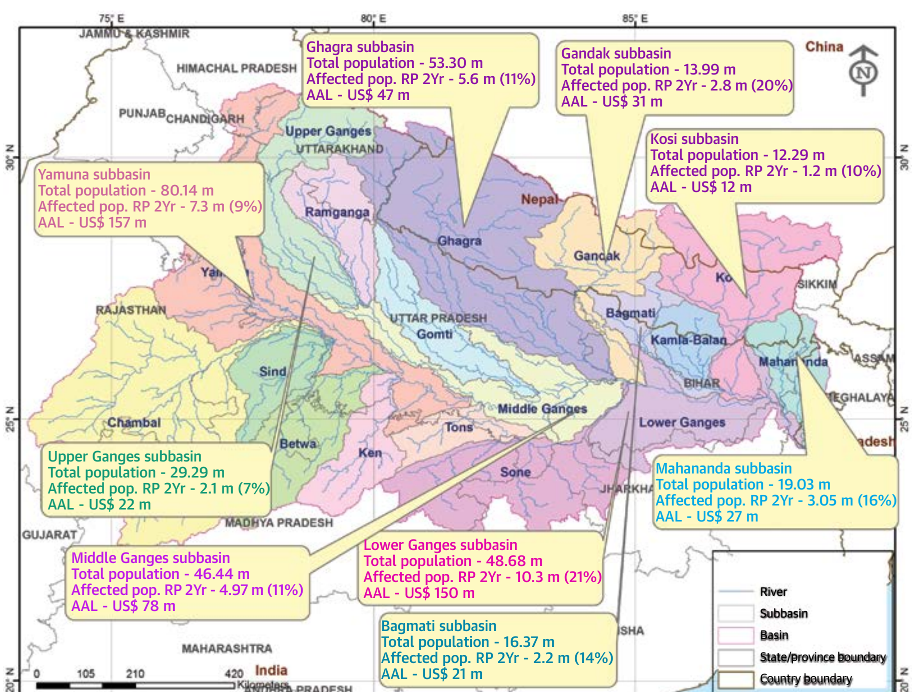
FIGURE 2.7. **Ganges Basin Risk Assessment: Populations Affected**



Source: RMSI.

Note: The flood risk assessment provides demographic information about the people affected by Ganges basin floods of various magnitudes.

MAP 2.6. **Ganges Basin Risk Assessment: Severely Impacted Subbasins**



Source: Modified from RMSI 2016a.

Note: Population numbers are given in millions (m). Average annual loss (AAL) is expressed in millions (m) of United States dollars (US$). Pop. = population; RP = return period.

TABLE 2.1. Ganges Basin Risk Assessment: Most Severely Affected States and Provinces

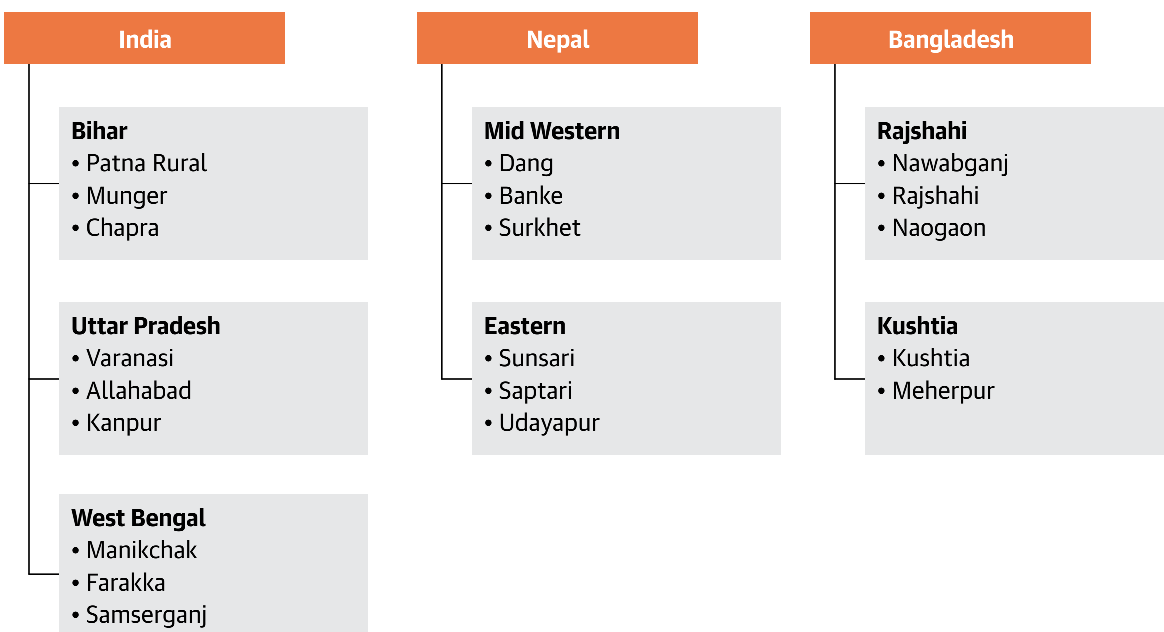
State/province	Affected population (millions [%])	State/province	AAL (US$, millions)
Rajshahi, Bangladesh	0.99 (44%)	Bihar, India	221
West Bengal, India	3.53 (30%)	Uttar Pradesh, India	205
Delhi, India	3.75 (22%)	Delhi, India	101
Bihar, India	18.12 (17%)	West Bengal, India	40
Uttar Pradesh, India	17.31 (9%)	Rajshahi, Bangladesh	14
Eastern Province, Nepal	0.15 (3%)	Eastern Province, Nepal	1
Mid-Western Province, Nepal	0.06 (2%)	Mid-Western Province, Nepal	1

Sources: Priya 2016; original data from RMSI 2016a.
Note: Data show states and provinces most severely affected by a flood with a return period of two years, listed in descending order for both population on left (number of people and as a percentage of the resident population) and AAL on the right. AAL = average annual losses.

as well as more severe floods. Map 2.6 shows the most severely impacted subbasins. Table 2.1 lists the most severely affected states and provinces. Figure 2.8 lists the most severely affected blocks.

For a Ganges River flood with a 25-year return period (a less frequent, more severe flood), the number of people affected is approximately 67 million (14 percent of the total basin population). Out of the total affected population of 66.95 million (about 52 percent male

FIGURE 2.8. Ganges Basin Risk Assessment: Most Severely Affected States/Blocks



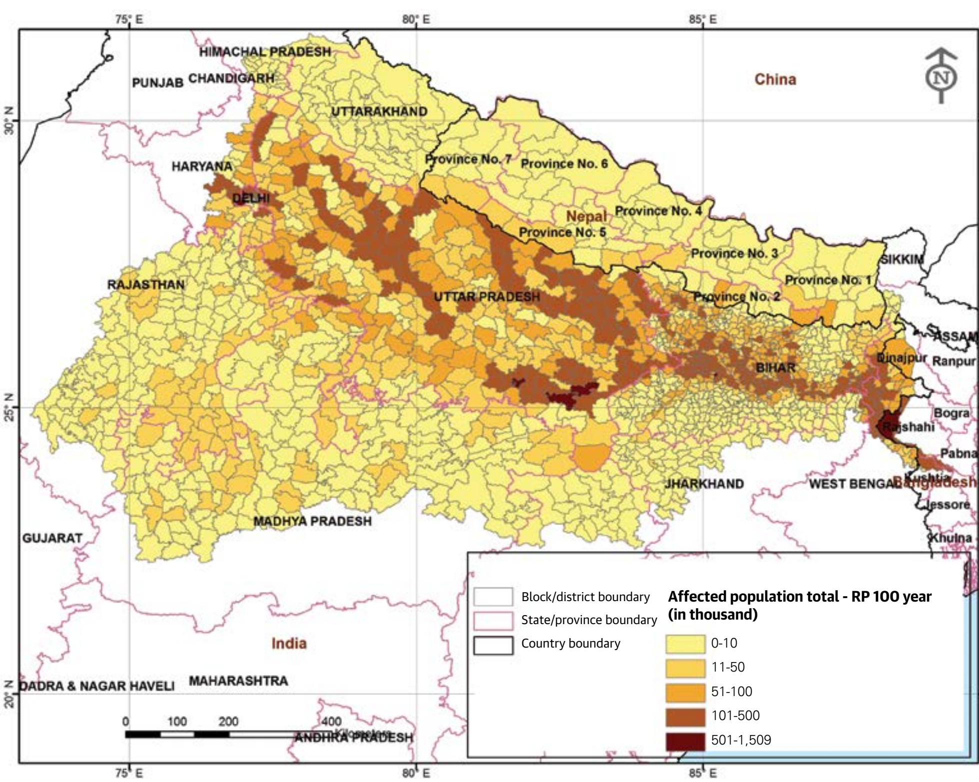
Source: Modified from Priya 2017, with contributions from RMSI.

and 48 percent female), an estimated 64.64 million persons (97 percent) are from India. Within this Indian subpopulation, 10.53 million are children (ages 0-6 years), 10.81 million are members of scheduled castes, and 0.87 million are members of scheduled tribes. About 5.03 million are girl children, 5.15 million are women from scheduled castes, and 0.42 million are women from scheduled tribes.

For a Ganges River flood with a 100-year return period (a major flood event), the number of people affected is approximately 73 million (16 percent of the total basin population; map 2.7). Out of the total affected population of 73.37 million (about 52 percent male and 48 percent female; figure 2.7), 70.75 million persons (96 percent) are from India. Within this Indian subpopulation, 11.54 million are children (ages 0-6 years), 11.89 million are members of scheduled castes, and 0.94 million are members of scheduled tribes. About 5.51 million are girl children, 5.67 million are women from scheduled castes, and 0.46 million are women from scheduled tribes.

Economic losses: Average annual losses. The AAL due to floods basin-wide is more than US$630 million. Almost all (96 percent) of these losses occur in India, especially the

MAP 2.7. Population Affected by a 100-Year Flood



Source: RMSI 2016.b

Note: The Ganges risk assessment mapped the populations affected by floods of various return periods. This example is for a 100-year flood. On the map, the darker the color, the greater the number of people affected. The total number of people estimated to be affected is about 73.37 million—roughly 16 percent of the total basin population. RP = return period.

TABLE 2.2. Average Annual Losses by Asset Class (Sector)

Exposure class	AAL, basin-wide (US$, millions)	Subbasins with highest AAL (% of basin total)
Residential buildings	410.7	Yamuna (30%) Lower Ganges (27%)
Commercial buildings	153.6	Lower Ganges (19%) Yamuna (18%)
Wheat	26.8	Ghagra (20%) Yamuna (17%)
Rice	17.0	Mahananda (27%) Lower Ganges (26%)
Other (miscellaneous) buildings	10.1	Lower Ganges (21%) Yamuna (19%)
Industrial buildings	3.7	Yamuna (44%) Lower Ganges (14%)
Road network	3.2	Middle Ganges (16%) Lower Ganges (14%)
Maize	2.8	Lower Ganges (32%) Kosi (11%)
Rail network	2.4	Lower Ganges (26%) Middle Ganges (17%)
Educational institution buildings	1.0	Lower Ganges (26%) Yamuna (22%)
Health care facilities	0.8	Yamuna (33%) Lower Ganges (23%)

Sources: RMSI 2016b.
Note: AAL = average annual loss.

downstream river states of Bihar (US$221 million) and Uttar Pradesh (US$205 million) (table 2.1). These losses are in line with public property losses reported for the Bihar floods of 2004 (approximately US$150 million).

The largest fraction of AAL (65 percent) is associated with damaged residential buildings (table 2.2). Commercial buildings also contribute significantly.

Most severe impacts: Bihar and Uttar Pradesh in India and some areas of Bangladesh. For a two-year return period flood, the following blocks and districts are among the most significantly affected: Patna Rural, Bihar, India, and Kushtia, Bangladesh, in terms of numbers of affected persons; Patna Rural and Dinapur-Cum-Khagaul, Bihar, India, in terms of residential building losses; Mohiuddinagar and Patepur, Bihar, India, in terms of commercial building losses; and Manikchak, West Bengal, and Mokameh, Bihar, India, in terms of industrial building losses. All of these losses are concentrated in the Lower Ganges subbasin.

Most severe impacts: The Lower Ganges subbasin. Flood disruption, damage, and losses are concentrated in low-lying areas of the Lower Ganges subbasin, which includes the Indian state of Bihar and parts of Bangladesh. Here, the flat topography allows even a two-year flood to spread over a vast swath of densely populated and extensively cultivated floodplain, thereby causing great damage. For a 100-year flood, overbank waters spread beyond the densely populated low-lying areas into sparsely populated outskirts. Thus, even though the 100-year flood depth is greater than the two-year flood depth, the resulting difference in disruption and damage is not proportional to the difference in flood discharge.

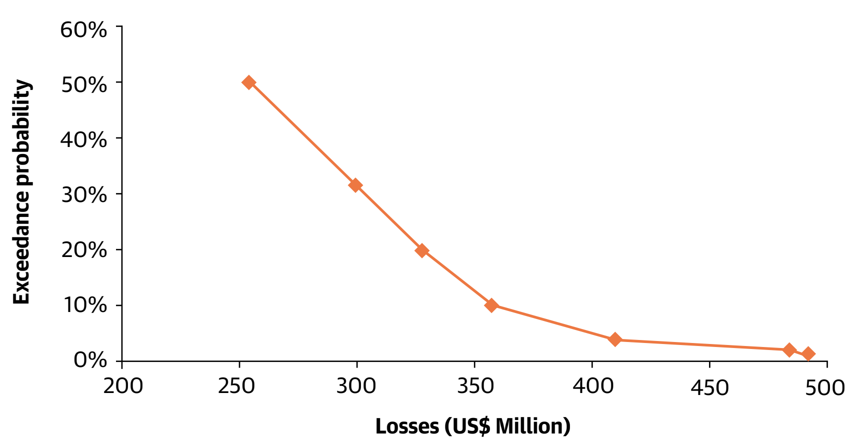
For a flood with a two-year return period, the affected Lower Ganges population is estimated to include approximately 8,000 people in Nepal, 717,000 people in Bangladesh, and 9,573,000 people in India. If these numbers are compared with the total population of the area of country lying in the subbasin, a clear picture emerges. This relatively mild flood is estimated to impact approximately one-tenth of the population living in the Nepalese portion of the subbasin, one-fifth of the population in the Indian portion, and nearly a third of the population occupying the portion in Bangladesh.

TABLE 2.3. Average Annual Losses within the Lower Ganges Subbasin by Asset Class

Exposure class	Exposure subclass	AAL (US$, millions)
Building	Residential	109.66
	Commercial	28.84
	Industrial	0.54
	Education	0.24
	Health	0.17
	Others	2.09
Infrastructure	Road	0.45
	Railway	0.60
Agriculture	Rice	4.29
	Wheat	1.93
	Maize	0.88
Total AAL of Lower Ganges basin		**149.68**

Source: RMSI, 2016a.
Note: AAL = average annual loss.

FIGURE 2.9. Loss Exceedance Curve for Lower Ganges Subbasin: All Assets



Note: The Ganges basin risk assessment determined that the Lower Ganges subbasin is the most severely impacted. The LEC for the Lower Ganges indicates that the probability of losses exceeding US$250 million within a single year is approximately 50 percent (a flood event with a 2-year return period). The probability of losses exceeding US$400 million in a single year is approximately 5 percent (a flood event with a 20-year return period). LEC = loss exceedance curve.

TABLE 2.4. Average Annual Losses within the Lower Ganges Subbasin by State or Province

Country	State/province	AAL (US$, millions)
Bangladesh	Kushtia	4.39
	Pabna	0.62
	Rajshahi	5.30
India	Bihar	119.32
	Jharkhand	3.83
	West Bengal	16.18
Nepal	Eastern Province	0.04

Source: RMSI, 2016a.
Note: AAL = average annual losses.

The Lower Ganges AAL is approximately US$150 million (table 2.3), with residential buildings contributing the greatest proportion (US$110 million, or nearly three-quarters of the total). Commercial buildings (US$29 million) and the rice crop (US$4 million) also contribute significantly. Figure 2.9 shows the LEC for the Lower Ganges subbasin.

Table 2.4 shows the state or province-level AALs within the Lower Ganges subbasin. The highest AAL, by far, occurs in Bihar—more than an order of magnitude greater than any other state or province in the subbasin. West Bengal in India and Rajshahi in Bangladesh also contribute significantly to the subbasin AAL (10.8 percent and 3.5 percent of the total, respectively).

According to media reports, the 2016 Bihar floods (along the main-stem Ganges) caused huge losses and damages—reportedly the worst in 10 years. The flood magnitude was not of a very high return period, but the damage was considerable and widespread. The primary reason, as noted above, was Bihar's gently sloping terrain and the concentration of extensive settlements and agriculture close to the river.

An important consideration for the Lower Ganges region is its extreme poverty. The monetary value of household assets (that is, individual economic exposure to floods) is very low, with some areas being poorer than Sub-Saharan Africa. As a result, floods that cause extreme suffering for the poorest of the poor do not show significant economic disruption and losses at the household level, even for return periods as great as 50 years. For a 100-year flood, the significant increase in estimated economic losses is driven by damage to high-value assets such as railways and roads. Impacts to agricultural assets are variable, depending in large part on flood duration.

Looking to the Future

According to the IWMI, global flood losses are expected to increase in the future—from more than US$100 billion to approximately US$450 billion by the year 2030. Large transboundary basins such as the Ganges and the Brahmaputra will contribute a significant share of these losses. Contributing factors include unplanned development, high population densities, modifications to the natural geography, and more frequent high-intensity rainfall events due to the changing climate. With these changing conditions, transboundary cooperation will become increasingly important.

Another important aspect of climate change is the increasing likelihood that the region may experience extreme weather events and climate conditions with no historical precedent. Flood risk assessments may therefore need to consider not only historical events but also the likely evolution of future conditions. Risk managers may need to consider the possibility of more catastrophic events in the future.

The Ganges basin risk assessment is static in the sense that it considers a "snapshot" of fixed assets in the basin (for example, roads and buildings) at a certain point in time, plus historical information about flood intensity. However, the framework of the analysis is, notably, *probability*-based. Because risks may change through time in response to climate change (among other factors), the Intergovernmental Panel on Climate Change (IPCC) views probabilistic risk assessment frameworks as an acceptable way forward for the consideration of climate change scenarios and climate risk management.

Policies to address uncertain risks—such as those that arise from climate change and future socioeconomic development—must be based on a robust but flexible approach. Adaptive management, wherein decisions are made as part of an ongoing science-based process, can be expected to become increasingly important in an era of rapid climate change combined with ongoing human-induced changes in the basin catchments. Adaptive management involves planning, acting, and then monitoring and evaluating outcomes. Adaptive management also incorporates new knowledge as it becomes available. This approach is already a core element of integrated flood management (see Section 1).

Recommendations for Further Risk Assessment Improvements

This risk assessment, though comprehensive, can in the future be further refined. Recommendations to improve the Ganges basin risk assessment include the following:

- Improve data availability
- Include additional asset classes (for example, bridges, pipelines, livestock) and losses due to business disruption
- Further analyze the sector-specific economic impacts of weather-related disasters
- Give greater consideration to social vulnerability and the adaptive capacity of people living in flood-prone areas
- Identify optimal mitigation measures for specific sites that are vulnerable to flooding

Additional technical recommendations can be found in the original RMSI risk assessment report (RMSI 2016a).

Even without additional refinement, the current findings can be used to address urgent needs—by applying the assessment results in management planning and resilience building by stakeholders.

Concluding Remarks

The findings of this risk assessment can help policy makers, disaster management authorities, and district and block development officials to minimize flood losses and flood impacts. Quantitative details and local-scale maps are available in the final technical report and the accompanying risk atlas. These resources show not only the areas that are highly flood prone but also the assets that are at risk. The results are expressed in terms of AAL, LECs, and thematic risk maps. As such, the results can help officials to identify priority areas for immediate flood-mitigation and risk-reduction activities, including flood forecasting.

Highly vulnerable areas of the Ganges River basin include the states of Bihar and Uttar Pradesh in India, as well as areas of Bangladesh. Many of these vulnerabilities—in terms of numbers of people affected and in terms of losses to various asset classes—are concentrated in the Lower Ganges subbasin.

The most severely affected subbasin, in terms of both affected population and flood losses, is the densely populated Lower Ganges. This subbasin is flood prone due to its downriver location and flat topography. The downriver location also gives the Lower Ganges subbasin the advantages of a potentially longer lead time for flood forecasting and warning. Longer lead times are most valuable in cases where flood risk is very high—for example, at the downstream part of the subbasin. Advance warning provides time for authorities to evacuate people, to better plan, and to protect critical assets from flood losses.

The Lower Ganges subbasin is therefore an ideal candidate for future flood mitigation and flood forecasting work. Other priority subbasins might include the Kosi, Bagmati, Ghagra, Gandak, Kamla-Balan, Middle Ganges, and Mahananda. These areas, too, are highly prone to devastating floods each year or at least every other year. A skillful flood forecasting system for these subbasins would be useful to the people, local authorities, and monetary organizations of the region. As an initial measure, flood protection measures could be provided along river banks.

Comprehensive flood risk assessment at the subbasin level goes hand in hand with flood forecasting. The risk assessment makes a strong case for operational flood forecasting in the Ganges subbasins that are extremely vulnerable to floods of low return period (that is, relatively frequent flooding). Risk assessment and flood forecasting are both essential components of a people-centered, end-to-end flood risk management and early warning system. Together, they can be used to give a broader, clearer picture of flood risk in the entire Ganges basin and to facilitate the estimation of potential damages.

Comprehensive flood risk assessment and flood forecasting are needed by public and private institutions across a variety of socioeconomic sectors. As demonstrated here, the scope of a flood risk assessment can include losses in terms of numbers of people affected; physical damage to residential, commercial, and public infrastructure; and losses to agriculture. Such information has many applications. For example, a forward-looking residential organization such as a housing society may require a flood risk assessment during a project's planning and management phase. Public disaster management institutions must have adequate information to demarcate flood-prone areas, manage land use and land development, develop flood control measures, alert public and acting authorities to impending flood threats, define zones of action during a flood, and then finally estimate damages after the flood. Small- and medium-size organizations need probable estimates of loss to direct human and financial resources to deal with flood disasters, whereas large companies and institutions may look at the overall effects of flood risk on their organizational systems. Agriculture sectors depend heavily on measures taken and warnings issued by public sector organizations. Risk assessment is central to the insurance industry and other financial planning agencies.

A comprehensive flood risk assessment and forecasting system, bolstered by cooperation from relevant institutions, would greatly aid in the mitigation of adverse flood effects. Such information, especially at the state or subbasin levels would also facilitate planning and management for the optimum utilization of water resources and the development of early flood warning systems.

A comprehensive flood risk assessment and forecasting system would also consider the evolution of flood risks and flood characteristics through time in response to climate change and human alterations in basin catchments. Such a system would include the ability to incorporate new knowledge as it becomes available. The risk assessment methods and forecasting developments highlighted in this report are probability-based and are therefore well suited to incorporate consideration of changing flood characteristics through time.

Detailed map-based risk assessments could be usefully initiated for other river basins in the region. Because every basin is unique, it is difficult to provide a detailed roadmap for the process. Nevertheless, the Ganges procedures might be useful in other basins; details are provided in the original technical report (RMSI 2016a). Important considerations in launching a risk assessment include the urgency of need, as well as the constraints of available funding, time, and data. The Brahmaputra River basin—known for its complex topography, very high annual rainfall (in some areas), and frequent flooding—would be a sensible next candidate.

People cross a makeshift bridge across the Kosi River in Bihar. Accurate rain and flood forecasts are very important in such places, so that people can be evacuated to higher ground in the event of a flood.

Section 3 Improving Flood Forecasts through Innovative Modeling and Data Incorporation

Introduction

Anticipating and preparing for the arrival of floodwaters is a proven cost-effective option for minimizing flood damage. According to the Asian Development Bank's Early Warning Study (as reported by Subbiah et al. 2008), for small famers in Bangladesh:

- A one-day flood-warning lead time yields estimated damage reductions ranging from 1 percent (reduced losses of chickens and ducks) to 33 percent (reduced losses of cultured fishes).
- A seven-day flood-warning lead time yields estimated damage reductions ranging from 15 percent (for school or office settings) to 90 percent (for household settings); estimated reductions for the agricultural and cultured-fisheries sectors are about 70 percent.

Longer warning times go beyond saving lives to ensuring livelihood support (box 3.1).

In 2007, Bangladesh experienced moderate floods (return period of five years). According to a 2009 background paper prepared for the World Bank (Teisberg and Weiher 2009), a forecasting and early warning system for these floods could have reduced damages by an estimated US$207.9 million. The sources of these benefits would have been the evacuation of movable assets, including livestock, plus the early harvesting of crops, fishes, and shrimp. The estimated benefits over a decade of typical flooding would amount to approximately US$1,700 million—more than 500 times the cost of the hypothetical forecasting and warning system.

BOX 3.1. Flood Forecast Warning-Time Considerations

Flash flood and short-range forecasts	→	Useful for saving lives and some assets
Medium-range flood forecasts (3–15 days)	→	Useful for preserving additional livelihood assets
Monthly and seasonal flow outlooks	→	Useful for sectoral planning (for example, agriculture, hydropower)

The longer the forecast lead time, the greater the forecast uncertainty. ESCAP therefore recommends to complement longer-lead (less certain) flood forecasts with shorter-range (more certain) forecasts.

Sources: Haque 2016; ESCAP and RIMES 2016; ESCAP 2016a; T. Hopson, NCAR.

Several groups are currently working to improve flood forecasts and increase flood warning times for the South Asia region.

This section reports on recent advances from a Ganges-Brahmaputra project at the National Center for Atmospheric Research (NCAR), United States.

A fuller description of the NCAR project is available in this publication: *Evaluation of Flood Forecasting Predictability: Technical Report* (Hopson and Priya 2017).

NCAR flood forecasts, data, and maps are available online on this website: World Bank - South Asia Water Initiative: Ganges and Brahmaputra Hydrometeorologic Predictability (http://indiawbg.rap.ucar.edu).

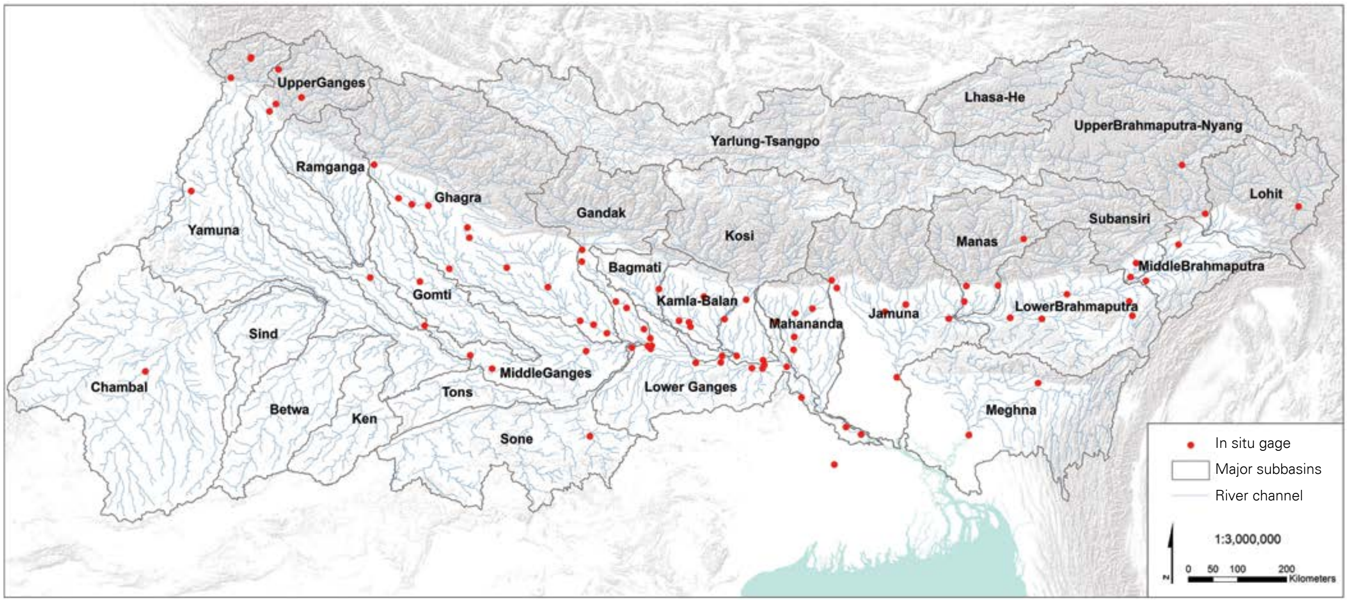
Addressing Gaps in Transboundary Flood Forecasting

Following up on regional assessments of operational flood capacity, NCAR conducted a technical study to develop and evaluate an advanced lead-time flood forecasting system for the Ganges, Brahmaputra, and Meghna rivers. The focus was on riverine flooding. Flash floods are inherently more difficult to predict, especially with long lead times.

The NCAR project included:

- Assessment of foundational data sets, with a focus on satellite-derived data and numerical weather prediction
- Integration of these data sets into an enhanced forecasting scheme, including an emphasis on operational forecasts for societal benefit
- Online posting of data and forecast files and web displays (visualizations), for potential benefit to on-the-ground operations and decision making
- Assessment of the overall skill of the system in forecasting river flooding

MAP 3.1. **NCAR River Forecast Locations**



Source: Modified from Hopson and Priya 2017.

Note: NCAR provides operational river forecasts for 87 locations across the Ganges-Brahmaputra-Meghna basins. The red dots show the forecasting sites (which coincide with river-gauge sites). The flood forecasts are available online: http://indiawbg.rap.ucar.edu/display/.

This work contributes to the broader body of ongoing efforts to strategically improve forecasting capacity in the region.

The NCAR flood forecasting system now provides 1- to 16-days-in-advance water-level forecasts for 87 river locations across the Ganges-Brahmaputra-Meghna (GBM) river basins (map 3.1). NCAR built significant new capabilities into an existing forecasting scheme and quantitatively evaluated the resulting gains in forecasting skill. The forecast locations are in Nepal (1), Bangladesh (4), and India (82). All of the stations in Bangladesh are near the India-Bangladesh border: one on the Brahmaputra River, one on the Ganges River, and two on the Meghna River.

- The NCAR forecasts are available here: http://indiawbg.rap.ucar.edu/display/.

NCAR also provides online access to near-real-time rainfall maps and other flood-related products. In support of transboundary knowledge sharing and data transparency, the NCAR flood forecasts and much of the supporting data are accessible to anyone with Internet access.

- Maps of predicted and observed rainfall are available here: http://indiawbg.rap.ucar.edu/precip/india.php.
- Water-level data are available here: http://indiawbg.rap.ucar.edu/display/.

NCAR developed methods to improve their GBM flood forecasts. These methods can also be used in other river basins and by other forecasters working in South Asia and elsewhere. Specifically, NCAR determined that flood forecasts can be improved through the input of multiple ensemble weather forecasts and multiple rainfall data sets, as well as the use of automated data-quality control and new observational techniques.

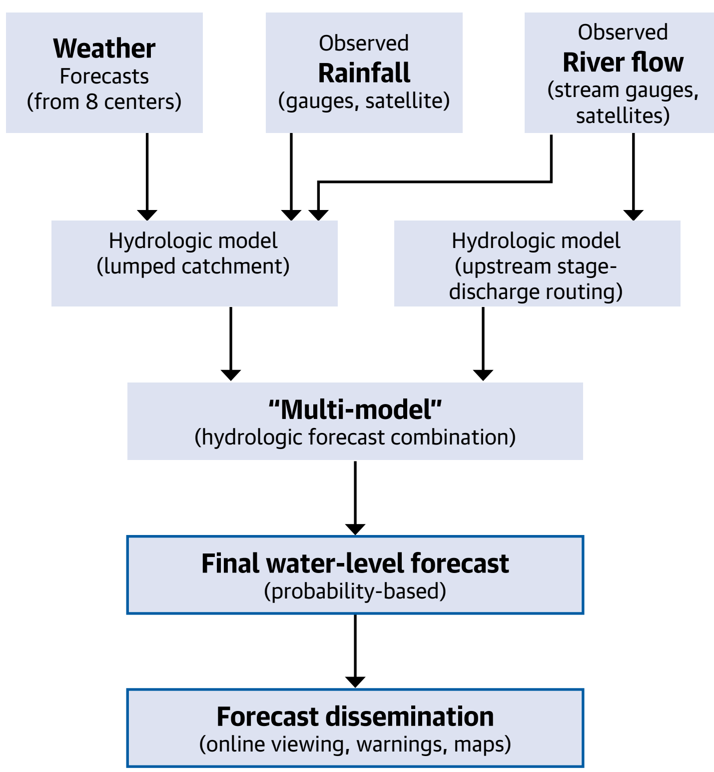
The following pages highlight selected aspects of the NCAR flood forecasting work.

Overview of the NCAR Flood Forecasting Scheme: Technical Aspects

Flood forecasting is a multistep process, with each step providing opportunities for improvement. The NCAR forecasting scheme (figure 3.1) builds on the Climate Forecast Applications for Bangladesh (CFAB) model to provide these new capabilities:

- Integrate ensemble forecasts from a greater number of global forecasting centers (increased from 1 to 8).
- Handle new, irregular, and intermittent data sets, with automated data quality control.
- Introduce new statistical forecasting, correction, and mapping techniques.
- Incorporate recent research that relates upstream river-stage observations to downstream (time-lagged) river flow.
- Produce output for a wide range of river basin scales and forecasting sites.

FIGURE 3.1. The NCAR Flood Forecasting Scheme for the Ganges and Brahmaputra Basins



Source: Modified from Hopson and Priya 2017.

Note: The NCAR "blending" flood forecasting scheme for the Ganges and Brahmaputra basins relies on multiple data sources and multiple internal models.

Rainfall is the driving force behind most South Asia floods, especially in lower basin reaches. Therefore, the flood forecasting process starts (figure 3.1) by looking at weather-center predictions of rainfall for the next two weeks, rainfall measurements during the preceding weeks, and various measures of river flow. Computer models and statistical methods then blend and process that information to produce a set of river forecasts for selected locations. Finally, the forecasts and some of the underlying data are packaged for dissemination to water-resources agencies, decision makers, and other stakeholders.

The NCAR forecasting scheme is unique in its reliance on "blending" techniques and redundancy safeguards. Specifically, the scheme is unique in its use of multiple probability-based rainfall forecasts, multiple sets of rainfall observations, and multiple internal forecasting models.

- *Blending techniques.* This approach is useful because strengths in one weather forecast or data set can compensate for weaknesses in another (figure 1.6).
- *Redundancy safeguards.* Having duplicate data sources helps to guard against system failure. If one instrument goes down—for example, if a satellite stops transmitting rainfall data—others are still available to guide the flood forecast.

The NCAR operational forecasting scheme provides short- to medium-range forecasts, with lead times ranging from one day to two weeks. Lead times of this length are useful for saving lives and preserving livelihood assets (box 3.1; table 3.1). NCAR focuses on riverine flooding (box 1.1), but some of the rainfall data and maps may also be useful for flash flood warnings (figure 1.6).

Probability-Based Information for Decision Making

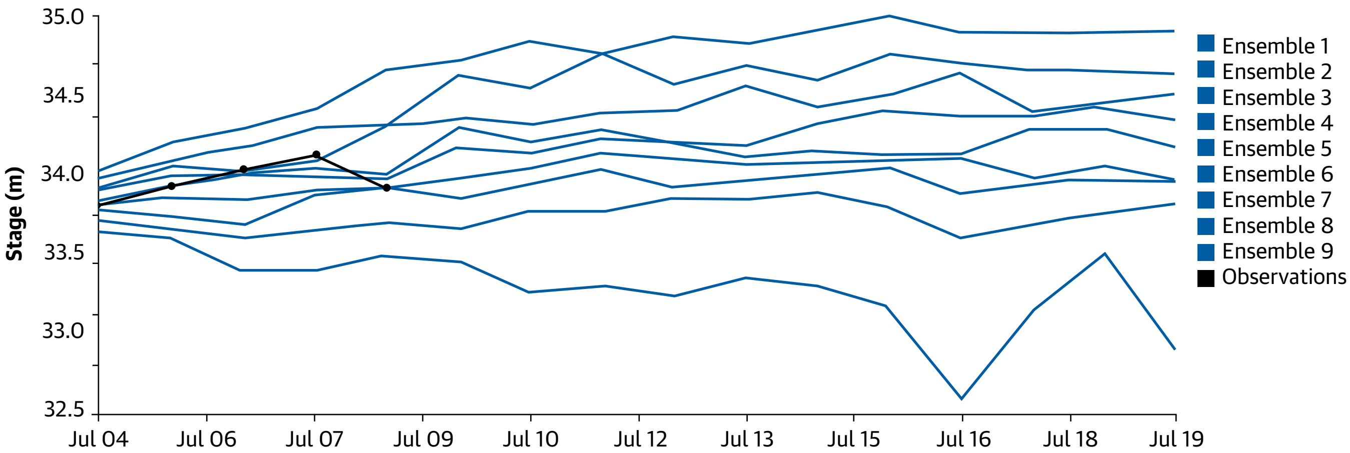
The NCAR flood forecasts are probability-based ("ensemble") forecasts, which provide extra information that is useful to decision makers. In an "ensemble"-type forecast, the predictions of river conditions are expressed as a collection (ensemble) of forecasts (figure 3.2). These calibrated collections express the likelihood (probability) that future water

TABLE 3.1. Forecast Lead Times Required for Community-Level Decisions

Lead time	Decisions
1 week	*Households:* Collect vegetables, bananas? Withdraw money from microfinancing institutions? *Char*[a] *households:* Store dry food, drinking water? Seek temporary shelter? *Fishers:* Protect fishing nets? *Disaster management committees:* Distribute water purification tablets?
10 days	*Households:* Store dry food, drinking water, food grains, firewood? *Farmers:* Harvest the broadcast Aman[b] rice crop early? Delay planting of the transplant Aman? *Fishers:* Harvest freshwater fish from small ponds?
20–25 days	*Disaster management committees:* Plan evacuation routes and boats? Make arrangements for women and children?
Seasonal	*Farmers:* Crop-system selection? Area of transplant Aman and subsequent crops? Sell cattle, goats, or poultry?

Sources: Modified from ESCAP and RIMES 2016; original source: RIMES, based on community-level surveys in Bangladesh.
Note: a. In Bangladesh, *chars* are sand or silt river islands.
b. The Aman rice harvest occurs in November and December.

FIGURE 3.2. **NCAR Ensemble Flood Forecasted Stage at Baltara**



Source: NCAR. Based on screenshot from http://indiawbg.rap.ucar.edu/display/.

Note: The NCAR flood forecasts are actually collections (ensembles) of individual member forecasts. The group as a whole conveys information about not only future water levels but also the appropriate level of confidence in the forecast. In this redrawn screenshot, the forecast outlook is for 16 days (from early July, 2017), and each blue line represents one member of the forecast ensemble. The *spread* of the blue lines indicates forecast uncertainty. Typically, near-term forecasts are more certain than longer-term forecasts—as indicated by the tight bunching of the blue lines for the early days of the forecast. The envelope of blue lines also indicates *probabilities*, which is useful for decision making. A download button (not shown here) allows users to download the forecast in table form. This example is for the Baltara stream-gauge station on the Kosi River in India.

levels will fall within a certain range or above or below a certain threshold. This type of information is especially useful for deciding whether to respond to a possibly developing flood event—and if so, how.

Ensemble-type forecasts inherently express the level of confidence that is appropriate for each forecast. Tightly clustered ensemble members indicate a higher degree of confidence (figure 3.2). The wider the spread, the greater the forecast uncertainty and the lower the confidence.

In other words, this type of forecast reports not only the most likely water-level value but also the *likely range*. Consider a flood forecast that predicts that next week's water level will be 70 meters. A 70-meter forecast with an accompanying (narrow) probable range of 69–71 meters is very different from a 70-meter forecast with an accompanying (wide) probable range of 60–80 meters—especially if the danger level is 75 meters. Knowing not only the most likely value but also the likely range helps people to make better-informed decisions.

Figure 3.2 illustrates an important forecasting principle: uncertainty (typically) increases as the forecast extends farther into the future.

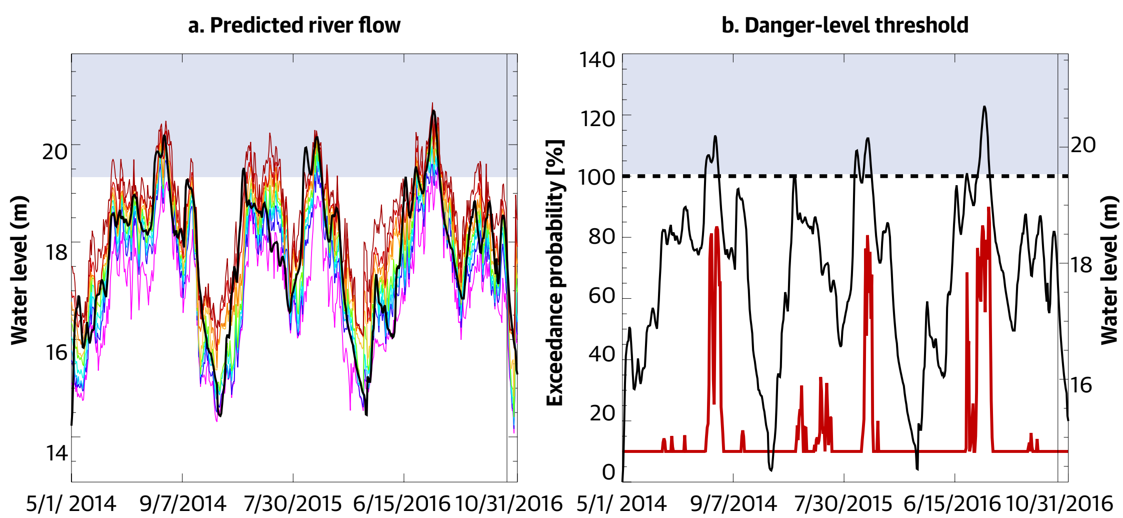
Ensemble-type forecasts inherently express danger-level probability. In other words, this type of forecast does not answer the question, "Over the next three days, is the river predicted to flood above the danger level—yes or no?" Instead, this type of forecast answers the question, "Over the next three days, what is the probability that the river will flood above the danger level?" Knowing whether the probability is 10 percent or 90 percent helps people decide when to take action (or not) and to judge what actions (if any) might be most appropriate.

Panel a of figure 3.3 shows the 12-day-ahead ensemble forecast for the Bahadurabad stream gauge during three monsoon seasons, 2014–2016. The thin colored lines show the individual members of the forecast collection (ensemble). The blue area shows the "critical discharge" (danger) flood level. The solid black line shows actual river flow. Every year danger-level floods were predicted (when the colored lines enter the blue zone), and every year danger-level floods did occur (when the black line enters the blue zone).

Panel b of figure 3.3 shows a different type of flood forecast. Here, the red line shows the 12-day-ahead predicted probability (likelihood) that river flow would exceed Bahadurabad's danger-level threshold. The predicted likelihood of a dangerous flood was very low most of the time. Then the likelihood increased sharply on three occasions. Disaster-preparedness officials can use this type of forward-looking "how likely?" information to help fine-tune their flood warnings and preparations.

Ensemble-type forecasts can map directly to decision-making considerations, including economic decision making. The value of a flood forecast depends not only on forecasting skill but also on how people use the forecast. For example, risk management officials must decide at what point public warnings should be issued and what recommendations

FIGURE 3.3. Forecasts for Bahadurabad (Brahmaputra River) for Three Monsoon Seasons (2014–16)



Source: T. Hopson, NCAR. Based on data from the Flood Forecasting & Warning Centre of Bangladesh (http://www.ffwc.gov.bd).

Note: Panel a shows one type of flood forecast: What is the predicted river flow 12 days from now? Each thin colored line represents one forecast ensemble member (12-day lead time), and the black line shows the actual (observed) water level. The blue area represents the "critical discharge" level (danger level). Panel b shows another type of forecast: What is the likelihood of exceeding the danger-level threshold 12 days from now? The red line shows the forecasted probability, and the black line shows actual water level.

should be made. For individual residents, many considerations go into deciding whether to act on a flood warning or not: Is my livelihood or life threatened? How much will it cost me to respond to the warning? How much damage might I incur if I ignore the warning? Probability-based forecasts can help people to make these decisions.

As a simple example, consider a community that farms large fields of paddy (rice). In 10 days, the rice will be fully mature and can be sold for US$100—but the 10-day flood forecast indicates a 60 percent chance of the nearby river flooding and ruining the crop during that time (table 3.2).

- Should the community act, given the 60 percent probability that the river will flood? Harvesting early comes with a cost: lower crop yield and quality, plus a longer drying time. The harvested crop will be 100 percent safe but worth only US$70.
- Should the community not act, given the 40 percent probability that the river will not flood? If the river stays within its banks, the crop will be worth US$100. But if the river does flood, the community loses everything.

If the flood forecasting model is properly calibrated, then the forecast probabilities provide guidance for these questions. For the scenario in table 3.2, simple mathematical calculations lead to the following conclusions:

- The community that consistently plays it safe and harvests the crop early will, over time, realize an average profit of US$70 per event.
- The community that consistently takes a chance and leaves the crop in the field will, over time, realize an average profit of US$40 per event.

The bottom line is that under these conditions, acting on the flood warning makes good economic sense.

But what about other conditions and other scenarios? More general insight comes from considering, for a given forecast user, the ratio of (a) the cost of acting on a flood warning to (b) the loss incurred by not acting and then losing assets to the flood. As a simple example, consider users at two extremes:

TABLE 3.2. Example of Flood-Related Decision Making

	Community acts (US$)	Community does not act (US$)	
		River does not flood	River does flood
Sale price of mature crop	100	100	100
Reduced yield and quality due to early harvest	−25	n.a.	n.a.
Additional drying time due to early harvest	−5	n.a.	n.a.
Loss of crop to floodwaters	n.a.	n.a.	−100
Net profit	70	100	0
Long-term average profit per event, for acting versus not acting	**70**	**40**	

Sources: T. Hopson, NCAR. Inspired by ESCAP and RIMES 2016.
Note: The table shows an example of decision making for a scenario of a 10-day flood forecast indicating a 60 percent probability of river flooding. n.a. = not applicable.

- Acting on a warning costs little, but the user's potential losses are high: this person will be inclined to act on a danger-level warning even if the probability of flooding is low.
- Responding to a warning is expensive compared with the user's potential losses: this person will be inclined to wait until the probability of flooding is high.

In fact, the break-even danger-level probability for any user to act on is theoretically equal to their cost-to-loss ratio. In the case of the rice-growing community of table 3.2, the cost of acting on the flood warning is US$30. The loss incurred by not acting and being flooded is US$100. So the community's cost-to-loss ratio is 0.3. Over the long term, then, the community will benefit economically by acting on a flood warning (harvesting early) whenever the danger-level probability is higher than 30 percent. When the danger-level probability is less than 30 percent, the best strategy is to leave the crop in the field.

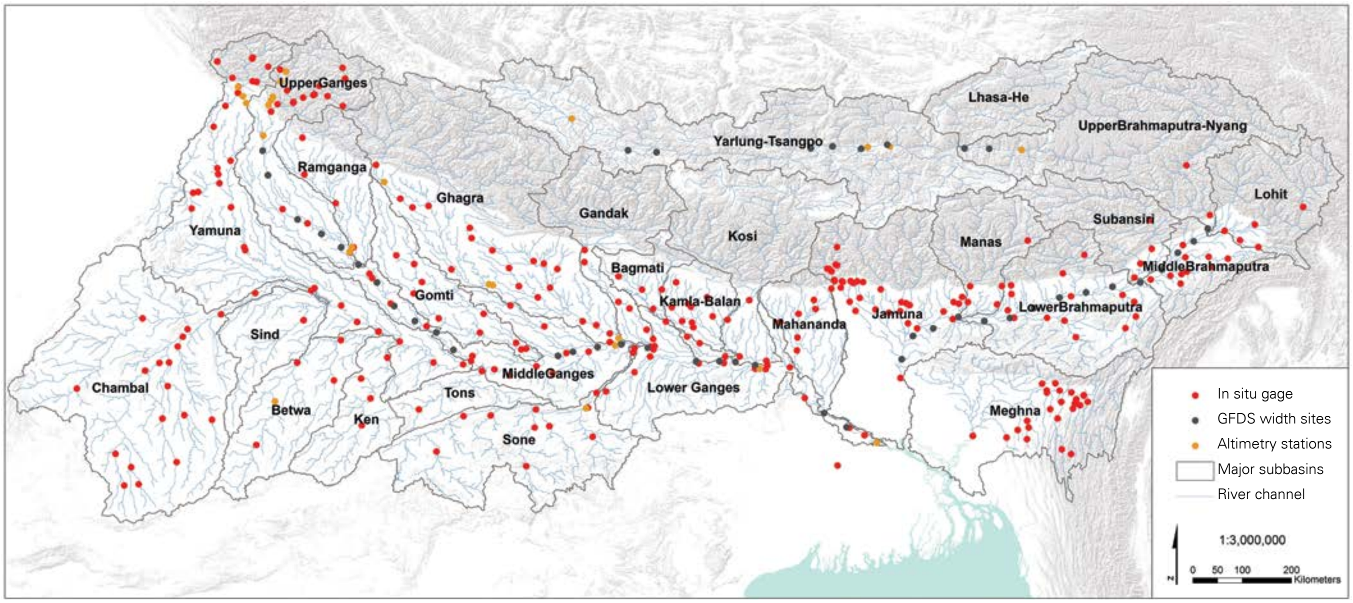
Ensemble-type (probability-based) flood forecasts can provide objective guidance for decision making. This hypothetical rice harvest example, though highly simplified, illustrates how probability-based flood forecasts can be used to provide objective guidance for making decisions. In "real life," similar principles—but with more sophisticated calculations—would be used. Similar considerations can be applied to flood-related choices in other sectors—for example, decisions about dam management or the relocation of livestock. Because of the usefulness of links like these, calibrated probabilistic flood forecasts are being increasingly used to guide objective decision support systems and to provide helpful visualizations related to flood risk.

Evaluating the Utility of New Forecasting Methods

Many types of information can be useful in predicting river conditions (figure 1.6). NCAR therefore evaluated and refined several tools relevant to its flood forecasting scheme, in the following ways:

- Developed a method to optimally site rain gauges
- Developed protocols to retrieve and process hourly data from hundreds of stream gauges (map 3.2)
- Identified appropriate stream-gauge locations to serve as forecasting locations (map 3.1)
- Developed methods to estimate river flow from measurements of river water level ("river height") (see http://indiawbg.rap.ucar.edu/RateFit/)
- Developed methods to predict river flow based on measurements of upstream water levels
- Evaluated accuracy of satellite-derived rainfall measurements and utility of satellite-based estimates of upstream river level and width
- Developed automated quality-control procedures for incoming data
- Developed methods to blend and calibrate rainfall and river forecasts, in order to produce flood forecasts tailored to specific catchments

MAP 3.2. NCAR Flood Forecasting Input: Multiple Sources of River Data



Source: Modified from Hopson and Priya 2017.

Note: The NCAR flood forecasting scheme incorporates multiple types of river data from across the Ganges, Brahmaputra, and Meghna basins. The red dots show the locations of the river gauges, which are maintained by India's Central Water Commission (CWC) and Bangladesh's Flood Forecasting & Warning Centre (FFWC). Gold dots mark the locations where satellite data are used to estimate river levels. Black dots mark the locations where satellite data are used to estimate river widths.

Many of these NCAR developments can be used in other basins or other forecasting models. Full details are available in the original technical report (Hopson and Priya 2017). Selected findings are highlighted below.

Producing local, multi-model flood forecasts. Not all catchments are the same. NCAR therefore developed an automated procedure to gather and blend input from a variety of sources, to produce "multi-model," catchment-specific, calibrated ensemble forecasts of future rainfall and stream flow:

- *Blending* multi-model input is important because the resulting forecasts are generally more skillful than forecasts that rely on only a single input.
- *Catchment-specific weighting* is important because some weather centers perform better for some catchments than others (the weighting is based on past performance).
- *Calibration* is important because it removes biases in the data and attaches an accurate estimate of likelihood to future rainfall or river conditions.

Measuring rainfall from space. A rain gauge can accurately measure rainfall at one particular point, but flood forecasting requires estimates from a large area. Satellites provide a basin-wide view and can help provide necessary information where rain gauges alone are insufficient.

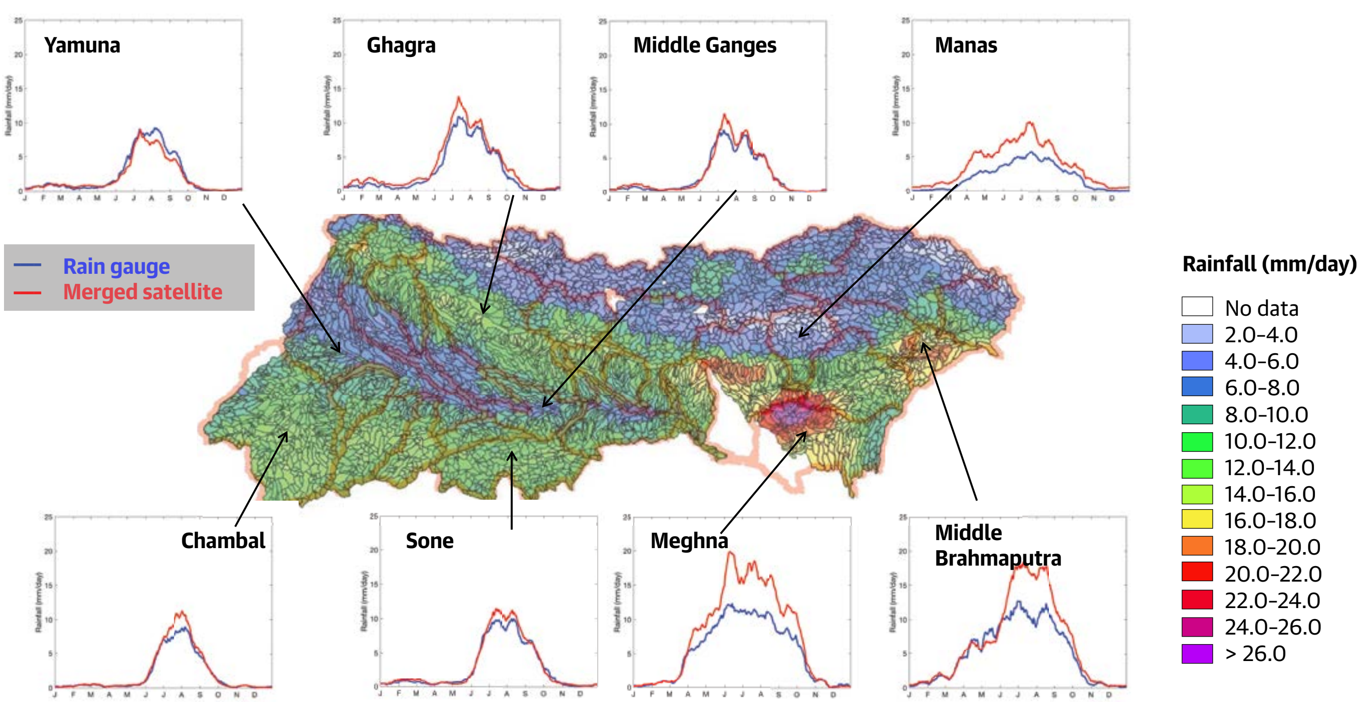
Satellite observations of rainfall are especially valuable where rain gauges are widely spaced or where data sharing is limited. For large areas of the Ganges and Brahmaputra basins, especially outside of India, ground-based measurements of rainfall are spaced far apart. Obtaining adequate rain-gauge data can be especially challenging in mountainous regions, where close spacing is required but the terrain is difficult to work in. Cost can also be a limiting factor. In some cases, rain-gauge data may be collected but may not be freely available to others. Satellite rainfall estimates (map 3.3) are therefore important for producing skillful flood forecasts throughout the basin catchments. The NCAR forecasting scheme uses rainfall measurements at scattered points (rain-gauge locations) across the basin, as well as basin-wide satellite-based rainfall estimates from three different organizations.

Satellite measurements complement but do not replace rain gauges. For specific (small-scale) locations, rainfall estimates from satellites are far less accurate than rain-gauge measurements.

Finding: Blending rainfall measurements from multiple sources can improve flood forecasts:

- Rain gauges work best (are most accurate) when used to represent rainfall over small areas.

MAP 3.3. NCAR Flood Forecasting Input: Rainfall Data



Source: Modified from Hopson and Priya, 2017.

Note: The NCAR flood forecasting scheme uses rainfall data from rain gauges and from satellites to help predict river flow. The map colors show average August rainfall, which ranges from less than 2 millimeters per day (white) to more than 26 millimeters per day (purple). The small graphs, which show average rainfall over the course of a year, illustrate that the estimates of rainfall from rain gauges (blue lines) and satellites (red lines) are mostly similar (January–December averages, 2000–15). The agreement is less good within basins where rain gauges are widely spaced (Meghna, for example).

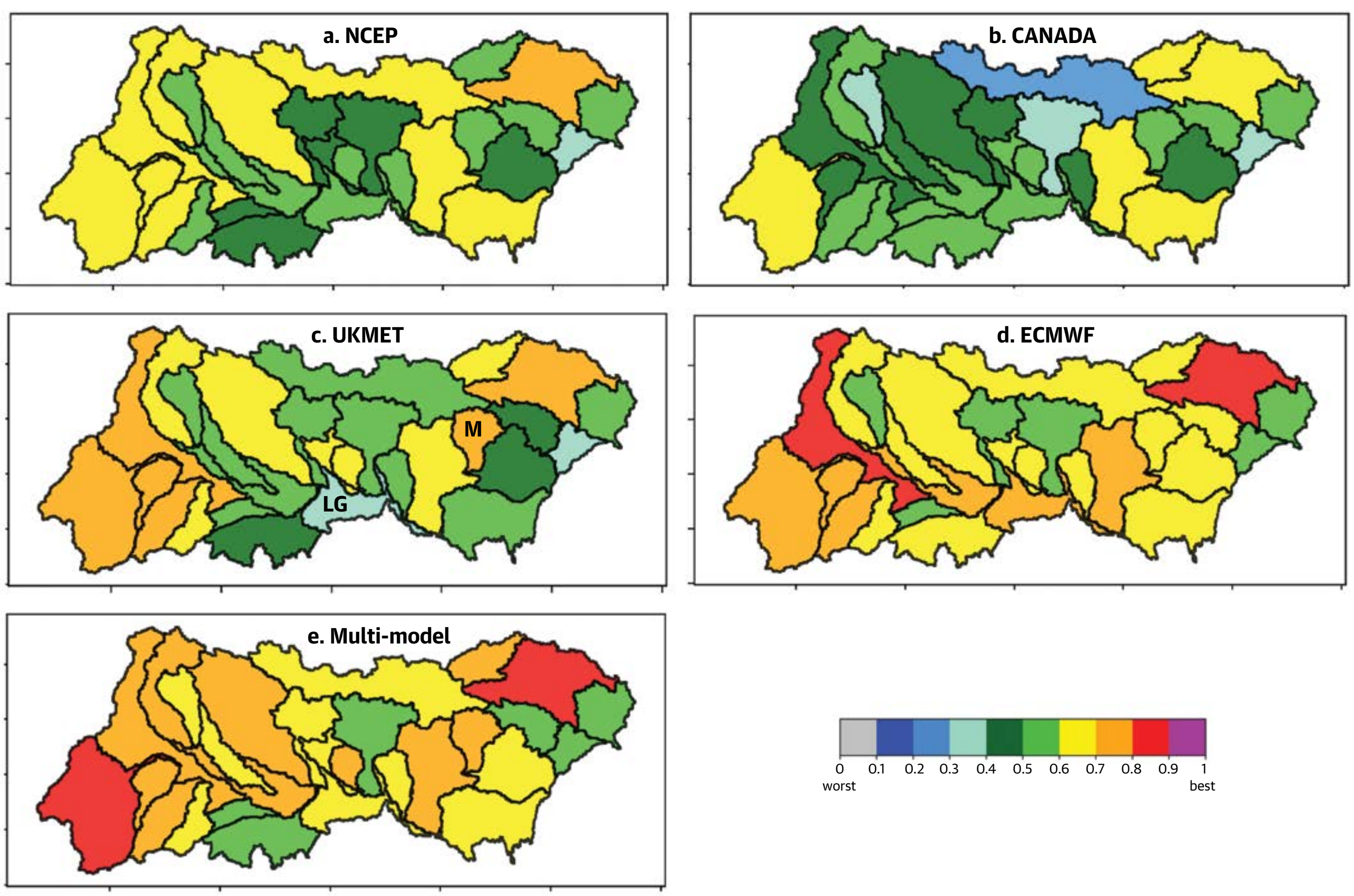
- Satellite-based rainfall estimates work best for larger areas where rain gauges are sparse.
- Blending estimates from multiple institutions reduces overall error.

Blending global weather forecasts. The NCAR flood forecasting scheme uses ensemble rainfall forecasts from eight weather centers around the world (which generate more than 300 ensemble members daily). The NCAR flood forecasting scheme is one of the world's first to incorporate information from so many different weather centers.

Finding: Blending rainfall forecasts from multiple weather centers can improve flood forecasts and provide longer lead times:

- Optimally combining weather forecasts leads to better flood forecasts with roughly two additional days of warning time beyond the skill of the single best model.
- The best mix of weather forecasts is different for different catchments, with no one center always performing best (map 3.4).
- ECMWF provides the single best overall forecast for this region, on average (map 3.4).

MAP 3.4. Blending Rainfall Forecasts from Different Weather Centers



Source: Emily Riddle, NCAR.

Note: Flood forecasts can be improved by using different rainfall forecasts for different catchments. Panels a–d show evaluations of rainfall forecasts from four different weather centers, each evaluated within individual catchments. The "hotter" the color, the better the rainfall prediction. For example, the UKMET forecast provides the best predictions for the Manas (M) catchment but the worst predictions for the Lower Ganges (LG) catchment. The single best overall forecast is the ECMWF. Panel e shows the results for a "multi-model" blended (simple average) forecast. In most catchments, the multi-model forecast is the best choice—as good as or better than the single best center.

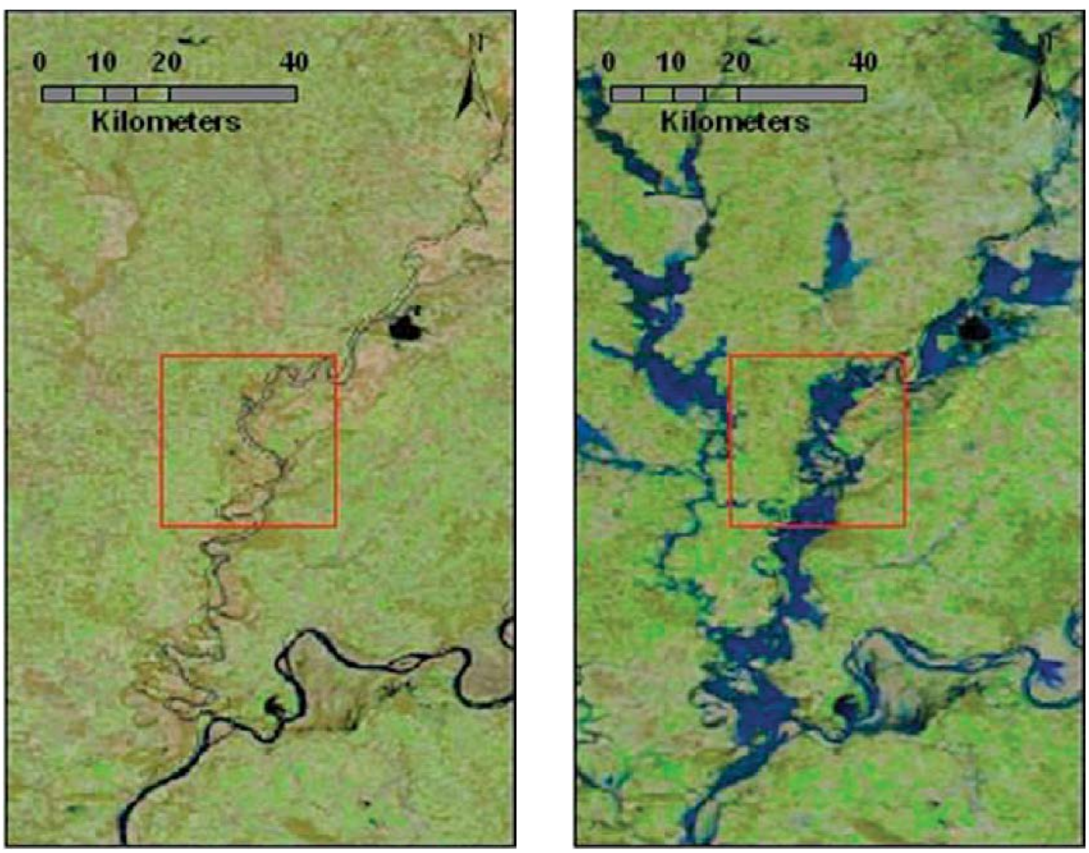
Using satellites to monitor river level and width: To help predict future water levels, NCAR combines information about upstream river conditions with estimates of water travel times (map 1.2). NCAR therefore evaluated the usefulness of incorporating different types of river data from locations upstream of the forecast sites:

- River level measured by stream gauges
- River level estimated by satellite (new)
- River width estimated by satellite (new)

Map 3.2 shows the locations of the satellite-based estimates. Figure 3.4 illustrates the concept of the new estimates of river width.

Information about upstream river conditions can be especially useful where rainfall is difficult to measure—for example, in areas of steep terrain. River-condition data from satellites are particularly useful for monitoring locations between stream gauges, as well

FIGURE 3.4. Satellite Estimation of River Width



Source: Robert Brakenridge, University of Colorado. Used with permission, from R. Brakenridge.
Note: Satellite-derived measurements of river width can be useful in forecasting later water levels at a downstream location. Satellite (microwave emissivity) measurements within the red box can differentiate the extent of inundation seen in these two example images from the Wabash River (United States). Map 3.2 shows where these types of measurements are made in the GBM basins.

as locations where data sharing may be slow or nonexistent. Even where stream gauges are closely spaced, satellite measurements can provide a helpful layer of redundancy.

Satellite measurements complement but do not replace stream gauges. Stream gauges are especially valuable because forecasters use them not only to generate river forecasts but also to evaluate new forecasting methods. Stream gauges must be accessible, calibrated, and regularly maintained. To be most effective, site-specific guidance must be used to convert gauge measurements of water level ("river height") to estimates of river discharge.

Finding: The new satellite-derived estimates of river water level ("height") yield significant benefits. NCAR has therefore developed routines to use this information in its flood forecasts. An improved satellite mission is scheduled to launch in about 2020 (the Surface Water and Ocean Topography mission).

Finding: The new satellite-derived estimates of river width range from useful to not useful, depending on location. Operational use of these measurements is promising but must include strict quality control. Overall, the satellite measurements of upstream river width can enhance forecast accuracy and are used routinely in the NCAR scheme.

Evaluating NCAR Forecast Skill and Reliability

There are many different ways to assess the skill and reliability of a flood forecasting system. A few examples are presented here.

Finding: The longer the forecast lead time, the greater the forecast uncertainty. NCAR provides flood forecasts for the next 16 days—but just as with weather forecasts, a flood forecast for tomorrow is (typically) more certain than a forecast for next week. This characteristic can be seen in the flood forecast shown in figure 3.2.

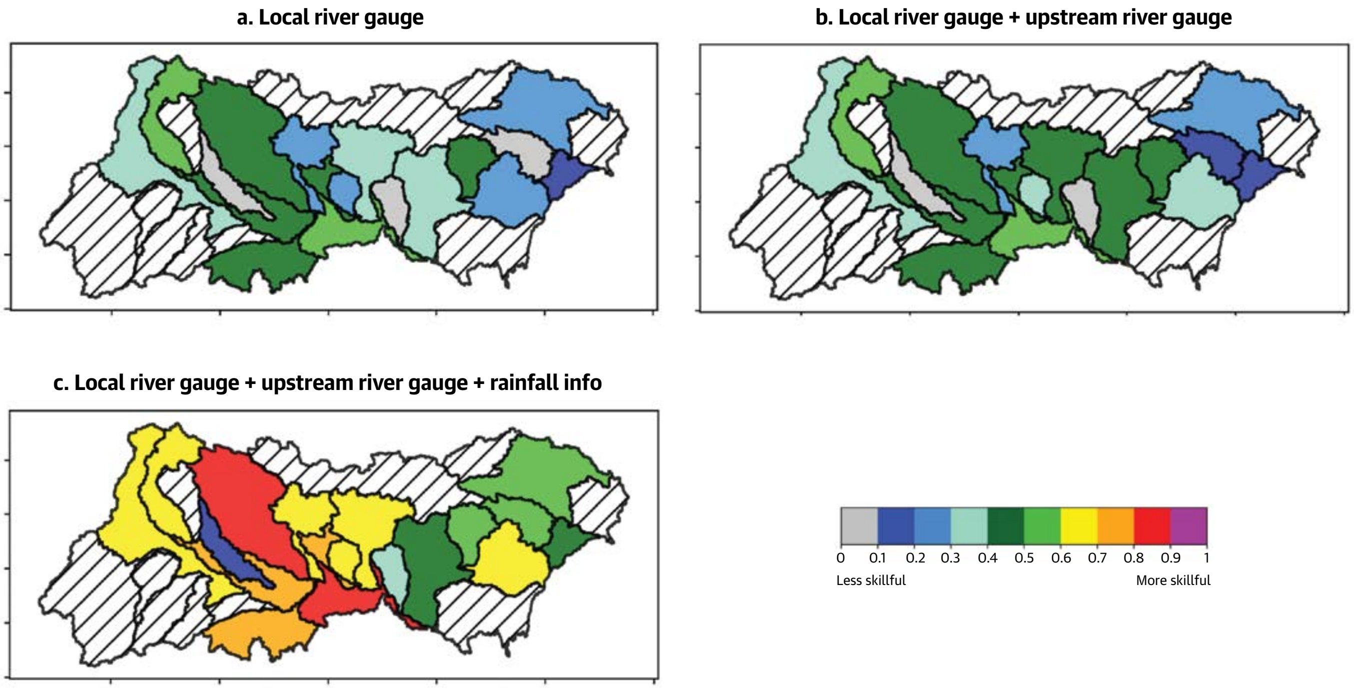
Finding: The blended NCAR forecast scheme provides generally greater skill and reliability than forecasts based only on individual data inputs. An important question is whether significant benefit accrues from using a complex (multi-model, multi-data) forecasting scheme rather than a simpler, more convenient approach. NCAR therefore assessed forecast skill for the different approaches at 18 different locations. The results were as follows:

- Forecasts based only on gauge measurements of upstream water levels provide lead times of 1 to 16 days.
- Forecasts based only on satellite measurements of upstream river widths provide lead times of 0 to 12 days.
- Forecasts based on both upstream gauges and satellite information provide lead times of 3 to 16 days.

Forecasts based on the full NCAR model provide the best skill and reliability—well past 16 days in all cases. These estimates of skillful lead times are conservative (because they are based on a demanding economics-based metric).

Map 3.5 illustrates, in a different way, the same point—that the multi-model, multi-data approach of the NCAR forecasting scheme does provide significant benefit in improving forecasting skill.

MAP 3.5. **Effect of the Multi-Model Approach on NCAR Forecast Reliability**



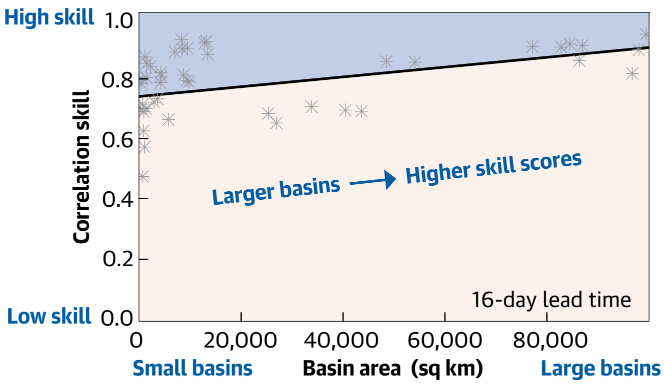
Source: T. Hopson, NCAR.

Note: These maps show outcomes for three different types of flood forecasts at 16-day lead times: panel a based on local river gauges, panel b based on local river gauges and upstream river information (river gauges and satellite-based river width), and panel c based on local and upstream river information, plus predicted and measured rainfall (the NCAR scheme). The outlines on the maps show catchments within the GBM basins. The "warmer" colors (purple, red, orange) indicate more skillful forecasts, and the "cooler" colors (blues) indicate less skillful forecasts. The hatched areas indicate catchments where data were not available.

Finding: Rainfall information is especially powerful in improving flood forecasts. Map 3.5 illustrates the increase in skill that rainfall information can provide. Panel a shows the skill of a multi-model forecast that relies only on river-level information from a local gauge. Panel b shows the improvement that comes with the addition of river information from upstream locations—about a one-day improvement in useful lead time. Panel c shows the dramatic improvement that comes from including rainfall information (weather forecasts + rainfall observations). This improvement translates to forecasts with skill out to more than three weeks in lead time.

Finding: For almost all basins, the NCAR flood forecasts show significant utility, even at long (16-day) lead times. Figure 3.5 shows one measure of forecast skill. The higher the "skill score," the better the forecast. For all basins, regardless of size, the NCAR forecasts score significantly better than zero. Other measures of forecast skill (not shown here) yield essentially the same result. The NCAR system limits its forecasts to 16 days because the underlying rainfall forecasts are available for only the next 16 days.

FIGURE 3.5. **Effect of Basin Size on Forecast Skill at 16-Day Lead Time**



Source: T. Hopson, NCAR.

Note: This graph shows one measure of forecast skill. The higher the skill score, the better the forecast. Each "star" symbol represents one subbasin (catchment). All of the forecasts show some utility, regardless of basin size (that is, they almost all score better than 0). Forecasts for larger basins display generally better skill than forecasts for smaller basins. Compared with the group as a whole, forecasts for basins in the blue area perform very well; those in the pink area are "underperforming."

Finding: The NCAR flood forecasts are generally better for stations with larger upriver catchment areas. Figure 3.5 illustrates this general principle. According to this particular measure of forecast skill, approximately 10 percent better predictability is gained with every 40,000 square kilometers of additional basin size. For some stations downriver of smaller catchment areas, the NCAR forecast exhibits utility to about 16 days. For some stations with larger upriver catchment areas, the forecasts can provide useful information well beyond 16 days in advance. Some of the smaller low-scoring basins might, with investigation and site-specific adjustment, see considerable improvement. Some of the larger basins might be suitable for the development of longer-lead forecasts.

Finding: The NCAR ensemble flood forecasts can reliably predict the likelihood of exceeding a given threshold—for example, the danger level for overbank flooding. A comparison of past forecasts and observed water levels consistently indicates that the NCAR forecast system is appropriately calibrated. This attribute is especially important for systems where extreme thresholds are a primary concern, as in the case of river flooding (see figure 3.3, for example).

Finding: The NCAR ensemble forecasts exhibit clear economic benefit for a wide range of users. As noted above, a theoretical "cost-loss" analysis is one way to identify whether users might benefit from an improved flood forecast. NCAR case studies suggest that users over a wide range of cost-to-loss ratios would economically benefit from the new probabilistic multi-model, multi-data forecasting scheme. The details of the benefits depend on forecast lead time.

Delivering Information Directly to Decision Makers

The NCAR flood forecasting system routinely posts rainfall and river information to public websites. Both forecasts and observations are available. Most of this near-real-time information is provided as user-friendly maps and graphs. Some is also available in the form of downloadable data files.

The landing page for the NCAR displays, "Development of Flood Forecasting for the Ganges and the Brahmaputra Basins," is here: http://indiawbg.rap.ucar.edu.

Note: These web displays are experimental. The data are not official, and the displays may experience occasional outages. Users requiring official river-stage observations and flood forecasts should consult official country agencies.

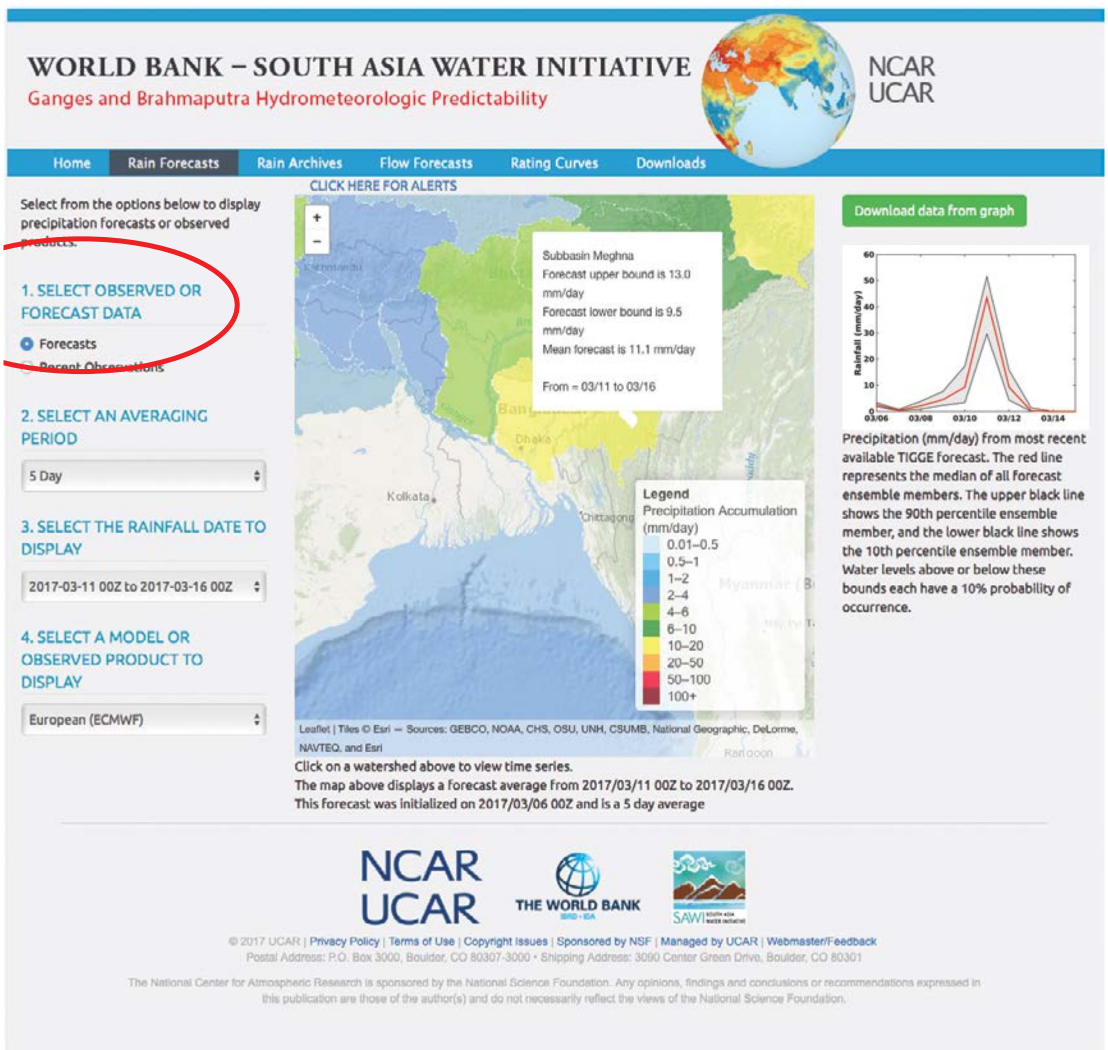
Rainfall, predicted and measured. Many flood events can be anticipated just by identifying areas of severe rainfall. This capability can be especially useful for anticipating flash floods, which develop quickly, cover relatively small areas, and are difficult to predict.

The NCAR project therefore provides online, interactive maps of rainfall for the major Ganges-Brahmaputra catchments (figure 3.6):

- Weather-center forecasts of near-future rainfall
- Satellite estimates (observations) of recent rainfall

For the forecast maps, predictions for the next 24 hours to 13 days are available. The maps of recent rainfall show data for the preceding 45 days. The system checks for new

FIGURE 3.6. NCAR Interactive Rainfall Map



Sources: NCAR. Base map courtesy of Esri Ocean Basemap and its partners. Screenshot is from http://indiawbg.rap.ucar.edu/precip/india.php.

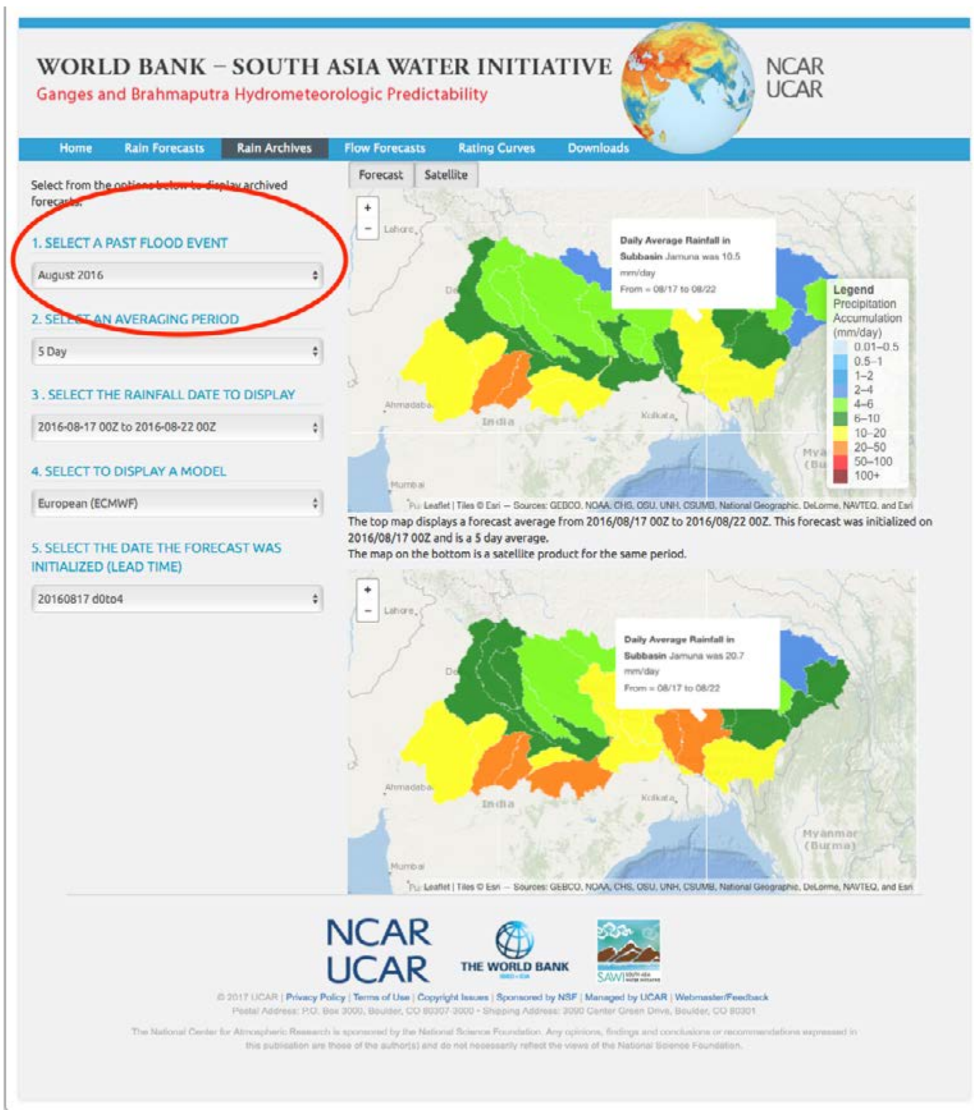
Note: NCAR provides interactive online information about catchment rainfall, predicted and observed. This information is available in map form (center) and, for individual catchments, as time-series graphs and downloadable data (upper right). The pop-up box on the map provides additional information. Users can also zoom in to view higher-resolution subcatchment information. These regularly updated rainfall displays are available at http://indiawbg.rap.ucar.edu/. This example is from a weather forecast for the Meghna basin during March 2017.

data every four hours. Viewers can also zoom in for a closer look. For individual subcatchments, time-series data are available both in graph form and as a downloadable table.

NCAR also provides online, interactive maps of rainfall associated with selected past flood events (figure 3.7):

- Weather-center forecasts of rainfall
- Satellite-based estimates (observations) of actual rainfall

FIGURE 3.7. Rainfall Associated with Selected Past Flood Events



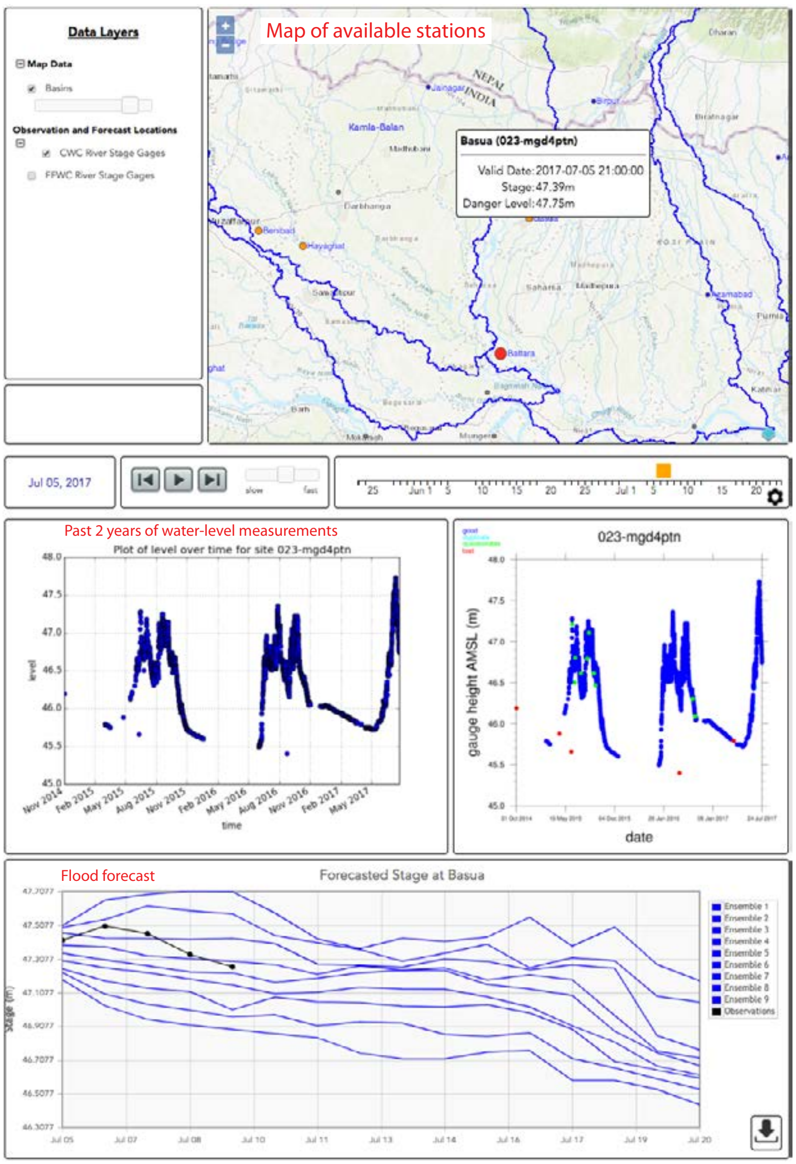
Source: NCAR. Base map courtesy of Esri Ocean Basemap and its partners. Screenshot is from http://indiawbg.rap.ucar.edu/archive/.

Note: NCAR provides interactive online information about rainfall that was predicted and observed in association with selected past flood events. This example is for the extreme flooding that occurred in August 2016 in the Indian state of Assam in the Brahmaputra basin. Upper map: Predicted rainfall (average daily rainfall for a five-day period in August 2016). The ECMWF forecasting center predicted strong rainfall (yellow) for the Yamuna catchment. Lower map: Satellite-observed rainfall (for the same five-day period), showing high rainfall (orange) in the catchment. On both maps, the pop-up boxes provide additional information. Users can also zoom in to view higher-resolution subcatchment information. These regularly updated hindcast rainfall displays are available at http://indiawbg.rap.ucar.edu/.

River levels, measured and predicted. The NCAR flood forecasting system provides historical, real-time, and forecast river information for nearly 90 stream-gauge locations throughout the Ganges and Brahmaputra basins. An interactive map (figure 3.8) provides access to the data sets for each station:

- Water-level reports, current and historical (figure 3.9)
- Water-level time-series plots, including indications of data quality (figure 3.10)
- Probabilistic 16-day water-level forecasts (figures 3.2 and 3.8)

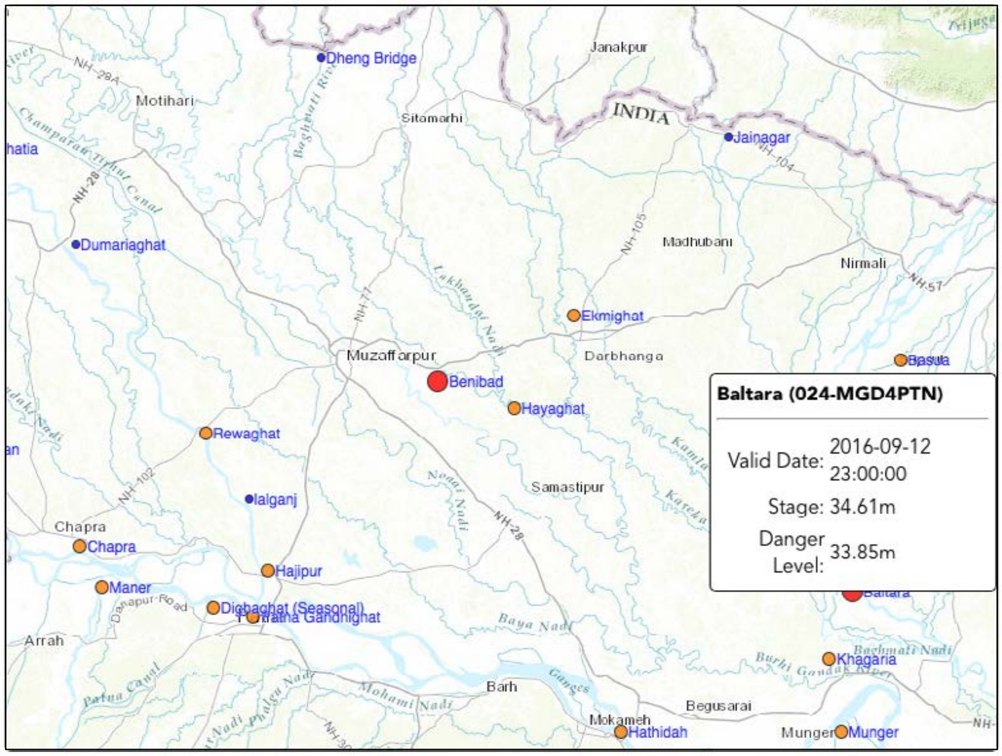
FIGURE 3.8. NCAR Interactive Online Information about River Levels



Source: NCAR. Screenshot is from http://indiawbg.rap.ucar.edu/display/.

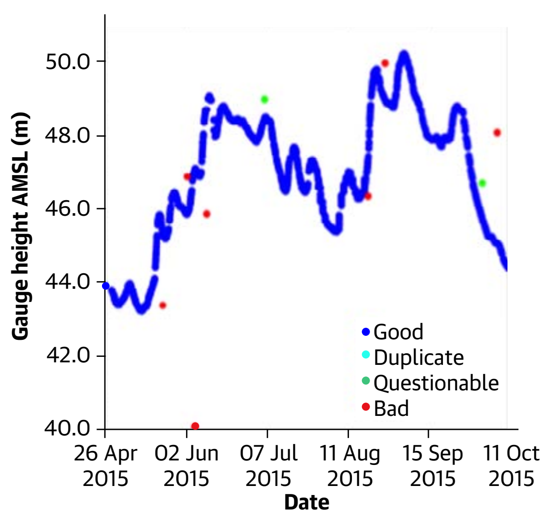
Note: NCAR provides interactive online information about river levels, predicted and observed. Real-time and recent stream-gauge measurements (from India CWC and Bangladesh FFWC gauges) are available, as are the NCAR 16-day flood forecasts. This example is from Basua, July 2017.

FIGURE 3.9. NCAR Interactive Online Water-Level Reports



Source: NCAR. Screenshot is from http://indiawbg.rap.ucar.edu/display/.
Note: NCAR provides interactive online water-level reports, historical and current. This example is from the Baltara station on the Brahmaputra River, September 12, 2016. Clicking on a station name produces a pop-up window that reports the water level ("stage") as recorded by the CWC stream gauge. Medium-sized orange dots indicate stations with a water level within 5 m of the danger level. Large red dots indicate water levels above the danger level.

FIGURE 3.10. Data Quality Information in NCAR Water-Level Displays



Source: NCAR. Screenshot is from http://indiawbg.rap.ucar.edu/display/.
Note: NCAR includes data quality information in its interactive online displays of water level. These data are from the Guwahati stream gauge on the Brahmaputra River. The blue dots indicate usable data points; the other colors indicate problematic data points. Automated quality control is an essential component of a flood forecasting system. AMSL = above mean sea level.

Most of the forecast locations are along primary river channels. India's CWC and Bangladesh's FFWC maintain the gauge network and provide access to the data.

For most of the stations, monsoon-season water-level information is available from February 2015 to the present time.

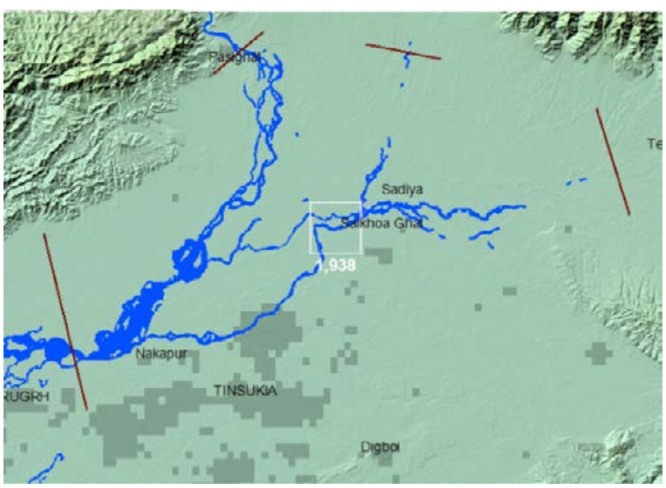
Seasonal forecasts. The collection of NCAR displays is continually being updated, and seasonal rainfall forecasts are the latest addition. The seasonal forecasts are available here: http://indiawbg.rap.ucar.edu/precip/india.php. (In the dropdown menu under "Select an averaging period," choose "1 month" or "3 months.")

Next steps: Linking river discharge forecasts and inundation maps. NCAR and the Dartmouth Flood Observatory (DFO) are collaborating to integrate two types of river flow information: the operational NCAR forecasts of future river flow and the experimental River Watch satellite observations of historical inundation. The prototype website for the Ganges-Brahmaputra Flood Awareness and Prediction System can be viewed here: http://floodobservatory.colorado.edu/GangesBrahmaputra/GangesBrahmaputraIndex.html.

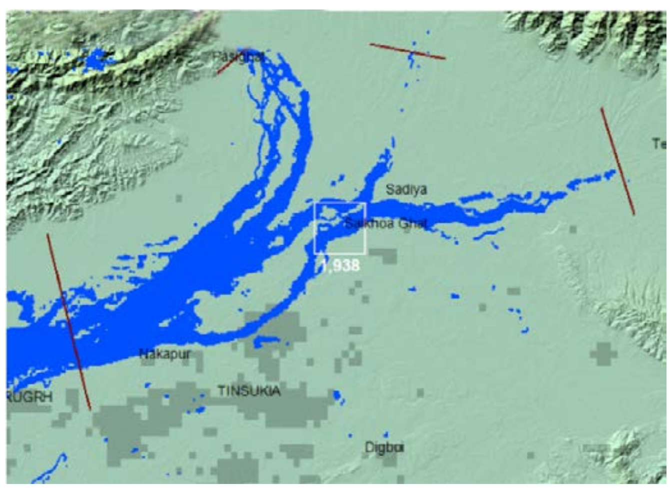
Converting the forecasts of river flow to maps of predicted inundation would be especially useful. Such maps provide an immediately accessible, visual sense of the likely extent of oncoming floodwaters. One approach (among several possibilities) is to relate NCAR's predicted discharge to DFO historical imagery from times of similar discharge (map 3.6). Other methods of integration are also being considered.

MAP 3.6. Forecast Maps of Predicted Flooding for Decision Makers

a. Normal flow



b. Flood, 2-year return period



Source: Hopson and Priya 2017; River Watch imagery courtesy of Dartmouth Flood Observatory.

Note: Forecast maps of predicted flooding would be especially useful for decision makers. Panel a shows inundation associated with normal flow conditions. Panel b shows a flood with a two-year return period, as was seen July 7–8, 2016. In late June (15 days earlier), the NCAR flood forecast had noted a 31 percent chance of this level of flooding (or more) for July 8. On July 7 (one day earlier), the forecast gave a 90 percent probability. This type of probability information helps people to make informed decisions about whether and when to take action to prepare for possible flooding. The Dartmouth Flood Observatory (DFO) produced these pilot-program maps using its archived River Watch imagery.

This approach would be most useful where river channels and overbank conditions have not changed appreciably over the period of record. The highly dynamic Brahmaputra River, with its rapid bank erosion and frequent channel shifts, is not an ideal candidate. The fact that inundation extent depends also on water contributions from downstream tributaries (that is, "backwater" effects) lends an additional complexity.

Recommendations and Options for Further Forecasting Improvements

Improve the networks of instruments that measure flood-related processes. Diverse observational networks provide the strongest input for flood forecasting. Different measurements provide different, complementary views of the processes that influence inland flooding and inform flood forecasting schemes. Strengths in one data set can offset weaknesses in another. Redundant or overlapping measurements help guard against detrimental data gaps. Stream gauges provide the most accurate information about flooding but also, by themselves, the shortest forecast lead times. Satellite data are relatively inexpensive and are especially useful for augmenting on-the-ground measurements of rainfall and river characteristics.

To strengthen observational networks, the following measures could be considered:

- Introduce additional gauges to measure rainfall and river flow at strategic locations (for details, see the original technical report, Hopson and Priya 2017).
- Consider using remotely sensed measurements to augment the gauge data, especially in inaccessible transboundary areas.
- Consider installing ground radar stations to measure precipitation.
- Implement a robust quality-control system.
- Consider using crowd-sourced "reporting" as a source of low-cost observations of river levels.

Improve the use of rainfall forecasts. Combining weather forecasts from a variety of weather centers provides the best predictions of catchment rainfall. The skill level of individual forecasts varies depending on location. Greatest benefit is attained through combining multiple weather forecasts.

To strengthen weather-forecast inputs to flood forecasting schemes, the following measures could be considered:

- Combine multiple rainfall forecasts for input to the flood forecasting scheme—ideally, the blending process should weight the incoming forecasts according to their past performance in the location of interest.
- If only a single weather forecast is to be used a priori (that is, without quantitative evaluation), use the ECMWF forecast.

Improve flood forecasting models. The use of multiple forecasting models that can work independently and in combination with each other provides advantages over the use of a single model. All three forecasting systems evaluated in this study were found to be effective: forecasting based on local time series, forecasting based on upstream river gauges, and full NCAR hydrological forecasting. Applying each scheme separately allows for identification of the strengths and skill of each. Applying the schemes in combination optimizes overall forecast skill. An example of a move toward an operational multi-model system can be seen in the Bagmati River subbasin (box 3.2).

To strengthen flood forecasting utility, the following measures could be considered:

- Use independent flood forecasting systems that can be combined to produce a single forecast informed by the different approaches.
- Explore the use of models that more adequately account for water-management practices that alter river flow (for example, reservoir storage and releases).

Improve online displays of flood information. Web-based displays and objective decision support systems can greatly improve the effective communication of flood risk. Mobile access can further enhance access and convenience.

To strengthen the communication of forecast-related information, the following measures could be considered:

- Invest in systems to display forecast information (including mobile access), hand in hand with investments in improving the forecasting models.
- Provide automated "push" alert systems to communicate flood threats (for example, emails or text messages to mobile phones).
- Explore the use of site-specific visual messaging (for example, the coupling of river flow forecasts with historical imagery of flood inundation).

General recommendations. To further enhance flood forecasting and communication for societal benefit, the following measures could be considered:

- Develop forecasting systems that provide accurate estimates of their own forecasting uncertainty.
- Consider using blended (multi-model) approaches.
- Continue to encourage collaborative research and data sharing, data quality control, and the use of international standards for data handling and sharing.
- Integrate flood forecasts into decision support and flood warning systems.

Additional details and technical recommendations are provided in the NCAR technical report (Hopson and Priya 2017).

BOX 3.2. Flood Forecasting: Next Steps for Bihar

Bihar, located along the Ganges River, is one of India's most flood-prone states. The Bihar Flood Management Information System (FMIS), administered by the state Water Resources Department, works to advance regional flood forecasting and communication. As a part of that effort, FMIS is setting up a new flood-forecasting model for the Bagmati River subbasin.

FMIS-Bihar is moving to a multi-modeling approach to flood forecasting. FMIS currently uses rain-gauge data and in-house forecasting models to provide deterministic flow forecasts with a few days lead time. The agency plans to begin incorporating "multi-model" 1- to 16-day rainfall forecasts. Through a World Bank initiative, NCAR has developed an algorithm to statistically assemble these forecasts, which are based on predictions provided by eight global weather centers around the world (the "global circulation models" shown in figure 1.6). For the Kosi basin simulations, these multi-model forecasts maintain a level of skill out to 16-day lead times. Going forward, multi-model rainfall forecasts from the eight global centers will be combined with the operational forecasts of the India Meteorological Department in a manner similar to the NCAR statistical blending approach.

In parallel, NCAR ensemble-type discharge forecasts and probability-based alerts will also be provided. This second set of water-flow predictions, developed through a 2015–16 South Asia Water Initiative (SAWI) and World Bank initiative, uses multi-model rainfall predictions, rain-gauge data, and two independent satellite-derived estimates of rainfall. Flood alerts from this system will be provided automatically through email, SMS, and websites for mobile devices.

These new forecasting tools will be used to improve flood warnings. The Bihar project will serve as a pilot exercise in the development of an operational flood forecasting system based on recent technical advances. Improvements in forecasting skill will be assessed in terms of reduced risks and losses in the coming years.

The Ganges River in Rishikesh (India).
© Sharlene Chichgar

Section 4 Concluding Remarks and Recommendations

In the Ganges-Brahmaputra-Meghna (GBM) river basins, historical and potential future losses to flooding are high, in terms of both human and economic costs. Large areas of the basins are considered to be high-risk flood zones.

- *River floods can be both beneficial and catastrophic, with adverse effects sometimes exacerbated by human choices.*
- *Flood-related losses and suffering can be diminished through the use of integrated flood management—the interweaving of land use management, water resources management, and risk management.*
- *Flood-related losses and suffering can be diminished through the use of people-focused, end-to-end early warning systems—which include both technical and societal considerations.*
- *ESCAP considers the enhancement of end-to-end early warning systems to be an area in need of urgent attention.*

Transboundary cooperation—between and within the countries of South Asia—will help to reduce human and economic losses to flooding. The GBM basins, which together constitute one of the world's largest river catchments, encompass portions of six countries and serve as home to about 10 percent of the world's population. In such basins, flood risk management requires international cooperation.

- *The success of technical advances in flood risk management (such as those highlighted in this report) depends ultimately on their operationalization—that is, on routine (operational) government-level inter-state (within the country) or transboundary* *(international) cooperation and on the translation of that cooperation into beneficial action.*

- *Opportunities for transboundary cooperation include collaborative research and the timely exchange of flood-related data, knowledge, experiences, forecasts, and warnings—for example, weather and river forecasts, rainfall and river data, and easy-to-understand visualizations.*
- *Operational sharing of transboundary flood-related information between hydrometeorological services and other stakeholders could usefully improve flood forecasting outcomes.*
- *ESCAP considers the promotion of regional cooperation in addressing risks associated with transboundary river basin floods to be an urgent regional need.*

Some formal data sharing already occurs between the countries of the South Asia region. Formal sharing mechanisms have been established, for example, between China and India, Nepal and India, Bhutan and India, and India and Bangladesh. ICIMOD's Hindu-Kush-Himalayan Hydrological Cycle Observing System (HKH-HYCOS) has also provided a venue for Pakistan, Nepal, Bhutan, and Bangladesh to work together to establish a flood-observing network in selected basins, as well as flood information systems to facilitate real-time data exchange and increase flood forecasting and warning lead times. There can be significant upstream-downstream and regional economic incentives for data sharing for flood forecasting and early warning.

- *Cross-border cooperation on data sharing has a humanitarian dimension, but also helps to lower the risk of displaced people ("environmental refugees") and to reduce impacts on production, especially in agriculture, which can minimize disruption to cross-border commodity trade.*

In an important step toward further operationalizing basin-level cooperation, participants at the 2015 Regional Flood Early Warning System Workshop expressed a desire to share national data and forecast information in the interest of reducing flood-related human and economic losses. This sharing will require a regional mechanism. Workshop participants therefore designed a regional program to address the challenges and capitalize on existing opportunities.

- *Regional cooperation on flood risk assessment, modeling, monitoring, response, mapping, and impact assessment could be usefully strengthened through agreed-upon regional and subregional strategies to share data, good practices, and knowledge.*

As another important step toward operationalizing basin-level cooperation, ESCAP, with support from RIMES, is now carrying forward the regional program designed by participants at the 2015 Regional Flood Early Warning System Workshop. As a part of its stepwise strategy toward extending regional cooperation for flood forecasting and early warning, ESCAP will convene an intergovernmental panel of meteorologists, hydrologists, and disaster risk management professionals from the operational organizations of the GBM riparian countries. Key partners may include ICIMOD, IWMI, and SAWI among others.

- *Policy makers and other stakeholders may consider supporting the new ESCAP platform for regional collaboration on transboundary flooding.*

Risk assessment is an essential first step in flood risk management. The quantitative, map-based flood risk assessment now available for the Ganges basin can help policy makers, planners, and other stakeholders to identify priority focus areas and strategies. Maps are a simple and especially powerful tool for conveying hazard and risk information—especially for events that occur infrequently compared with human lifetimes (for example, major flood events with a 100-year return period).

- *The findings of the 2016 Ganges basin flood risk assessment can usefully guide future floodplain planning—for example, land use and evacuation planning.*
- *The methods of this analysis could be usefully applied in other river basins—for example, the Brahmaputra basin.*

Flood risk assessment shows that the most severely affected subbasin, in terms of both affected population and flood losses, is the Lower Ganges. Average annual losses (AAL) in this subbasin are more than US$100 million, due primarily to damage to residential and commercial buildings and the rice crop. Residential buildings alone account for nearly three-quarters of the total AAL.

- *Due to its high vulnerability and its downstream location, the Lower Ganges subbasin is an ideal candidate for targeted flood mitigation and forecasting improvements.*
- *Other priority subbasins might include the Kosi, Bagmati, Ghagra, Gandak, Kamla-Balan, Middle Ganges, and Mahananda, which are also highly flood prone.*

Risk information—though essential—is by itself insufficient to effect significant change.

- *The 2005 Hyogo Framework for Action named the identification, assessment, and monitoring of disaster risk as one of its top five priority actions.*
- *Accessible and usable risk information helps to increase risk awareness.*
- *Risk information empowers decision makers at every level to reduce flood risks by making informed decisions about land use planning, insurance, emergency response planning, water supply management, and the engineering and construction of infrastructure and buildings.*
- *Effective risk management requires not only information but also effective governance that places a high priority on disaster risk management.*

Flood forecasting is one of the most cost-effective nonstructural options for flood risk reduction. In South Asia and elsewhere, flood management is increasingly turning to nonstructural methods to complement traditional structural methods such as dams and embankments. Forecasting in combination with early warning has proven to be effective in saving lives and property. However, scientific forecasting advances may face delays in transitioning to operational systems.

- *The findings and methods of the NCAR flood forecasting evaluation project could be usefully implemented within other operational forecasting schemes.*

- *The operational NCAR flood forecasts could be usefully incorporated into objective decision support systems and flood warning and visualization products.*
- *Decision makers and other stakeholders may benefit from guidance in fully utilizing the benefits and capabilities of probability-based flood forecasts.*

Lack of data remains a major challenge for the region. The GBM countries have differing capacities in terms of risk assessment and flood forecasting, but lack of data is a challenge shared by all. Essential on-the-ground networks are being expanded, and complementary satellite-derived data have already proven helpful in quantifying flood drivers and flood impacts. Satellite-derived information, when used with a clear recognition of its limitations, can be especially useful in areas that are remote or otherwise inaccessible. All forms of risk-related information (hazard, demographic, statistical, and economic) tend to be less available in developing countries, especially in the least developed countries such as Nepal, Bhutan, and Bangladesh.

- *A useful first step in data-gathering activities is the collection and recording of relevant hazard information (for example, rainfall amounts and river discharge).*
- *Demographic, economic, statistical, and insurance data are also important, as is information about disaster occurrences, characteristics, and impacts.*
- *Data gaps highlighted at the 2015 Regional Flood Early Warning System Workshop include insufficiencies in topographical data, river-channel hydrographic survey data, and hydrometeorological data.*
- *Satellite-derived information would be especially useful for the Ganges and Brahmaputra basins, which both encompass large areas that are remote or otherwise inaccessible.*
- *Dedicated data centers can help to ensure that data are not only collected but also monitored for quality control and then made available to end users in a usable form (for example, according to international standards).*

Technologies play a key role in not only data acquisition but also risk assessment, data sharing, flood forecasting and warning, and information dissemination and communication.

- *Efforts to design and expand cost-effective observing networks and capitalize on new sensor technologies could help to address current data gaps.*
- *The adoption of relevant linchpin technologies—such as geographic information system (GIS) mapping, data ingestion and processing algorithms, and information visualization and communication tools—could help to strengthen operational end-to-end flood warning systems.*
- *ESCAP has identified the promotion of innovative technology as an area in need of urgent attention.*

Capacities for flood forecasting and other flood-risk mitigation activities vary widely between countries, districts, states, and divisions. All of the GBM countries need to build capacity in terms of technology and staff training. A great deal of flood-relevant information, including critical geospatial data, is freely available. Often, however, agencies may not house the technical capacity to obtain or process these data. For full benefit, relevant institutional, community, and human resources must be developed at a pace commensurate with technological developments.

- *Data availability can be improved by strengthening the capabilities of local scientific and technical institutions to monitor hazards and collect and record data.*
- *Risk information is best utilized when developed alongside efforts to strengthen the public institutions responsible for delivering that information and guiding appropriate responses.*
- *Ongoing training and capacity building at every level would serve the region well in efforts toward reducing flood-related human and economic losses.*

Climate change increases the likelihood that the region may experience extreme weather events and climate conditions that have no historical precedent. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), it is expected that the average seasonal rainfall of the South Asian monsoon will increase, as will its duration. Variability is also expected to increase, leading to larger swings in extreme conditions such as periods of drought or increased flooding.

- *Consideration of future risks must be firmly grounded in a clear understanding of current risks.*
- *Flood risk assessments may eventually need to consider not only historical events but also the likely evolution of future conditions.*
- *Risk managers may need to consider the possibility that more catastrophic events may occur in the future.*

Stakeholder partnerships are important in user-relevant, end-to-end flood forecasting and warning systems and integrated flood management. As noted at the 2015 Regional Flood Early Warning System Workshop, the development of an end-to-end system is expensive, not only in terms of funding but also in terms of investment of time and people. The same is true of integrated flood management. These costs are, however, low compared with the typical scale of flood damage.

- *Stakeholder partnerships can provide supplementary or complementary resources, facilitate user engagement, and contribute to program sustainability.*
- *Examples of stakeholder partners include government agencies, media outlets, emergency responders and relief services, community/amateur radio groups, academic and research institutions, and members of the business community.*

Stakeholder involvement and effective information dissemination and two-way communication are essential ongoing processes in integrated flood management. The work highlighted in this summary report is not an end in itself. Ongoing efforts include interactive workshops and other forms of stakeholder collaboration designed to maximize the benefits of this work—for example, with the National Hydrology Project (India), the Bihar Kosi Basin Development Project, and the Uttar Pradesh Water Sector Restructuring Project (all financed by the World Bank)—as well as the national and state agencies responsible for monsoon flood warnings. Under the National Hydrology Project, a real-time decision support system for flood risk management is planned for pilot testing within some Ganges and Brahmaputra river subbasins in India. *To fully realize the benefits of technical advances in flood risk management:*

- *The design of the technical work and its outcomes would, from the outset, be deliberately aligned with the work of stakeholders engaged in managing floods and responding to flood events.*
- *New tools and techniques would be incorporated into accessible and usable operational platforms—for example, real-time, operational decision support systems are one important way of translating technical advances into real-world benefit.*
- *An effective communications strategy would be deployed, to ensure that new tools and other technical outcomes are accessed and used, with a variety of participatory approaches targeting a wide range of stakeholders.*
- *Mechanisms for effectively gathering feedback and incorporating continuous upgrades would be developed.*
- *Advances would be continually assessed in terms of real-world benefits, such as reduced flood risks and losses, and new knowledge would be incorporated as it becomes available.*

Glossary

Calibration: The process of using historical data to estimate parameters in a hydrological forecast scheme (U.S. National Weather Service, http://www.nws.noaa.gov/om/hod/SHManual/SHMan014_glossary.htm)

Capacity: The combination of all the strengths, attributes, and resources available to an individual, community, society, or organization, which can be used to achieve established goals (IPCC 2012)

Catchment: An area that collects and drains precipitation (IPCC 2012)

Disaster response: Actions taken in the aftermath of a disaster to ameliorate its impacts (World Bank, Independent Evaluation Group, no date)

Early warning system: The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities, and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss (IPCC 2012)

Ensemble hydrological forecasting: A process in which a continuous hydrological model is successively executed several times for the same forecast period by the use of varied data input scenarios or a perturbation of a key state variable for each model run (U.S. National Weather Service, http://www.nws.noaa.gov/om/hod/SHManual/SHMan014_glossary.htm)

Exposure: The presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected (IPCC 2012)

Flood: The overflowing of the normal confines of a stream or other water body, or the accumulation of water over areas that are not normally submerged (IPCC 2012)

Flood control: The prevention of the overflow of a large amount of water beyond its normal limits or the restriction of the effects of such an overflow (Oxford Dictionaries, https://en.oxforddictionaries.com)

Forecast: Scientific prediction about a future state—for example, of water level (NOAA 1999)

Forecast point: A location that represents an area (a river reach) where a forecast is made (U.S. National Weather Service, http://www.nws.noaa.gov/om/hod/SHManual/SHMan014_glossary.htm)

Forecast skill: A statistical evaluation of the accuracy of forecasts (American Meteorological Society, http://glossary.ametsoc.org/wiki/Skill); a general term that expresses how well forecasts compare to observations or to defined reference conditions (for example, historical climatological conditions or the persistence of current conditions)

Gauge: A device for indicating the magnitude or position of a thing in specific units—for example, the elevation of a water surface or the amount of precipitation (U.S. National Weather Service, http://www.nws.noaa.gov/om/hod/SHManual/SHMan014_glossary.htm)

Global circulation model: Sophisticated computer simulations used to model the circulation of the earth's atmosphere and oceans; can be used to provide weather forecasts or climate projections

Hazard: The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources (IPCC 2012)

Hindcast: Scientific prediction about a past state—for example, of water level; incorporates past or historical observational data (NOAA 1999)

Mitigation (of disaster risk or disaster): The lessening of potential adverse impacts of physical hazards (including those that are human-induced) through actions that reduce hazard, exposure, or vulnerability (IPCC 2012)

Nowcast: Scientific prediction about a present state—for example, of water level; incorporates recent (and often near real-time) observed meteorological, oceanographic, and/or river flow rate data; covers the period of time from the recent past (up to a few days) to the present (NOAA 1999)

Prediction: A forecast or "most likely" projection (IPCC Data Distribution Centre, http://www.ipcc-data.org/guidelines/pages/definitions.html)

Projection: A potential future evolution of a quantity or set of quantities, often computed with the aid of a model; projections are distinguished from predictions in order to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty (IPCC 2012)

Resilience: The capacity that people or groups may possess to withstand or recover from emergencies, which can stand as a counterbalance to vulnerability (Jha et al. 2012)

Return period: Average interval of time between events that equal, or exceed, a given magnitude (Jha et al. 2012)

Riparian: Land bordering a watercourse (Jha et al. 2012)

Risk: The probability of harmful consequences or expected losses resulting from a given hazard to a given element at danger or peril over a specified time period (Jha et al. 2012)

River basin: See Watershed

Runoff: That part of precipitation that does not evaporate and is not transpired, but flows through the ground or over the ground surface and returns to bodies of water (IPCC 2012)

Stage: The level of the water surface above a given datum at a given location (U.S. National Weather Service, http://www.nws.noaa.gov/om/hod/SHManual/SHMan014_glossary.htm)

Streamflow: Water flowing in a stream channel; often used interchangeably with "discharge" (U.S. National Weather Service, http://www.nws.noaa.gov/om/hod/SHManual/SHMan014_glossary.htm)

Time of concentration: The time needed for water to flow from the most remote point in a watershed to the watershed outlet; a concept used in hydrology to measure watershed response to a rain event

Tributary: A smaller watercourse joining a larger one, thus adding to total flow (the meeting point is known as a confluence) (Jha et al. 2012)

Uncertainty: An expression of the degree to which a value or relationship is unknown; can result from lack of information or from disagreement about what is known or even knowable (IPCC 2012)

Vulnerability: The propensity or predisposition to be adversely affected (IPCC 2012)

Watershed: An extent or area of land over which surface water from rain and melting snow or ice converges to a single point, usually the exit of the basin, and joins another water body (such as a river, lake, reservoir, estuary, wetland, sea, or ocean); other terms include catchment area, catchment basin, drainage basin, drainage area, river basin, or water basin (Jha et al. 2012)

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