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SAWI SOUTH ASIA WATER INITIATIVE

Report No. 67668-SAS

Ganges Strategic Basin Assessment

A Discussion of Regional Opportunities and Risks

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World Bank South Asia Regional Report

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Contents

FIGURES

TABLES

BOXES

Acknowledgments

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Acronyms

ABC	Asia brown cloud
ADPC	Asian Disaster Prevention Center
BADC	British Atmospheric Data Centre
BBS	Bangladesh Bureau of Statistics
BCM	billion cubic meters
ENSO	El Ñino Southern Oscillation
FMIS	Flood management information system
GCM	Global Circulation Models or General Climate Model
GDP	Gross Domestic Product
GIS	Geographic Information System
GLOF	Glacier Lake Outburst Flood
GRDC	Global Runoff Data Center
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
IWM	Institute for Water Modeling
JRC	Joint Rivers Commission
JCWR	Joint Committee on Water Resources
KWh	Kilowatt hour
MW	Megawatt
NCAR	National Center for Atmospheric Research
NGRBA	National Ganga River Basin Authority
OCHA	Organization for the Coordination of Humanitarian Assistance
SAARC	South Asian Association for Regional Cooperation
SAWI	South Asia Water Initiative
SBA	Strategic Basin Assessment
SRTM	Shuttle Radar Topography Mission
SMEC	Snowy Mountain Engineering Corporation
SWAT	Soil and Water Assessment Tool
TWH	Terawatt Hour
UNDRO	UN Disaster Relief Organization
UNFCCC	United Nations Framework Convention on Climate Change
UP	Uttar Pradesh
USGS	United State Geological Survey

Executive Summary

The Ganges river basin is the most populous in the world. The daily lives of its 655 million inhabitants rely on the water it provides. The river presents great opportunities and great challenges. It provides drinking water, agricultural water, hydropower generation, and navigational and ecosystem services across more than 1 million square kilometers. But the river is destructive as well; devastating floods and periodic droughts are routine and undermine development.

All countries in the basin benefit from the Ganges and suffer from its extremes; all could benefit more and suffer less. Benefits from potential hydropower development and agricultural modernization remain untapped, while flood and drought management systems are inadequate to protect lives and livelihoods. Better management of the Ganges – to sustain the river ecosystem, capture its potential benefits, and mitigate its mounting costs – requires enhanced regional knowledge and cooperation.

Currently, most development in the basin is through incremental, project-by-project activities within each of the riparian countries. There has been surprisingly little systematic regional research on the basin's development options and challenges using modern analytical tools that go beyond sector, country, or state analysis to examine the systemwide strategic questions that the basin faces. In addition, long-held perceptions of the current condition and the future development path of the Ganges Basin vary dramatically within and among different stakeholder groups, institutions, and countries.

The objective of the Ganges Strategic Basin Assessment (Ganges SBA) is to build knowledge and promote an open, evidence-based dialogue on the shared opportunities and risks of cooperative management in the basin. It is hoped that this will lead to greater cooperation in the management of this shared river system, beginning with a shift from information secrecy to information sharing. The key feature of this regional research is the development of a set of nested hydrological and economic basin models, along with targeted analyses on social vulnerability and climate change. The mosaic of information produced using these tools and approaches can be used to examine alternative scenarios across a range of possible Ganges futures.

Until now, there has been no basinwide knowledge base and analytical framework that could be used by riparian states to explore options and facilitate cooperative planning in the Ganges. Information and data are surprisingly scarce and difficult to obtain. In particular, very little information is available on hydrology and irrigation withdrawals in India. Significant efforts were made to assemble the data sets used in this analysis, drawing on publicly available data in Bangladesh, India, and Nepal, and on global data sets. The effort was undertaken by a World Bank team in cooperation with several leading regional research institutions and involved repeated exchanges with policy makers and opinion makers in the basin.

The Ganges SBA begins to fill a crucial knowledge gap, providing an initial integrated systems perspective on the major water resources planning issues facing the basin today, and on some of the most important infrastructure options that have been proposed for future development. A set of reliable hydrological and economic models for the Ganges system has been developed and tested. These models are believed adequate for assessing the impact of existing and new hydraulic structures on flooding, hydropower, low flows, water quality, and irrigation supplies at the basin scale. It is important to emphasize that this report focuses only on basin-level dynamics; any specific projects under consideration would still require full economic, environmental, and social assessments with specific attention to local ecological, seismic, and cultural contexts. Although the work has been constrained by important data limitations, and significant climate change uncertainties persist, the basic conclusions of these assessments are robust and have been used to develop some strategic insights.

The new information contained in this report challenges many long-held beliefs about the Ganges River Basin. The system is so large (over 1 million square kilometers) and so complex (with thousands of tributaries fed by glacier and snow melt, monsoon rains, and groundwater base flows) that it simply cannot be understood intuitively. As a consequence, it appears that some of what has long been considered 'common knowledge' is, in fact, inaccurate.

In particular, the findings of this study refute the broadly held view that upstream water storage (i.e., reservoirs) in Nepal can control basinwide flooding; however, at the same time it finds that such dams could potentially double low flows in the dry months. The value of doing so, however, is surprisingly unclear and similar storage volumes could be attained through better groundwater management. Hydropower development and trade are confirmed to hold real promise (subject to rigorous project level assessment with particular attention to sediment and seismic risks), and in the near to medium term pose less significant trade-offs than expected among different water uses.

The Ganges SBA study focused on ten fundamental questions.

Question 1:
Is there substantial potential for upstream reservoir storage in the Himalayan headwaters of the basin?

Much has been written about the potential for large water storage structures in the Himalaya. It is generally assumed that this potential could be harnessed through large multipurpose dams to produce hydropower, deliver more timely irrigation water, and regulate the extreme flows of the Ganges River.

Although there are many reservoir sites that are attractive for the development of multipurpose water storage infrastructure, the steep terrain and mountain gorges mean that surprisingly little water can be stored behind even very high dams. Developing all of the structures examined in this report would provide additional active storage equivalent to only about 18 percent of the basin's annual average flow. This is very little storage on a basinwide scale. Moreover, the extent to which dams in Nepal can be operated to efficiently pass the large amounts of sediment eroded from high in the Himalaya remains unclear.

Question 2:
Can upstream water storage control basinwide flooding?

Large Himalayan dams are commonly seen as the answer to the flooding that plagues the Ganges plains and delta, especially in areas of Bangladesh, Bihar, and eastern Uttar Pradesh. Model results and research reveal a different picture.

On a basinwide scale, the potential to control floods using upstream storage is very limited. The full active storage potential that has been identified to date in the system (existing storage plus the additional 18 percent examined in this report) amounts to approximately 25–30 percent of average annual river flows. This is simply too small a percentage to meaningfully regulate the full river system. This limited scale of potential storage severely constrains riparians' ability to ever truly regulate this river system, even assuming an aggressive development of system storage. On the positive side, the lack of substantial regulation will preserve a more natural hydrology in the river system, which provides a wide variety of services that have not been quantified in this report, such as ecosystem services and navigation.

The Ganges SBA models indicate that even the very large proposed Kosi High Dam could not completely control flood peaks because the dam, which would provide only 9.5 billion cubic meters of live storage, would be built on a river with an average annual flow of 55 billion cubic meters (much higher in many years). Moreover, the important question is not whether the Kosi High Dam could reduce flood peaks; but whether reducing flood peaks in the Kosi River would stop flooding in Nepal and Bihar. Unfortunately, the evidence suggests that the dam's impact on flooding would likely be modest because most of the flooding in Nepal and Bihar lies outside the Kosi subbasin. The majority of floods are a consequence of intense local rainfall and/or high flows in other river systems that would not be affected by building the Kosi High Dam.

In fact, the Ganges SBA models showed that most flooding events in the basin are caused by localized rainfall, high flows in small tributaries, and embankment failures – not by peak flows overtopping embankments in the major tributaries where large storage reservoirs could be built. Even though a moderate amount of flow could be stored in reservoirs on major tributaries, almost all of the major tributaries in the basin are fully embanked. Lowering flood peaks within these embanked rivers is unlikely to have a significant effect on flooding events.

Question 3:
Can upstream water storage augment low flows downstream?

In addition to holding back floods, Himalayan reservoirs are expected to release water stored during the wet season for use in the dry season. These releases could augment low flows for ecosystems, agriculture and other uses across the basin especially in the dry months preceding the monsoon.

In physical terms, the modeling results confirm this expectation. Low-flow augmentation could indeed be significant if all the large dams under consideration were built, approximately doubling low flows in the months with the lowest flows. Storing even a minor portion of the flood flows until the dry season could significantly increase low flows especially in a very dry years. Low-flow augmentation may be large relative to current low flow, but it is negligible compared to peak flow, so the integrity of the hydrological system as it currently stands is unlikely to be threatened by infrastructure development.

However, the economic value of this low-flow augmentation is unclear because of low agricultural productivity and localized waterlogging. Water is not seen to be the crucial constraint to agricultural productivity in the specific parts of the Ganges Basin that could receive these additional low flows. Even if these dams were built (at high costs and likely over decades) agricultural modernization is required to increase productivity. This modernization would be beneficial regardless of upstream dam construction. The effects of increased low flows may make important contributions in the Ganges delta areas to better manage saline intrusion, enhance the Sundarbans ecosystem, and maintain navigation services. These are important issues that require additional research.

Question 4:
Are there good alternatives or complements to reservoir storage in the Himalaya?

Many believe that large human-created infrastructure (dams) is the only option of adequate scale to meet the basin's needs, given the region's growing populations and economies. Although underground aquifers, lakes, glaciers, snow, ice, and even soils are all forms of natural water storage, it is widely believed that they are relatively small, that the basin's groundwater is being drastically overexploited, and that its glaciers are melting rapidly.

In fact, contrary to the increasingly dangerous levels of groundwater overabstraction elsewhere in South Asia, there are vast, untapped groundwater resources in the central and lower reaches of the Ganges Basin. These additional groundwater resources, held in natural underground aquifers, can be sustainably used. Increased strategic and sustainable use of this groundwater, in conjunction with a well-managed surface water system, could provide water supply benefits on a scale comparable to the full suite of dams considered in this report; and it could possibly do so more immediately, at national, state or local levels, and at lower financial, social, and environmental costs. Moreover a conjunctive-use strategy could be designed to help manage soil waterlogging and enhance the reliability of water supplies to tail-end users in surface irrigation schemes and/or downstream irrigators in the eastern basin. Achieving all of this, however, would require significant reforms particularly in the policy and energy-pricing environment, and real changes in farmers' behavior.

QUESTION 5:
Is there substantial untapped hydropower potential in the Ganges Basin?

The Himalaya has long been seen as holding enormous hydropower potential, adequate to meet domestic energy needs in Nepal (where potential supplies far outstrip potential demand) and provide a significant surplus for trade in the region.

This report confirms that potential. In Nepal more than 40,000 megawatts of economically feasible hydropower potential exists in the Himalayan headwaters of the Ganges. Less than 2 percent of that potential has been developed. The suite of dams examined in this report, the 23 largest of them currently under consideration in Nepal, would have an installed capacity of about 25,000 megawatts, generating an estimated 65-70 terrawatt hours of power annually. The net economic value of this potential hydropower is estimated at some US$5 billion annually, quite significant relative to Nepal's 2011 gross domestic product (GDP) of $18.9 billion (current US $). It must be noted, however, that hydropower development on this scale would require considerable capital investment and take many years, and that sediments will need to be effectively managed. Nonetheless, hydropower is an important source of clean energy in a region that is enjoying high economic growth and hence rapidly growing power demands.

QUESTION 6:
What is the magnitude of potential economic benefits from multipurpose water infrastructure, and what are the tradeoffs among different water uses?

There is a general sense in the region that the development of multipurpose infrastructure will bring significant economic benefits, but there is no shared understanding about the relative values of hydropower, flood control, and low-flow augmentation. It is also widely believed that the design and operation of multipurpose dams will significantly skew the distribution of benefits among water uses (and hence users). The tradeoffs are believed to be very large, and therefore are a matter of concern and contention particularly in negotiations between India and Nepal on the development and financing of large multipurpose water infrastructure.

This report finds that the gross economic benefits of hydropower from the 23 large dams examined under different scenarios of infrastructure development would be in the range of US$3–8 billion per year (assuming that 25 percent of it could be sold as higher-value peaking power.) For the most part, the economic tradeoffs among hydropower, irrigation, flood control, and ecological objectives are small, because there is little difference in the way upstream dams would be operated to maximize hydropower generation on the one hand, and downstream water supply on the other (since the objective for both of these is to store peak flows to achieve steadier dry-season releases); and because options to control downstream flooding are limited regardless of how operating rules are designed. There is a tradeoff in the quantity of water used for irrigation in the Ganges plains versus low-flow augmentation in the delta, but there is currently insufficient evidence to determine whether this tradeoff is economically significant: the evidence suggests that the marginal economic benefit associated with surface water irrigation in the plains is currently quite low and the economic value of increased low flows for ecosystem services is uncertain.

QUESTION 7.
What are the cost- and benefit-sharing dynamics of upstream water storage development?

Perceptions differ by country, but it is generally perceived that downstream countries will benefit greatly from upstream development and therefore should share the costs of that development. Some believe that the majority of benefits from upstream water storage will not accrue from hydropower development upstream, but rather from flood control and irrigation benefits downstream. A common understanding of the distribution of benefits is essential to negotiating equitable benefit-sharing arrangements on infrastructure developments that have cross-border impacts.

If upstream multipurpose dams were built today, with current low agricultural productivity and little flood benefit, this study finds that the overwhelming share of economic benefits would be derived from hydropower. In the future, if agricultural productivity rises dramatically, the distribution of benefits could change. The principal unknowns in this equation are the ecosystem and navigation values of enhanced low flows in the delta, which could be significant. The study's findings suggest, however, that the benefit-sharing calculus is simpler than previously assumed because downstream flood control and agricultural benefits are smaller than anticipated – at least in the near to medium term. The benefits and costs to be shared in the near term will be predominantly associated with hydropower. In the long term, if the value of low flows to agriculture and ecosystems increase, the benefit-sharing calculus becomes more complex because the benefits received by India and Bangladesh could become significant.

QUESTION 8.
Is large infrastructure the best strategy for protecting communities from floods?

Infrastructure is often seen as the most effective and reliable way to protect communities from endemic flooding in the Ganges plains. The findings of this report, however, show that a strategy exclusively focused on large infrastructure cannot protect basin communities.

There is no simple solution to the problem of flooding on the Ganges plains. In some areas of the world, a focus on large infrastructure (dams and embankments) has been fairly effective. However, in the highly variable monsoon-driven Ganges system with its thousands of tributaries, these solutions will not be fully effective. To protect communities in the Ganges Basin, a shift in focus is needed from 'flood control' to 'flood management,' a combination of structural and nonstructural interventions marked by a greater emphasis on regional forecasting and warning systems, embankment asset management, drainage, and, importantly, more localized 'soft' responses including disaster preparedness, land use zoning, safe havens, flood insurance, and training and communications campaigns. Indeed, in recent years, this shift has been the subject of a great deal of thoughtful advocacy. Flood protection for basin communities and the livelihoods of their people requires a broad, balanced combination of 'hard' and 'soft,' as well as local and transboundary, responses.

QUESTION 9.
Is it possible to control sediment in the Ganges?

Many believe that in the Ganges, like elsewhere in the world, a combination of watershed management to control erosion and upstream storage structures might control sedimentation in the river. But the Ganges is different.

The Ganges is one of the three most sediment-laden rivers in the world. Most of the sediment comes from erosion in the high Himalaya. Both the high volume and the source of this sediment make it extremely difficult to manage. The volume of sediment is so large that capturing it behind large dams would be extremely costly; the reservoirs behind these large, expensive structures would fill quickly and, thereafter, produce very few benefits. The high altitude and terrain of the sediment source regions, as well as the nature of the sediment and the ongoing tectonic processes, make it impossible to undertake the scale of watershed management interventions necessary to have any measurable impact on basin sediment loads. Sediment, like floods, is a challenge that must be managed in the Ganges; it cannot be fully *controlled*.

QUESTION 10.
What will climate change mean for the basin?

Many fear that the Himalayan glaciers will melt and change the Ganges River from a perennial to a seasonally flowing river, and that changing temperatures and precipitation patterns will create crippling water stress as well as more severe and more frequent droughts and floods.

This study found that climate change uncertainties in South Asia and the Ganges Basin in particular are extreme, but that the range of mean basin runoff predictions is roughly comparable to the recent historical record and the basin's highly variable climate today.

The study estimated temperature, rainfall and runoff for the Ganges Basin using all 16 United Nations Framework Convention on Climate Change (UNFCC)-recognized Global Circulation Models (GCMs). Although there appears to be a clear trend toward rising temperatures, predictions regarding rainfall and runoff vary widely and point to the possibility of either increasing or decreasing water availability. The range of model results underscore their uncertainty, and their predictions can mask extremes, but these results do suggest that the scale and focus of today's climate challenges – unpredictable and intense rainfall, alternating extremes of flood and drought – will continue to be the key climate challenges in the coming decades. A focus on managing current hydrological variability (whether or not it is attributable to climate change) is, therefore, a good place to start addressing the future climate change challenges of the Ganges.

Even the most extreme climate scenarios do not change the basic findings of this report. In fact, greater climate extremes, variability, and uncertainty only strengthen the logic of this report's basic recommendations, whereas the effectiveness of large-scale infrastructure for flood control, and the reliability of existing large-scale diversions of surface water for irrigation, could prove susceptible to climate change. The recommendations of this study are likely to become more valuable under greater climate extremes. Regardless of changes in rainfall and hydrology, an emphasis on enhanced forecasting and warning systems, in concert with a suite of tailored, localized responses, is urgently needed. Similarly, the need and potential for enhanced conjunctive use of surface water and groundwater only becomes more compelling as temperatures, and hence evaporation rates of surface storage, increase, and the timing of surface flows becomes less predictable.

With regard to the glaciers, the study found that while the rate of glacier melt is likely to increase somewhat, glacier melt contributes only about 2 percent of basinwide flow. In addition, melting occurs mostly during the high-flow season in the Ganges. In contrast to Europe and North America, or even in the western Himalaya, where glacier melt contributes substantially to low summer flows, the Himalayan glaciers in the Ganges Basin melt during the monsoon season when temperatures are highest but rainfall is also heaviest. Thus, while changes in glacier melt will be an existential challenge for some melt-dependent mountain communities, it is not a major driver of basinwide hydrology in the Ganges.

Summary Findings

The Ganges SBA highlights the uniqueness and the complexity of the Ganges Basin, and demonstrates the urgent need for a shared evidence-based understanding of the full basin system. It calls for significantly enhanced regional cooperation in water, weather, and climate information, modeling and warning systems which are essential for the sustainable management of the basin and the safety and prosperity of its people. The report's sometimes counter-intuitive findings highlight the need to revisit commonly held perceptions using modern data sources and modeling techniques to come to fact-based understandings about the basin's resources and possible future development paths.

The Ganges Basin holds clear and immediate opportunities for regional cooperation in information management to enhance the productivity and sustainability of the river, and at the same time safeguard lives and livelihoods. Systematic collection and exchange of appropriate, modern water, weather, and climate data; cooperative efforts in advanced modeling, forecasting, and communications and warning systems; and a shared information base for basin planning will help the countries seize the basin's opportunities and manage its risks. The pieces are all in place. There is tremendous expertise in the region. Bangladesh boasts world-class water modeling institutions and cutting edge flood warning systems. India's long experience in water engineering is now coupled with burgeoning satellite and information technologies sectors, essential for modern hydrometeorology. Nepal, with its wealth of water resources, sets an excellent global example for information sharing by making real time hydrological data available online. Moreover, all three countries are involved in or planning significant investments in hydromet monitoring systems, systems that could be made interoperable for basinwide information management.

Cooperation could take many forms, from a network of national institutions with an agreed information-sharing protocol; to a dedicated task for or agency that would gather, analyze, and then disseminate crucial hydromet and climate data; to an inclusive river commission that could develop a shared knowledge base and operational model of the basin, establish norms and protocols for transparency and information sharing, and identify and pursue opportunities for cooperative development projects. A strengthened regional information system would provide the scientific information needed by planners to sustain and develop the basin; by farmers to enhance productivity and food security; by disaster risk management professionals to safeguard lives and assets; and by climate researchers to understand, predict, and adapt to the changing – but also immediately challenging – climate in the Ganges Basin.

Immediate opportunities are also apparent for hydropower development and trade. There is significant untapped potential in the basin and a steadily growing demand for clean energy. Moreover the benefit-sharing calculus appears simpler than commonly believed, for several reasons. First, the tradeoffs among different water uses are modest. Infrastructure would be designed and operated much the same way whether the goal was to maximize hydropower, or to maximize flood and irrigation benefits downstream. In addition, the small storage compared to the river flows should make the pace of filling reservoirs not a major issue. Negotiations over the design and operation of multipurpose infrastructure with transboundary impacts should therefore be tractable. Second, the current economic value of downstream irrigation is surprisingly small compared with hydropower benefits, due to low agricultural productivity. At least in the near term, the direct economic benefits of upstream reservoirs would derive overwhelmingly from hydropower. Co-benefits for agriculture should be amenable to transparent negotiations. Third, flood benefits (if any) are confined to tributaries. Upstream storage will have negligible basinwide flood impact. Benefit sharing with regard to flood protection could, therefore, be appropriately negotiated at the tributary scale (i.e., between two countries), rather than basinwide. Conversely, benefit sharing with regard to enhancing low flows for irrigation and ecosystems remains an appropriate issue for basinwide discussions. Finally, models, such as those developed for this study, could provide a new set of tools to help quantify basin impacts and support information-based negotiations on hydropower development.

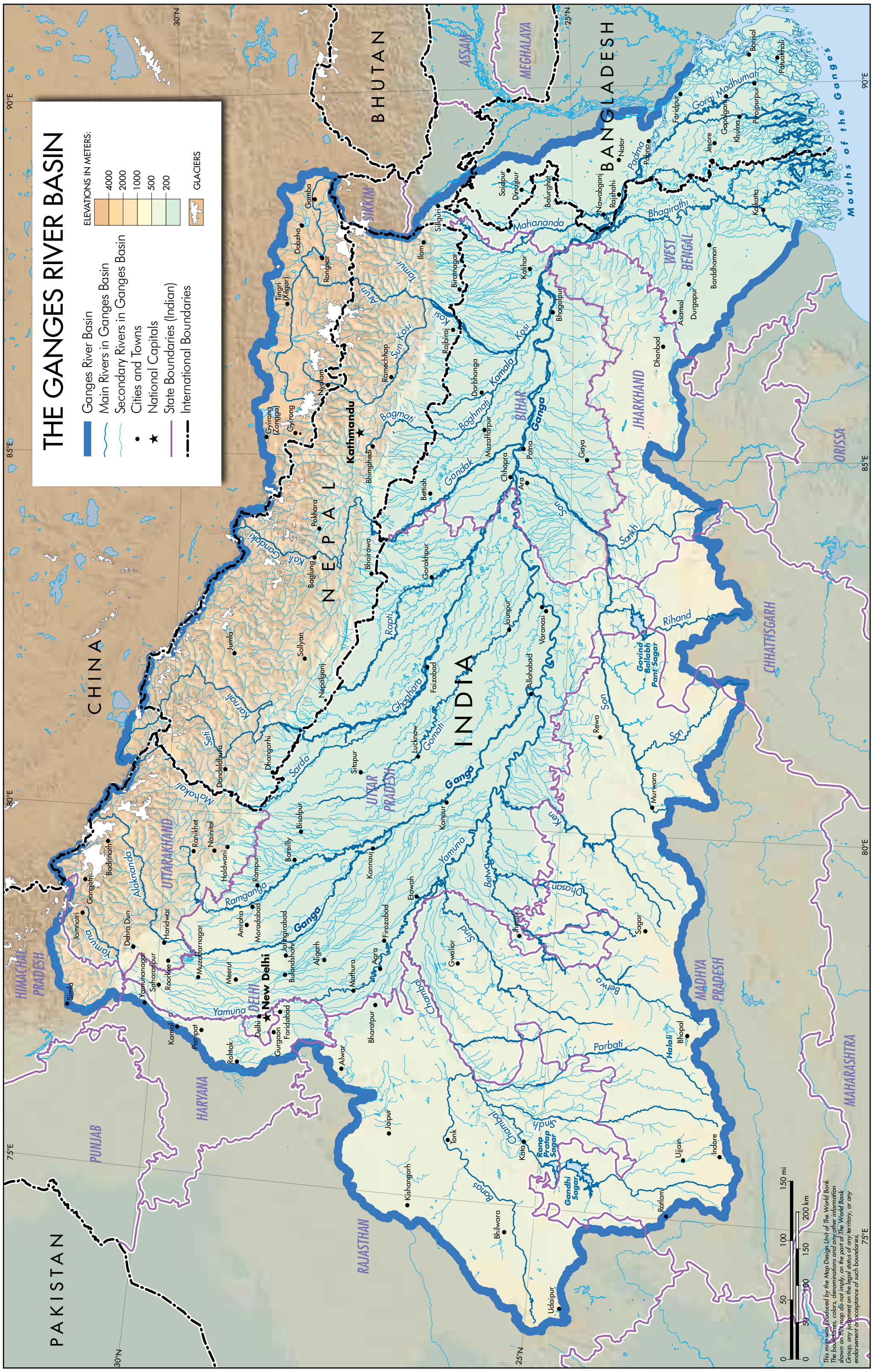
The basin also holds promising possibilities for enhancing low-season water availability. Low flows can be significantly augmented (potentially doubled in the dry months) as a co-benefit of developing multipurpose storage reservoirs upstream. But the development of upstream storage reservoirs is a costly undertaking, and this report suggests that storage investments would not be economically justifiable solely – or even significantly – on the grounds of their immediate contribution to enhancing agricultural productivity in the basin. In fact there are large areas of waterlogged land whose productivity could potentially be diminished if more water were applied during the dry season, which is a time that usually allows for recovery. Upstream storage alone will not modernize agriculture in the basin. A range of interventions is needed (and some are underway) to enhance agricultural productivity and support the livelihoods of poor farmers. These interventions are anticipated to be beneficial regardless of the development of upstream storage.

Enhanced low-season flows may hold important potential to sustain ecosystem services, particularly in the fragile Sundarbans (mangrove forests) of the Ganges delta. Yet the ecosystem values of increased low flows downstream, e.g. in distributary rivers such as the Gorai (which was once the mouth of the Ganges)—while possibly quite high—remain unsubstantiated. Interventions such as much-less-expensive dredging through the sandbar that currently impedes flow of Ganges water into the Gorai in the non-flood season could improve low flows into that system even without upstream augmentation. A final important unknown is the economic value of augmented low flows in combating saline intrusion in the delta, and the importance of the Ganges freshwater plume for the dynamics of currents and storm patterns in the Bay of Bengal. More study of the morphology and ecosystems values in the Ganges delta is urgently needed.

A promising alternative to upstream water storage reservoirs is the potential to augment low-season flows by increasing groundwater utilization, within an appropriate energy-pricing and policy environment and in conjunction with a well-managed surface water system. In eastern Uttar Pradesh, enhanced groundwater use could produce additional storage (and hence augment dry season water availability) on a scale comparable with the Himalayan dams, but likely much more rapidly, at lower cost, and more scalable. If upstream multipurpose dams are found to be economically, socially, and environmentally justified by the bundle of benefits they can produce (predominantly hydropower), additional dry-season water could prove to be an important co-benefit perhaps to complement more immediate interventions in conjunctive use.

Still the basin faces persistent challenges, in particular in managing floods and sediment. Large dams built to hold back flood waters high in the Himalaya have long been seen as the preferred strategy for managing the region’s devastating floods. But as an exclusive strategy, this is untenable. The physical storage volume available in the mountains is simply too small to have a meaningful impact on basinwide floods, although reservoirs may provide some amelioration within tributaries. Flood and sediment management is needed, but basinwide flood and sediment control is not possible. Effective flood management requires regional information and warning systems, coupled with a range of hard and soft, national and local level investments.

The Ganges River Basin



Finally, significant climate-change uncertainties remain in the basin. Current data and models give little clear evidence of what the future holds. But perhaps this uncertainty itself could be a reason for enhanced cooperation. It appears that mean hydrological variability in the future will be similar to the pronounced variability seen in the basin today but extremes may well be greater. Greater climate extremes, however, would only strengthen the justification for the basic recommendations of this report. Investing in cooperative information management and modeling systems at the regional level, along with a range of tailored interventions at the national and local levels, would enhance productivity and resilience in the Ganges Basin today as well as the capacity to manage climate change in the future.

Implications and Opportunities

Four areas stand out as opportunities for action based on the findings of the Ganges SBA: (1) development of cooperative basinwide information systems and institutions; (2) flood management using both hard and soft techniques; (3) hydropower development and trade; and (4) groundwater development for irrigation.

1. Cooperative regional information systems, ideally institutionalized in an inclusive river basin committee or commission, could enhance the productivity and sustainability of the river system and help manage water related hazards.
2. If floods cannot be controlled, they must be managed. Infrastructure alone is not the answer. Planners should develop regional information, forecast, and warning systems; and national/local flood management strategies that combine both hard and soft techniques.
3. The potential for hydropower development and trade is significant (if sediment issues can be effectively managed), and should be simpler to negotiate than previously thought.
4. Agriculture planners should look for water storage underground, not just upstream. There is an opportunity for sustainable, conjunctive use of significant additional groundwater resources especially during the low-flow season.

Further Research

In addition to refining and enhancing the current models, this study points to several priority areas for further focused research. Key issues for future focus should include:

- Agricultural productivity in the Ganges plains
- Ecosystem values of dry season water in the Ganges delta
- Climate change in the basin and region

The Ganges SBA has used the best available knowledge and tools to examine the fundamental strategic questions of the Ganges Basin. It has examined a number of commonly held perceptions and concluded that many are unrealistic. It is hoped this new knowledge will help the riparian states explore new visions and move ahead in a cooperative manner to sustainably manage this extraordinary basin and its ecosystems for the benefit of its present and future generations.

1.

Why Undertake A Strategic Basin Assessment?

The Ganges is the most populous river basin in the world. It presents both great opportunities and great challenges for its 655 million inhabitants whose daily lives rely on the water it provides. The river system provides drinking water, agricultural water, hydropower generation, and navigational and ecosystem services across more than 1 million square kilometers.

But the river is destructive as well; devastating floods and periodic droughts are routine and undermine development. With growing populations and increasing water withdrawals putting pressures on the river system, and climate change likely to intensify the seasonal variability, strategic examination of the development potential of the basin's water resources is urgently needed.

All countries in the basin benefit from the Ganges and suffer from its extremes; all could benefit more and suffer less. Benefits from potential hydropower development and agricultural modernization remain untapped, while flood and drought management systems are inadequate to protect lives and livelihoods. To better manage the Ganges – to sustain the river ecosystem, capture its potential benefits, and mitigate its mounting costs – requires enhanced regional knowledge and cooperation.

Development in the basin today is largely the result of incremental, project-by-project activities within each of the riparian countries. There has been surprisingly little systematic regional research on the basin's development options and challenges using modern analytical tools that go beyond sector, country, or state analysis to examine the system-wide strategic questions that the basin faces. In addition, long-held perceptions of the current condition and the future development path of the Ganges Basin vary dramatically within and among different stakeholder groups, institutions, and countries.

The complexity of this river system and the extremes of its landscape call for an evidence-based study of the entire basin system. The very large, poor, and climate-vulnerable population of the basin underscores this need. There has been no common knowledge base or basinwide model that riparian countries could use to explore options and facilitate cooperative planning at the basin level. This is a critical knowledge gap.

The objective of the Ganges Strategic Basin Assessment (Ganges SBA) is to gain a better understanding of the dynamics of the river basin from a system-wide perspective, by creating a knowledge base and suite of modeling tools that can be used to examine the potential impacts of development in the basin and support an information-based dialogue within and between riparian countries.

This new information is envisaged to encourage, rather than conclude, debate on critical transboundary management issues in the Ganges. It is clear that the current understanding of the basin is often fragmented, and that a system-wide perspective can provide important insights to enduring challenges across borders and within riparian states. This report does not provide a roadmap for basin development, nor does it examine the viability of individual investments, but it does provide evidence of sufficient clarity to advance a more focused, information-based dialogue on critical issues in a basinwide context. Importantly, it also highlights the value of a basinwide knowledge base and hence the importance of greater basinwide information sharing, research and modeling – ideally undertaken cooperative by the basin countries – to build a shared knowledge base for basin planning, enhancing agricultural and energy productivity, improving disaster management and longer-term climate research.

Recognizing the wealth of expertise in the basin, this study was carried out by a World Bank team in cooperation with several leading research organizations including the Institute for Water Modeling (Dhaka), Indian Institute of Technology (Delhi), and the Indian Statistical Institute (Delhi). It also benefitted from numerous consultations with policy makers and opinion makers in Bangladesh, India, and Nepal, as well as the members of the Abu Dhabi Dialogue Group;[1,2] and it draws on a vast collection of regional and international literature in which these crucial questions have been debated for many years.[3]

The Ganges Strategic Basin Assessment attempts to sort through the significant amount of information available and answer fundamental questions about the potential and limitations of sustainable, cooperative development in the basin. The centerpiece of this work is the development of a set of nested hydrological and economic river basin models used to examine alternative scenarios across a range of possible Ganges futures, and a social component that studies the social implications of water variability in the basin. This report does not set out project-level cost benefit analyses of different investment options. Nor is its scope adequate to properly reflect the true range of cultural and ecosystems values embodied in the basin. Nonetheless, the Ganges SBA marks an important early step in filling a critical knowledge gap.

Chapter 2 examines the river, its natural history, its usage today, its economic and institutional context, and its emerging challenges. Chapter 3 sets out the analytical framework for the Ganges SBA. Chapter 4 provides a summary of findings and explores possible future implications.

[1] Those who contributed to or were consulted during the development of this report have not necessarily endorsed it.
[2] The Abu Dhabi Dialogue Group is a partnership of senior members of government, academia, and civil society from the seven countries that share the rivers of the Greater Himalayas, namely: Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan. It is an informal, non-attributable platform for discussions on water resources in the region, supported by the World Bank and the South Asia Water Initiative. Its vision is: 'A cooperative and knowledge based partnership of states fairly managing and developing the Himalayan river systems to bring economic prosperity, peace and social harmony, and environmental sustainability from the source to the sea.'
[3] The literature on the Ganges is extensive and rich, representing a range of perspectives and a great deal of research. For example see Adhikari et al., 2000, Ahmad et al., 2001, Crow 1995, Dhungel and Pun 2009, Revelle and Lakshminarayan 1975, Rogers et al., 1989, Subba 2001, Verghese 1990 and others in the bibliography.

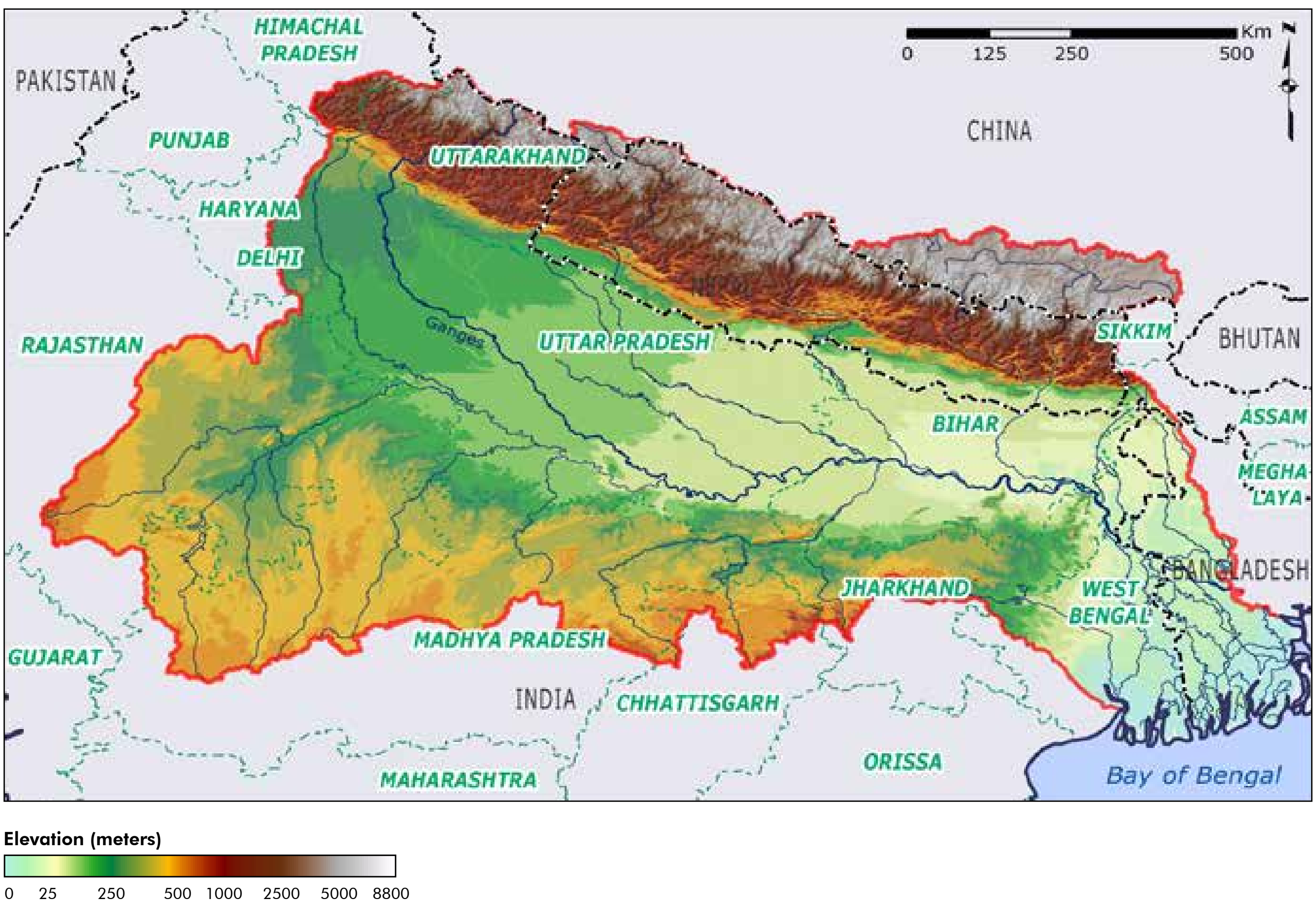
2.

Overview

The Ganges River Basin

The Ganges rises in the Himalaya, travels across the fertile Ganges plains, and flows into the Bay of Bengal through the Earth's largest mangrove ecosystem. In the western reaches of the basin, tributaries flow south from the Himalaya and north from the Deccan Plateau to form the main stem of the Ganges. Within approximately 200 kilometers, the landscape plunges from an area with peaks that include Mount Everest at 8, 848 meters, to the flat Ganges plains at less than 100 meters above sea level. The Deccan Plateau in the south of the basin is generally low elevation with hills up to 1,200 meters punctuated by rocky outcrops (see **Figure 1**). The eastern part of the basin is a flat delta characterized by the extensive and delicate Sundarbans mangrove systems, or 'beautiful forest.' The basin is home to a host of rare and iconic species, including the snow leopard, tiger, and Gangetic dolphin.

Figure 1
Elevation Map of the Ganges Basin



Source: Based on Shuttle Radar Topography Mission (SRTM) data from the United States Geological Survey (USGS)

The total area of the basin is estimated at 1 million square kilometers,[4] covering all of Nepal, about a quarter of the land area of Bangladesh, and nearly one third of India.

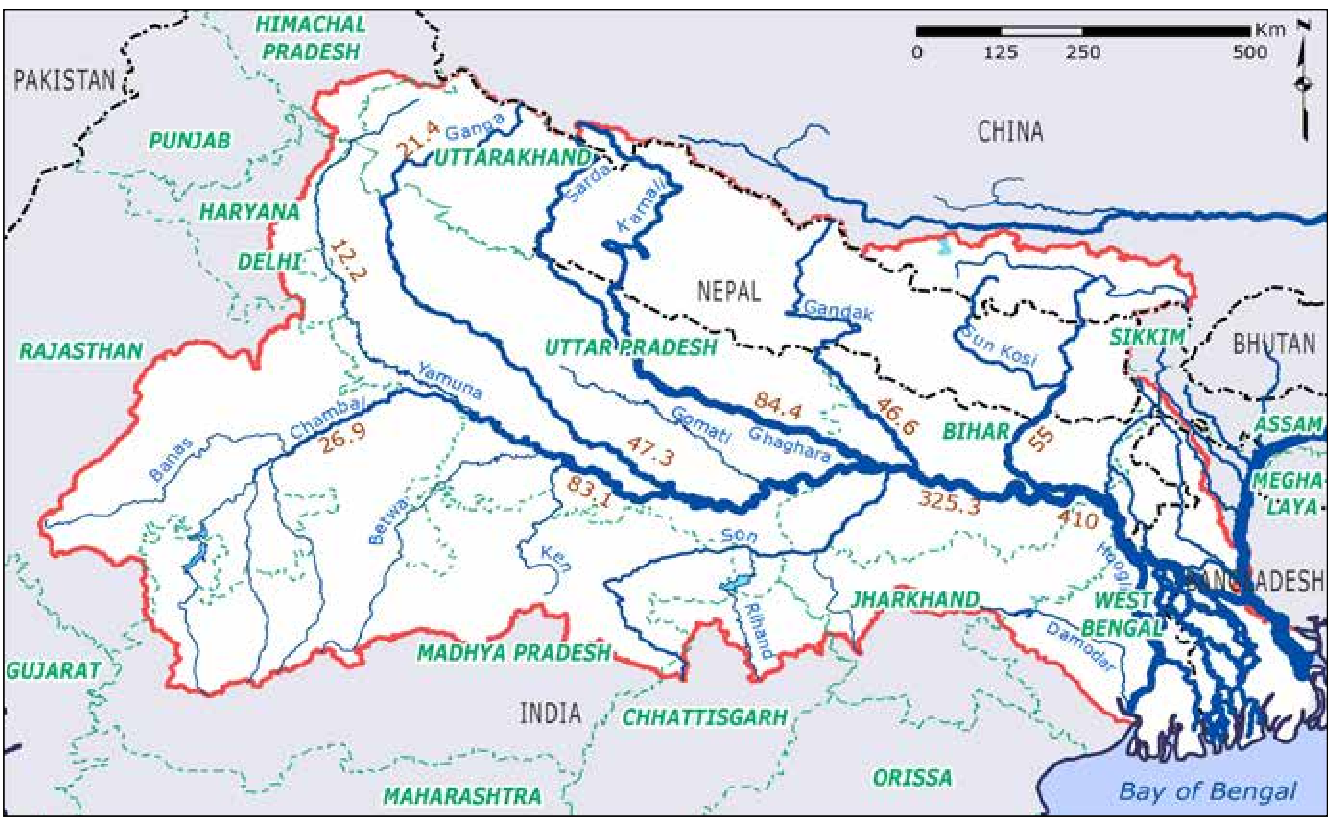
The Water System

The tributaries and distributaries of the Ganges flow through Bangladesh, China, India, and Nepal. The Ganges originates in the Gangotri Glacier at about 4,000 meters above sea level in the Indian state of Uttarakhand, and flows more than 2,500 kilometers to Bangladesh and the Bay of Bengal. Its major tributaries include the Himalayan tributary rivers of the Yamuna, Mahakali, Karnali, Gandaki and Kosi and Mahananda rivers from the North. These northern Himalayan tributaries rise primarily in Nepal and India, with some portion of the Kosi, and to a lesser extent the Karnali, rising in China. From the south, the tributaries of the Yamuna (the Chambal, Sindh, Betwa, and Ken Rivers), and the Tonnes and Son Rivers flow north into the main stem of the Ganges.

Figure 2

Schematic of the Major Tributary Contributions of the Ganges

Ganges Basin - Average Annual Flows



Source: Based on data from Rao (1979).

Annual Flow (BCM)

< 10	20-25	40-45	65-75	200-350
10-12.5	25-30	45-50	75-100	350-400
12.5-15	30-35	50-55	100-150	400-600
15-20	35-40	55-65	150-200	> 600

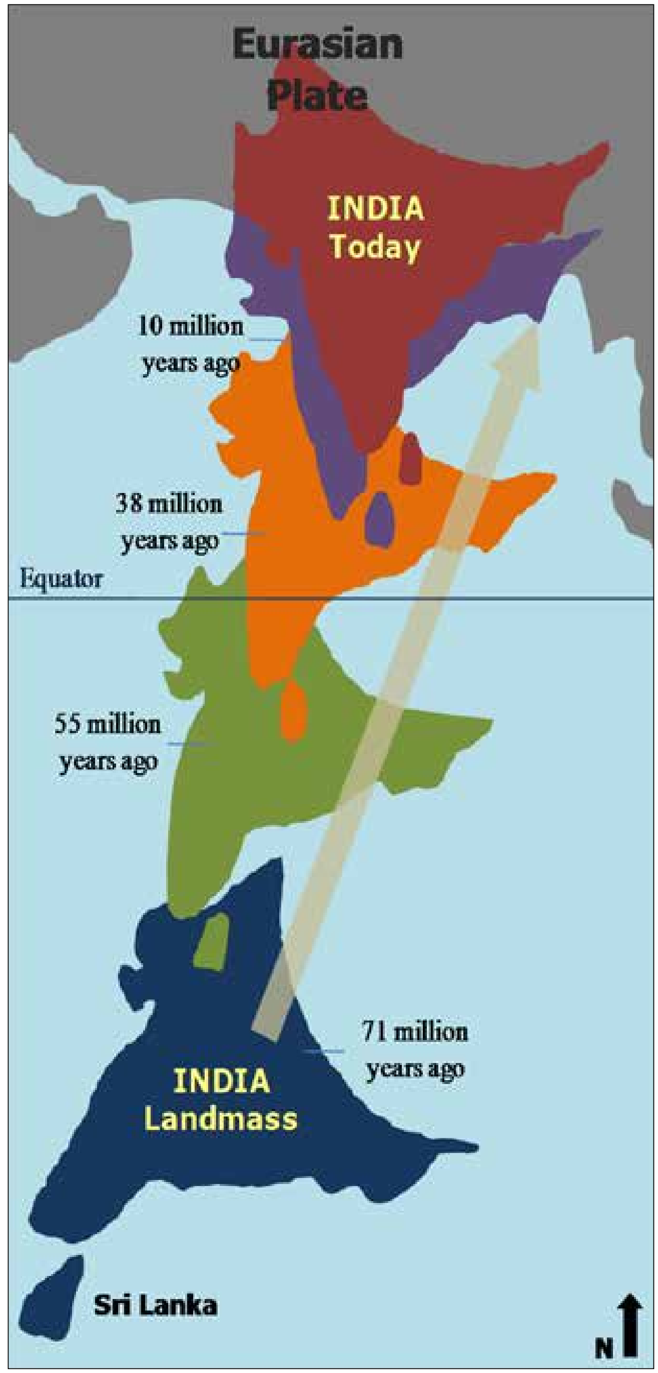
[4] WRI (2007)

Figure 2 indicates the contributions of the major tributaries of the Ganges Basin. The Yamuna River, the Mahakali/Karnali/Ghaghra River, the Kosi River, and the main Ganga River are the system's biggest flow contributors. The distributary system is also extensive. In India, the Damodar-Hooghly River system defines a distributary system that flows out to the Bay of Bengal near Kolkata. The main outlet of the Ganges, however, is in Bangladesh where the main stem of the Ganges (called the Padma in Bangladesh) merges with the Brahmaputra (called Jamuna in Bangladesh) before flowing into the Bay of Bengal through a 380-kilometer-wide delta.

A continental collision created the Himalaya. The geomorphic history of the Ganges suggests that the basin was shaped by the collision of the Indian tectonic plate with the Eurasian plate about 20 million years ago **(Figure 3)**. This event caused the formation of the Himalaya, which were uplifted by the collision. The Himalaya continue to grow as the Indian plate continues to push northward under the Eurasian plate causing it to rise. Some of the Ganges tributaries (e.g. Ganga, Karnali, Kosi) are 'antecedent rivers' that existed before the Himalaya were pushed up. These rivers rise north of the Himalayan range and appear to run 'up and over' the mountain range to drain in the south. These powerful rivers sustained their southward flow by cutting deep gorges even as the mountains rose up around them.

The Himalaya are the 'water tower' of Asia, the source of the Ganges and many great rivers. The Greater Himalayan Region sustains the largest mass of ice outside of the north and south poles, and is therefore often referred to as the 'third pole.' From this region rise more than a dozen major rivers including the Ganges, Indus, Brahmaputra, Salween, Mekong, Yangtze, and Yellow. The rivers of the plateau flow west as far as Iran (where the Helmund River terminates in the swamps and lakes of the Afghan-Iranian border), and flow east as far as the East China Sea where the Yangtze River empties near Shanghai.

Figure 3
Creation of the Himalaya

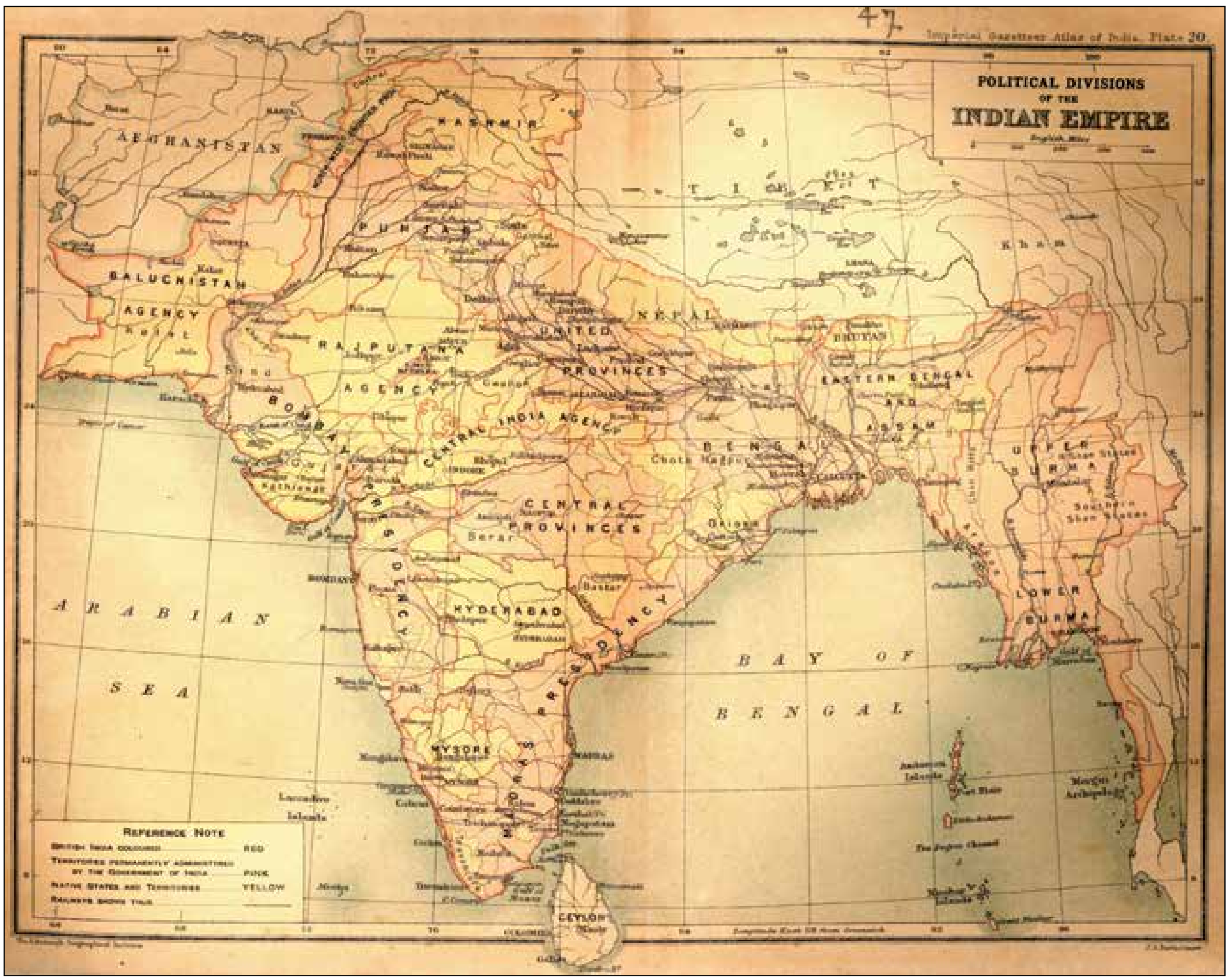


Source: Based on USGS (2011).

The Ganges is a massive, meandering river system whose channel has gradually moved eastward. The morphology of the Ganges-Brahmaputra delta over the past several thousand years suggests that the Ganges River course has moved eastward[5] while the Brahmaputra has largely remained in its current course.[6] According to early maps of the region – as recently as a few hundred years ago – the Ganges and Brahmaputra had separate outlets to the sea **(Figure 4)**. As a result of the Ganges's eastward movement it has abandoned a series of channels that no longer receive significant amounts of water from the main river. The Hoogly River, for example, was once the main outlet of the Ganges emptying into the Bay of Bengal at Calcutta.[7] The majority of the Ganges flow shifted eastward to

Figure 4

Historical Map of South Asia with Separation of the Ganges and Brahmaputra Rivers
Source: The Imperial Gazetteer of India (1909)



[5] Allison 1998.
[6] Kuehl *et al.*, pp. 413-34. 2005.
[7] The Hoogly River today receives controlled flows delivered by the Farakka Barrage.

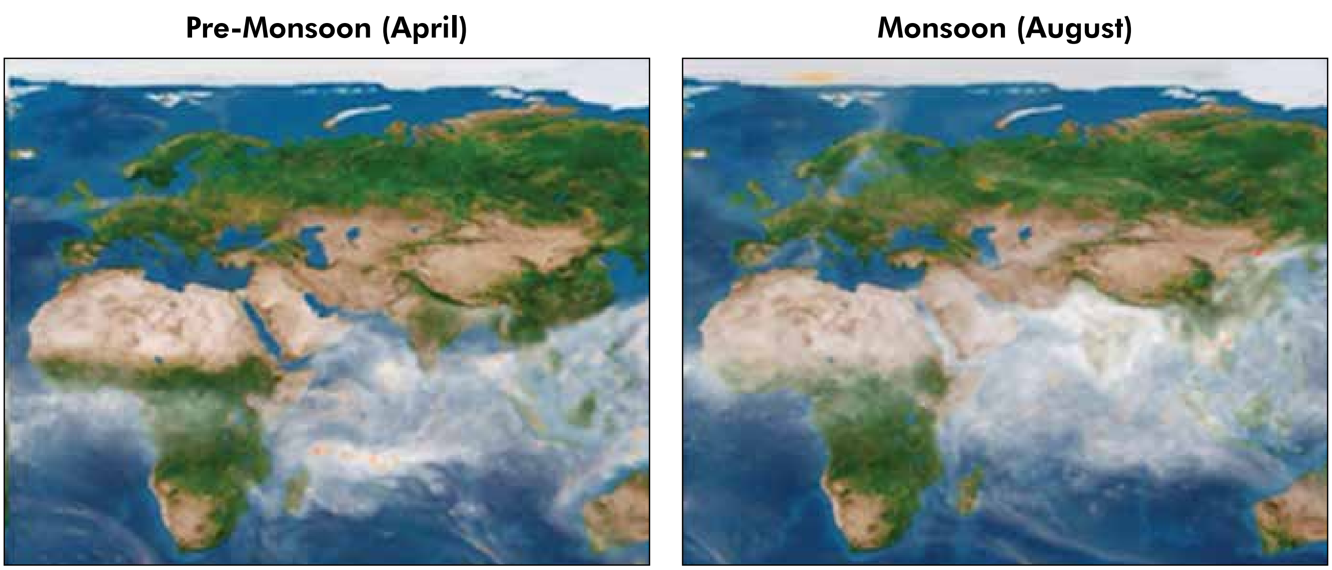
the Gorai River system in southwest Bangladesh, and eventually to its current primary outlet in southeast Bangladesh. Even after the merger of the Ganges with the Brahmaputra, the while Ganges-Brahmaputra-Meghna system continues to move eastward, with a corresponding movement of the active delta. Attempts to control this massive moving river have been likened to 'putting handcuffs on a snake.'[8]

The Ganges river system is a complex interplay of monsoonal runoff, glacier and snow melt, and groundwater resources. The system's complex natural features – monsoon rains, the Himalayan mountain range, and its vast plains and delta – make it difficult to comprehend. Added to the diversity and extremes of the landscape is a pronounced seasonality. A systemwide understanding of the hydrology and climate is fundamental to effectively managing virtually any stretch of the river.

The Himalayan mountain range plays a key role in the hydrological environment of the Ganges by blocking the northerly push of the monsoon and confining it to the subcontinent. Simulations from a Global Circulation Model (GCM) developed by the National Center for Atmospheric Research (NCAR) show how the South Asian monsoon is contained in the subcontinent by the Hindu Kush–Himalaya range **(Figure 5).** In the pre-monsoon period (April) there is little precipitation over South Asia. In the monsoon period (August) the subcontinent is draped in cloud, with a sharply delineated northern edge that follows the arch of the Hindu Kush–Himalaya range.

The South Asian monsoon system largely defines the climate and hydrology of the Ganges river system. Two arms of the South Asian monsoon sweep across the continent along either coast of peninsular India **(Figure 6)**. During an average hydrological year, some 1,200 billion cubic meters of precipitation falls in the basin. Of this, about 500 billion cubic meters flows into the river system and becomes the Ganges River

Figure 5
Confinement of the South Asian Monsoon



Source: National Center for Atmospheric Research (NCAR)[9]

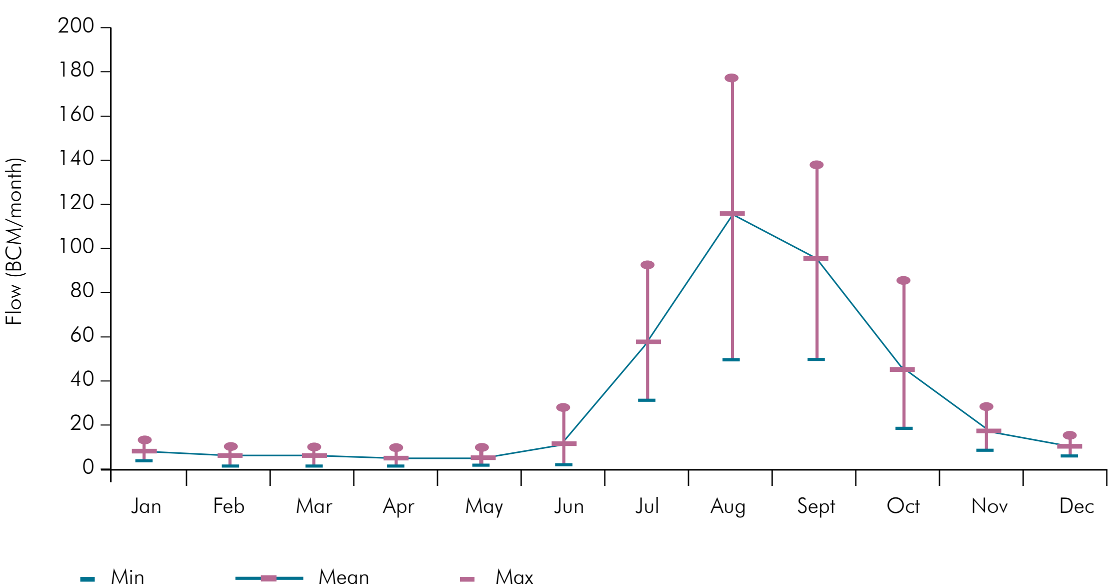
[8] Don Blackmore, personal communications.
[9] Atmospheric configuration and simulation by James Hack (Oak Ridge National Lab), Julie Caron, and John Truesdale, National Center for Atmospheric Research (NCAR). Visualization by James Hack and Tim Scheitlin, copyright 2007, NCAR.

flow. The remaining 700 billion cubic meters of water is captured in the landscape, recharging groundwater or returning to the atmosphere through evapotranspiration.

The monsoon brings heavy rains three months a year. The monsoon delivers about 80 percent of annual rainfall in just three months of the year (mid-June through mid-September) with a corresponding peaking in the river flows in July to October. **Figure 7** depicts the flow of the Ganges at Farakka Barrage near the India-Bangladesh border. The peak is caused by intense monsoon rains from mid-June through mid-September, against the relative low flows for the remainder of the year. April and May are the lowest flow months with negligible rainfall and a low base flow into the system. In addition to the significant seasonal variation within years, there is also great variability between years (especially in monsoon months), depicted by the vertical lines that indicate the minimum and maximum flows recorded for each month.

Figure 6
Path of the South Asia Monsoon

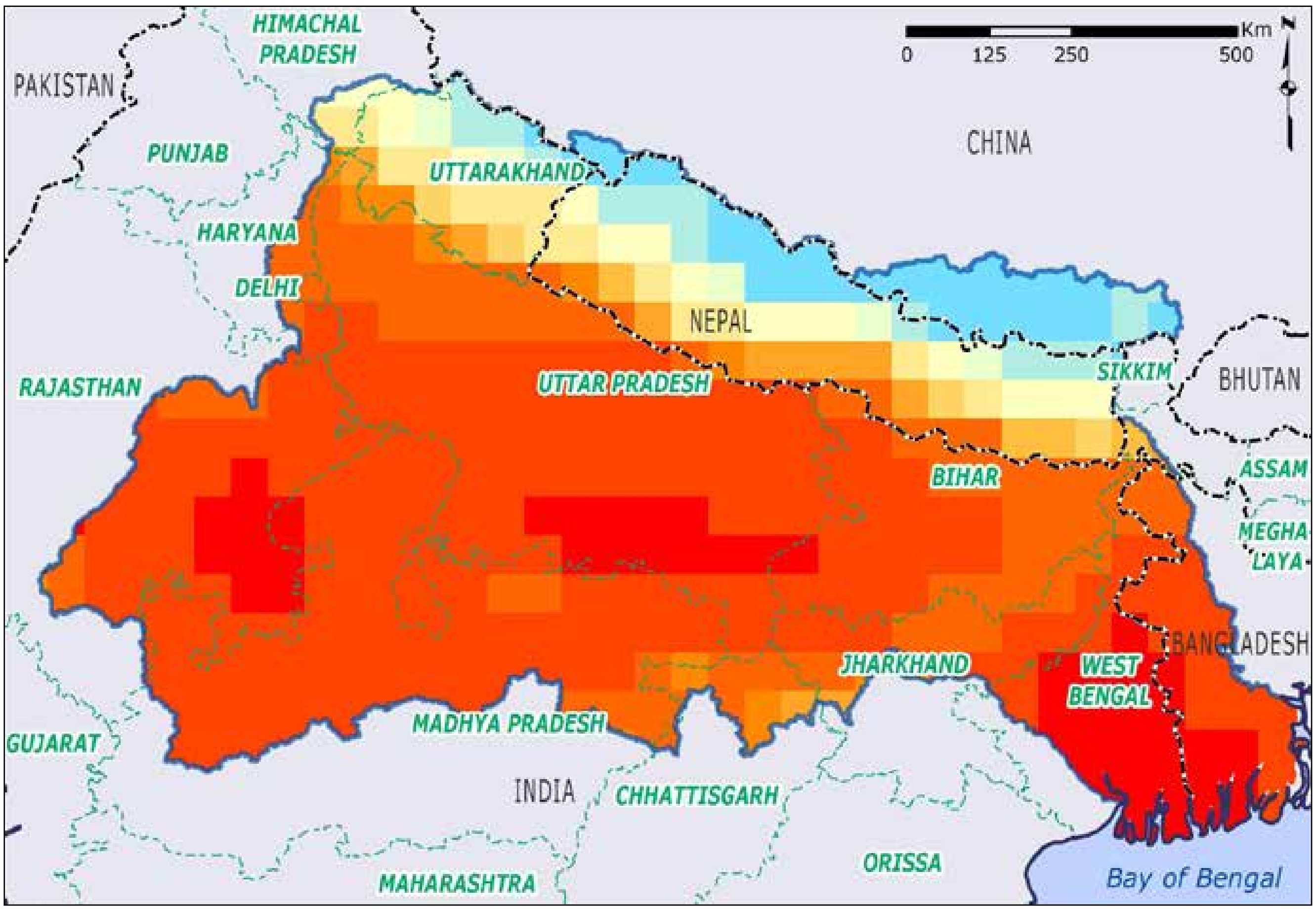
Figure 7
Seasonal and inter-annual variability of flow in the Ganges at Farakka. Data from Global Runoff Data Centre 1949-1973



The non-monsoon months are generally hot and dry. Temperatures are high most of the year in most of the basin except for the Himalaya **(Figure 8)**. Precipitation is highest (more than 2,000 millimeters annually) in the eastern Himalayan belt and in the delta areas of the basin, and lowest (less than 250 millimeters annually) in the Thar desert of Rajasthan in the west. There is general scientific consensus that climate change will increase temperatures throughout the basin, leading to impacts such

Figure 8
Temperature and Precipitation in the Ganges Basin

Temperature



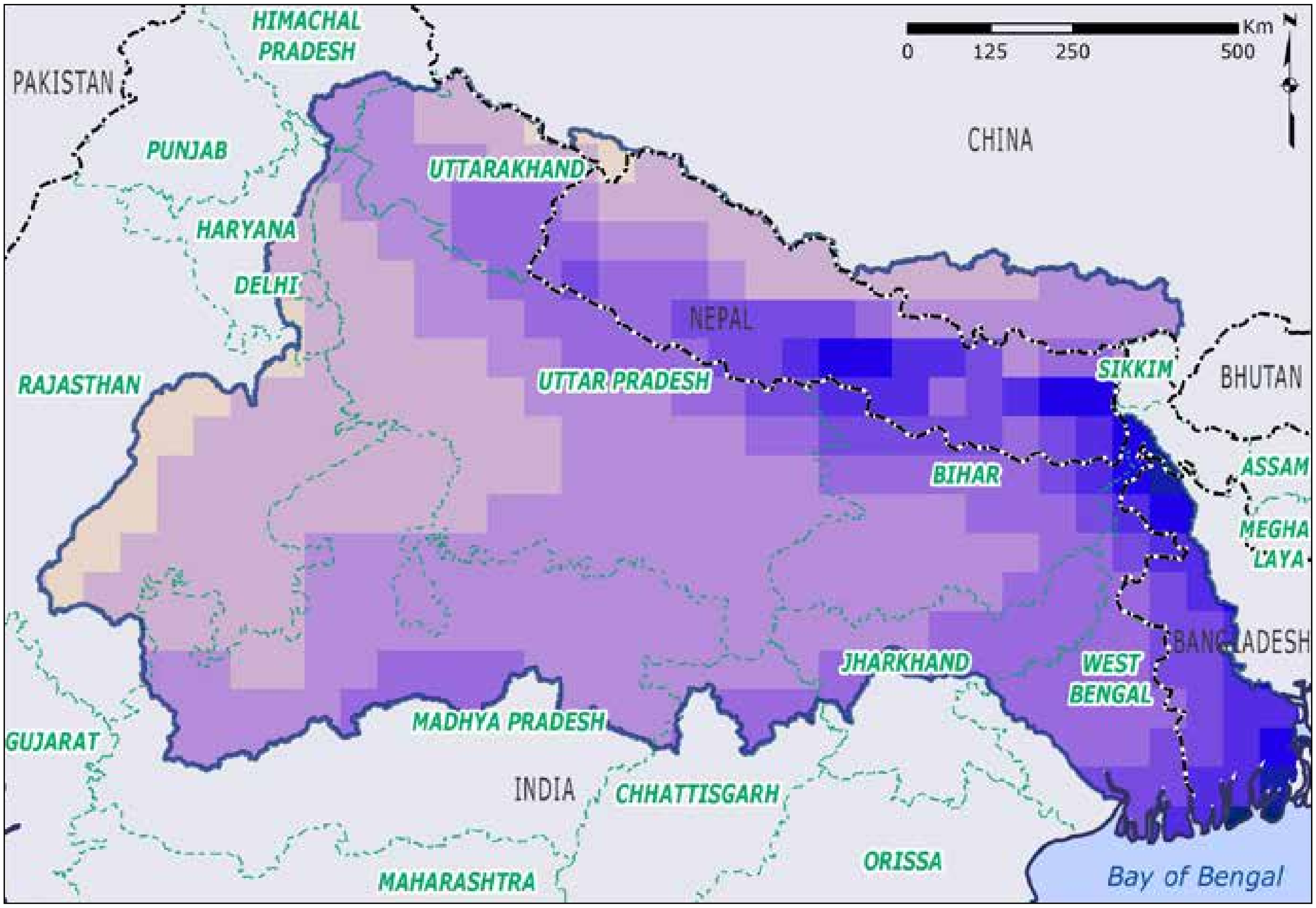
Annual Average Temperature (°C)

< 0 | 0 - 5 | 5 - 10 | 10 - 15 | 15 - 20 | 20 - 21 | 21 - 22 | 22 - 23 | 23 - 24 | 24 - 25 | 25 - 26 | 26 - 27 | 27 - 28 | 28 - 29 | 29 - 30

< 300 | 300 - 600 | 600 - 900 | 900 - 1200 | 1200 - 1500 | 1500 - 1800 | 1800 - 2100 | 2100 - 2400 | 2400 - 2700 | > 2700

Source: Based on CRU TS 2.0 climate dataset from the British Atmospheric Data Centre (BADC), University of East Anglia.

Precipitation



Annual Average Precipitation (mm/year)

< 0	10 - 15	21 - 22	24 - 25	27 - 28	< 300	900 - 1200	1800 - 2100	> 2700
0 - 5	15 - 20	22 - 23	25 - 26	28 - 29	300 - 600	1200 - 1500	2100 - 2400	
5 - 10	20 - 21	23 - 24	26 - 27	29 - 30	600 - 900	1500 - 1800	2400 - 2700	

Source: Based on CRU TS 2.0 climate dataset from the British Atmospheric Data Centre (BADC), University of East Anglia.

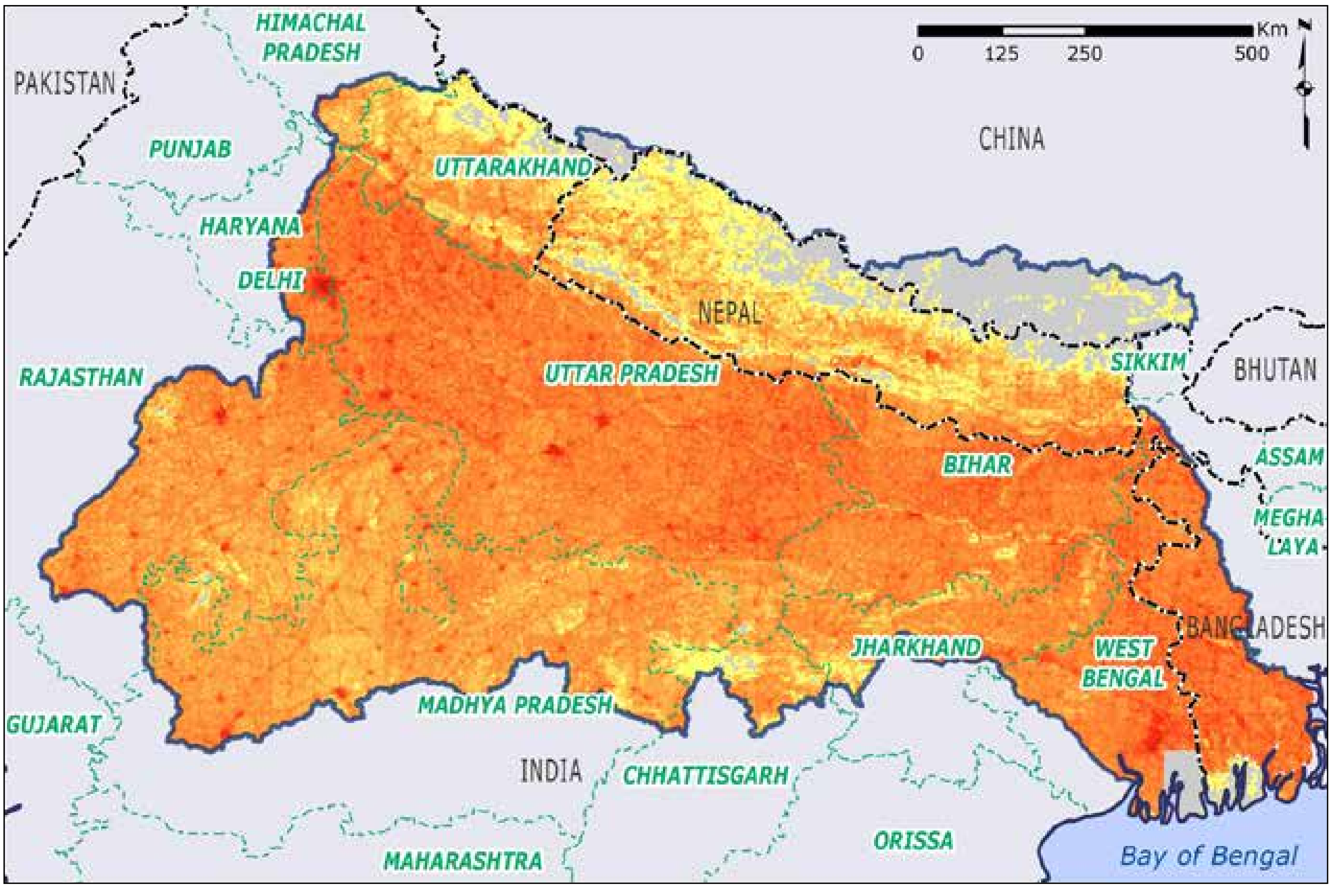
as increased evaporation, increased crop water requirements, changes in snow formation and melt, and changes in glacier accumulation and melt.

The basin's climate is highly variable, prone to both flood and drought. Climate variability is seen most dramatically in floods, droughts, and the uncertain timing of the onset of the monsoons.

Large areas of the basin routinely suffer from both droughts and floods **(Figure 9)**. Floods already take a significant toll on lives and livelihoods in the Nepal lowlands known as the terai, as well as in Bangladesh and the Indian states of Bihar and eastern Uttar Pradesh. Floods account for 90 percent of the economic cost of natural disasters in Nepal. See **Box 1** for efforts to manage floods.

Figure 9
Drought and Flood Affected Populations in the Ganges Basin

Exposure to Droughts



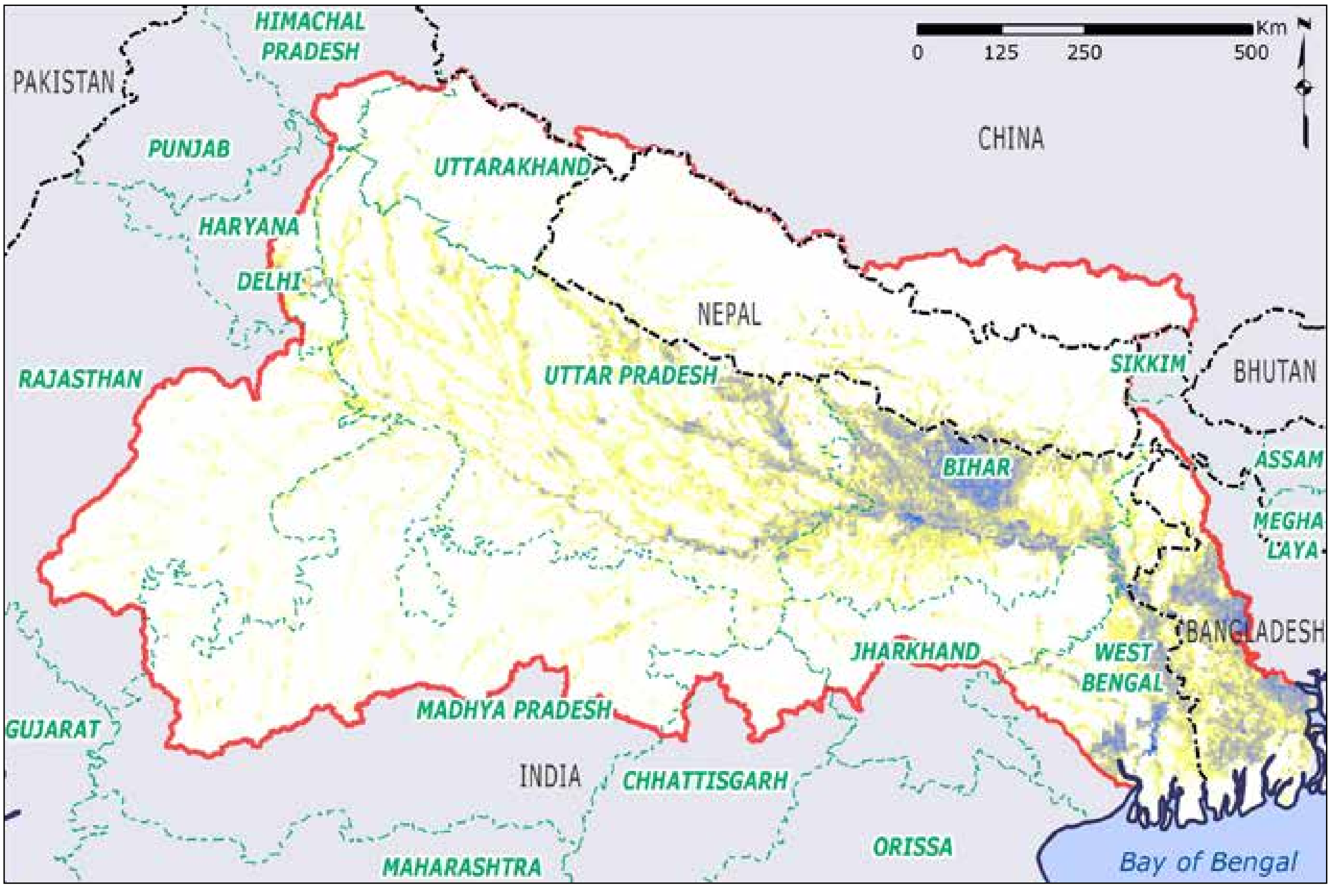
Population 2010 exposed
(Thousands of people per year)

None / No Data
< 0.025
0.025 - 0.05
0.05 - 1
1 - 0.25
0.25 - 0.5
0.5 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 25
25 - 50
50 - 100
100 - 250
250 - 500
500 - 1000
1000 - 2500
2500 - 5000
None
< 0.025
0.025 - 0.05
0.05 - 1
1 - 0.25
0.25 - 0.5
0.5 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 25
25 - 50
50 - 100
100 - 250
250 - 500

Source: Based on data from Global Risk Data Platform, UNEP/GRID (2011).

Glaciers contribute a small share of the total Ganges flow. Glaciers and snow provide water storage that contributes to the perennial flow of these highly seasonal river basins. It should be noted, however, that in contrast to Europe and North America where glacial melt contributes to low summer flows, the Himalayan glaciers melt during the monsoon season when temperatures are highest but rainfall is also heaviest. In the Ganges Basin, glacier melt water accounts for just 2

Exposure to Floods



Population 2010 exposed
(Thousands of people per year)

None / No Data	0.25 - 0.5	10 - 25	500 - 1000	None	0.25 - 0.5	10 - 25
< 0.025	0.5 - 1	25 - 50	1000 - 2500	< 0.025	0.5 - 1	25 - 50
0.025 - 0.05	1 - 2.5	50 - 100	2500 - 5000	0.025 - 0.05	1 - 2.5	50 - 100
0.05 - 1	2.5 - 5	100 - 250		0.05 - 1	2.5 - 5	100 - 250
1 - 0.25	5 - 10	250 - 500		1 - 0.25	5 - 10	250 - 500

Source: Based on data from Global Risk Data Platform, UNEP/GRID (2011).

percent of annual flow in the main river system.[10] (In contrast, the Himalayan glaciers that feed the Indus provide some 20–30 percent (e.g., Bolch et al., 2012; Yu et al., 2013.) Within the Ganges Basin, glacier contribution to stream flow varies enormously and glacier melt does play an important role in many glaciated sub-basins. In Nepal's Budhi Gandaki Basin, for example, the glaciers' contribution to the total measured stream flow is about 30 percent, whereas in Nepal's Likhu Khola Basin it is just 2 percent. The average for all Nepal's rivers is approximately 10 percent. A better understanding of this glacier system will be essential to protecting vulnerable communities and managing climate adaptation in South Asia.

[10] Alford and Armstrong 2010.

Box 1
Enduring Challenge of Floods Tackled by Modern Technologies

Bangladesh has piloted a range of innovative approaches to flood management in recent decades, including innovative forecasting (hydrologic forecasts based directly on weather forecast ensembles), modeling (using a suite of hydrologic and hydrodynamic modeling tools), and communications (using cell phones and community warning systems). These innovations have been highly effective in reducing flood losses.

The Indian state of Bihar recently created a new Flood Management Information Systems Center to improve its capacity for flood forecasting and response. Nepal is investing in crucial real-time information that will strengthen forecasting and warning capacity. Real-time data from Nepal is routinely shared with India's Central Water Commission to issue flood warnings in downstream areas. National systems are being updated in all countries. Significant opportunities remain, however, to improve data acquisition, public data access, forecasting techniques using integrated ground and satellite systems, modeling, and communication systems. In addition to technological innovations, robust institutional arrangements both within and among basin countries will be needed to diminish annual losses of lives and livelihoods caused by floods.

Sedimentation is an enduring challenge in the Ganges Basin. The Ganges Basin was formed as eroded materials from the Himalaya were deposited to fill what was once a cape and is now the Ganges plains, creating large floodplains and deep aquifers. The Ganges is one of the most sediment-laden river systems in the world, with a silt load that is an order of magnitude larger than most rivers. **Table 1** shows the world's top ten rivers in terms of suspended annual sediment load; together they account for about 30 percent of the world total.[11] The Ganges-Brahmaputra River systems carry more than 1 billion tonnes of silt[12] to the delta every year. This is an extremely high sediment load, and one that is not particularly fertile.[13] It is important to understand, however, because the dynamics of erosion and accretion have been constantly redefining the coastal contours of Bangladesh and the Indian state of West Bengal.

Table 1
Average Annual Suspended Sediment Load

River	Average Annual Suspended Sediment Load (million tonnes)
Amazon	1,200
Yellow (Huang He)	1,080
Ganges/Brahmaputra	1,050
Yangtze (Chang Jiang)	480
Irrawaddy	260
Magdalena	220
Mississippi	210
Godavari	170
Mekong	160
Orinoco	150

Source: Adapted from: Milliman and Mei-e Ren 1995.

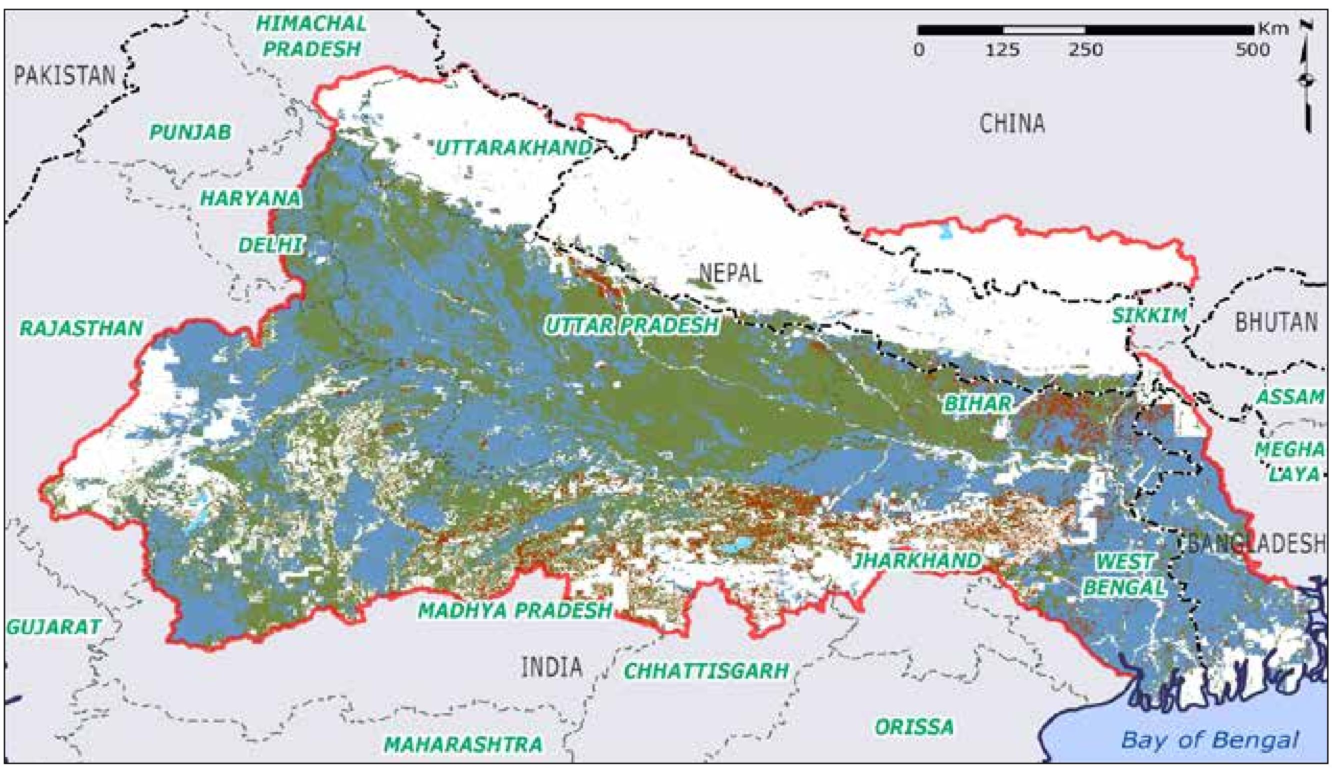
[11] Milliman and Mei-e Ren 1995.
[12] Kuehl et al., 2005.
[13] Subramanian and Ramanathan 1996.

Water Management in the Basin

Agriculture dominates both surface and ground water use in the basin. Irrigation represents about 90 percent total water use in the Basin, though increasing demand from urban centers and industry can be expected to shift this balance in the coming years. The basin is home to some of the largest irrigated areas in the world. The state of Uttar Pradesh alone has about 9 million hectares at least partially irrigated with surface water, and an additional 8 million hectares that rely solely on groundwater **(Figure 10).**

Agricultural productivity in the basin is low, however, and water availability is not always a binding constraint. A recent study by the Water for Food Challenge Program of the Consultative Group on International Agricultural Research (CGIAR) found that in the eastern basin (Uttar Pradesh, Bihar, and West Bengal in India, eastern Nepal terai, and all of Bangladesh) 'Rich alluvial soils and abundant surface and groundwater provide high agricultural potential; however, for a variety of reasons including inadequate drainage, unfavorable land tenure, and inadequate infrastructure and institutional arrangements including marketing, combined rice-wheat productivity is estimated to be just 4-8 tonnes per hectare per year.'[14] Wheat yields in the Indian State of Bihar, part of West Bengal and Bangladesh are as low as 0.70 to 1.58 tonnes per hectare.[15]

Figure 10
Irrigation in the Ganges Basin



Irrigated Areas

Surface   Ground   Conjunctive Use

Source: Based on Global Irrigated Area Map by IWMI.

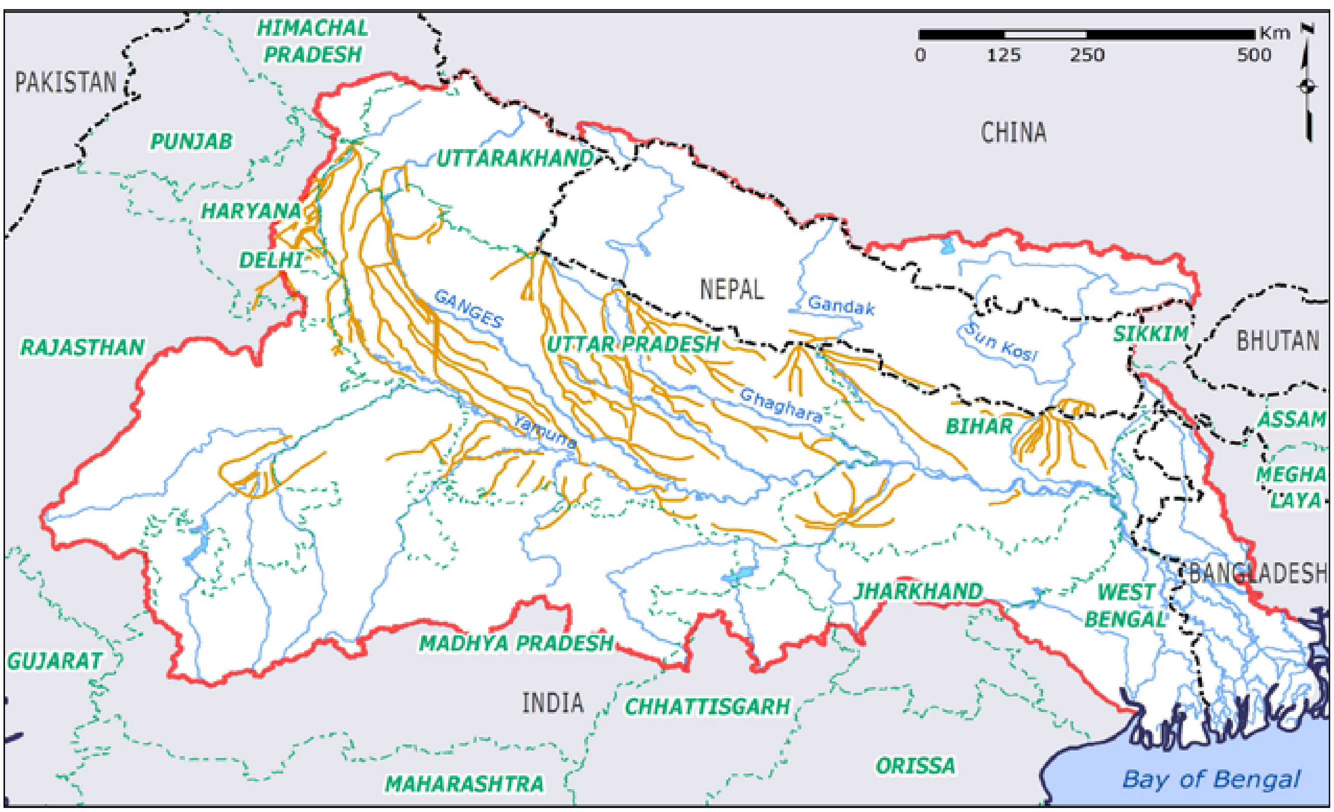
[14] Sharma 2008.
[15] Cai et al., 2010.

Although additional water in the dry season may be a welcome resource for some communities (and likely of significant value to ecosystems), it is clear that upstream dams alone will not modernize agriculture in the Ganges. National-level investments and policy reforms are needed to enhance agricultural productivity, which would benefit poor farmers even in the absence of upstream water storage development.

Extensive surface irrigation schemes have been developed in the Ganges plains, particularly in India. The surface irrigation canal network in the basin **(Figure 11)** has developed in various phases, starting primarily in the British period (mid-19th to mid-20th centuries) for example, with the Upper Ganga Canal system. But the area is not solely surface irrigated. Extensive conjunctive use of groundwater permits cultivation of a second crop in the dry season. Groundwater is also used to buffer against the erratic surface water supply. Much of this conjunctive use is unplanned, undertaken by individual farmers using primarily deep (electric) tubewells in the western part of the Ganges Basin, and shallow (diesel) tubewells in the east.

Although some of the older irrigation systems (e.g. in western Uttar Pradesh) are in good condition with reasonably good productivity, much of the surface irrigation system is in poor condition (e.g. in eastern Uttar Pradesh) and the soil suffers from waterlogging and poor productivity. In Bangladesh, groundwater irrigation with shallow tubewells helped make the country self-sufficient in food production, although challenges (including naturally occurring

Figure 11
Irrigation Canals in the Ganges Basin



Canal

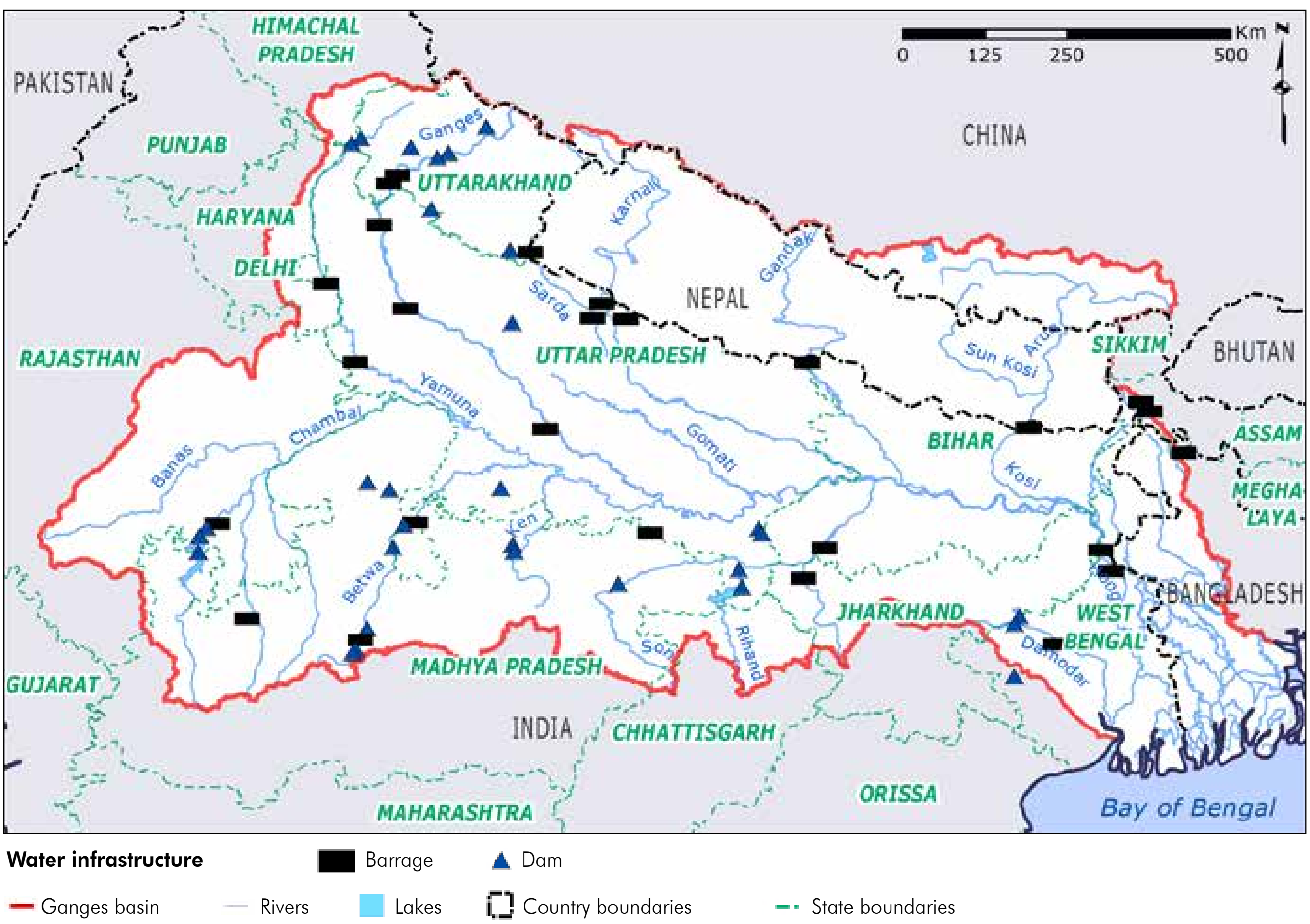
Source: Based on data from RMSI Pvt. Ltd.

arsenic in the groundwater) remain in the continuing management of water.

To a large extent, the surface and groundwater irrigation systems in the Ganges plains are interlinked. The surface irrigation canals often serve to recharge the groundwater and the groundwater systems are often used to supplement surface water, especially in eastern Uttar Pradesh. Eastern Uttar Pradesh also has large areas where pre-monsoon groundwater levels are either at or just below the surface, resulting in waterlogged areas with poor productivity.

There is little active water storage in the system today. The Ganges Basin has more than 1,000 dams in its 1 million square kilometers with heights varying from 10 meters to 260 meters **(Figure 12)**. Only five of them are more than 100 meters tall. The system's surface storage capacity is about 55 billion cubic meters, with about 36 billion cubic meters currently active. This storage capacity, compared with an annual system flow of about 420 billion cubic meters (and rainfall approaching three times that value), is only 13 percent of the total water available annually. As a point of reference, many developed rivers have storage-to-annual-flow ratios of 100–200 percent. Thus, there is very little capacity to regulate the system to reduce flooding, augment low flows for winter (rabi) irrigation or operate storage-backed hydropower production.

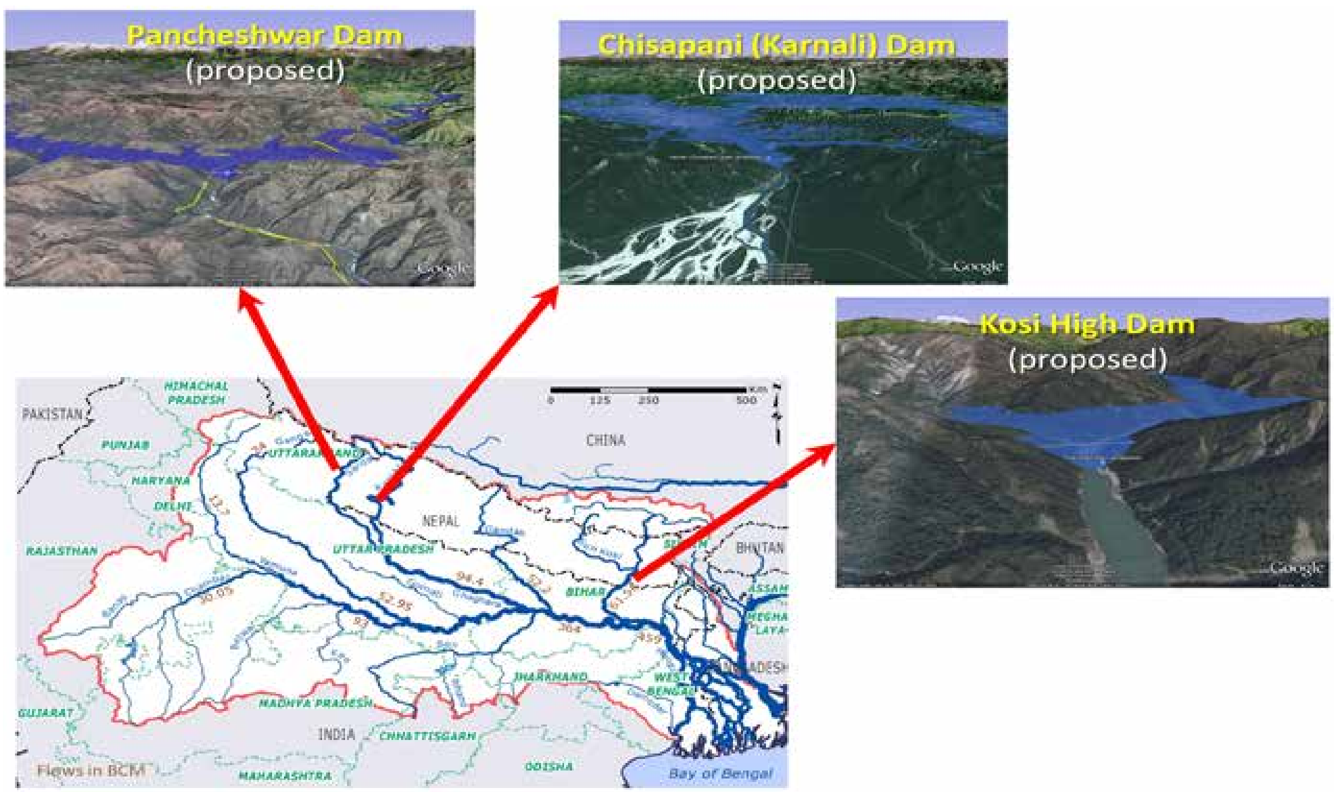
Figure 12
Major Dams and Barrages in the Ganges Basin



The basin offers significant opportunities for additional water development and use. The Ganges Basin has been extensively developed for irrigation, but a range of additional water development opportunities remain. The Himalayan Mountains offer potential multipurpose dam sites, the plains could support enhanced irrigation, and deep aquifers with good-quality groundwater resources could be tapped.[16] Although many of these options could be pursued by riparian countries, some would require effective regional cooperation. Many such options (e.g. multipurpose dams in the Himalaya) have been discussed for decades with little action. In particular, three proposed large dam sites in the Nepal Himalaya – the Pancheswar Dam on the Mahakali River, the Chisapani Dam on the Karnali River, and the Sapta Kosi High Dam on the Kosi River **(Figure 13)** – have long been considered for development. The combined installed hydropower generation capacity of these three dams would be roughly 30 times Nepal's current total installed capacity.

Embankments have become a pervasive feature of the Ganges landscape. Construction of embankments to control flooding began on a large scale began during British rule. The majority of embankments, however, were built following India's independence.[17] Between 1954 and 1997, around

Figure 13
The Sites and Simulated Reservoirs of the Three Largest Dams under Consideration in Nepal



Ganges Basin · International boundaries · State boundaries · Rivers

Source: Using Google Earth imagery.

[16] See SMEC 2009 and Sharma et al., 2008.
[17] Mishra 2008.

16,200 kilometers of embankments were constructed in India, and around 7,555 kilometers (including around 4,000 kilometers of coastal embankments) were constructed in Bangladesh. This construction resulted in the protection of 17 of the 40 million hectares prone to floods on the Ganges plain in India,[18] and 3.5 million hectares in Bangladesh, about a quarter of its total land area.[19] In Nepal, only a few hundred kilometers of embankment has been constructed.[20]

Socioeconomic Context

The Ganges is the most populous river basin in the world, home to more than 655 million people in its total area of 1 million square kilometers.[21] As a point of comparison, the next most populous basin is China's Yangtze River Basin with some 400 million people and considerably more land area. The Indian state of Uttar Pradesh, which falls entirely within the Ganges Basin, has roughly the same population as Brazil, the world's fifth most populous country **(Table 2)**.

Poverty is widespread, with average GDP per capita under $2 per day and poverty rates around 30 percent. In Nepal, where the entire population resides within the basin, average GDP per capita is $470 and the proportion of the population with a standard of living below the poverty line is 31 percent.[22] In India and Bangladesh, poverty in the Ganges Basin districts is higher than the national average **(Figure 14)**. India's 2005 national poverty estimates show 27.5 percent[23] of its population living below the poverty line; however, in the vast majority of states with some or all districts inside the Ganges Basin, these percentages were higher, rising to around 40 percent in Bihar, Chhattisgarh, Jharkhand, Madhya Pradesh, and Uttarakhand.[24] Poverty estimates for Bangladesh also show those districts in the basin to have a slightly higher poverty rate than the national average. The districts of Bangladesh in the Ganges Basin recorded total poverty rates (upper poverty line) of 44 percent, as compared with the national average of 40 percent.[25]

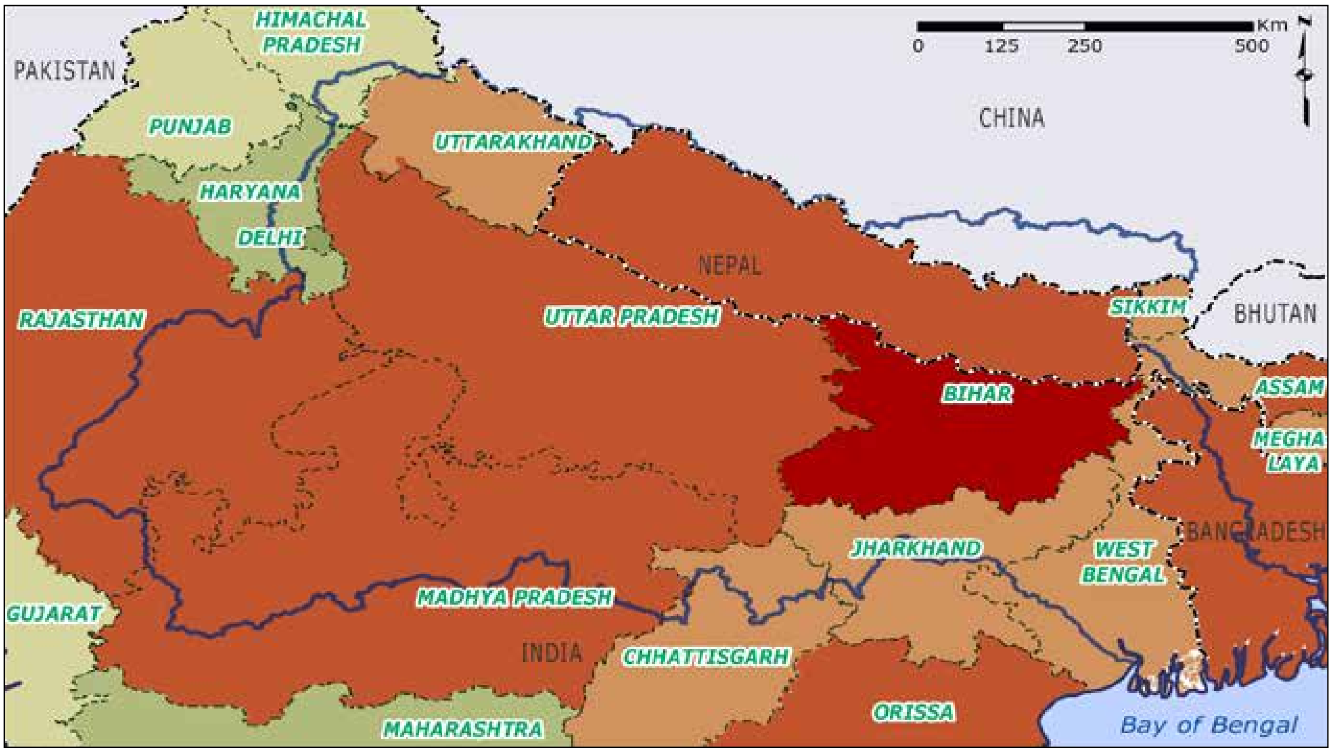
Table 2
Population Profile of the Ganges River Basin

Country	Basin Population in 2000 (2011 est.)[a] Thousands	Average Population Density per sq. km (2011	Basin Area (sq. km)	% of Country Area within the Basin	% of Basin Area within the Country[b]	% of Country Population within the Basin	% of Basin Population in Country
Nepal	28,504	194	147,184	100	12	100	4
Bangladesh	50,680	1,285	39,452	27.4	3	38	8
India	576,344	575	1,002,609	30.5	84	47	88
Total	655,528	551	1,189,246				

Note: a. Population estimates include the total population of Nepal, and the populations of districts within the Ganges Basin for Bangladesh and India. Nepal's 2011 population is estimated using the 2001 census figures and the presumed decadal growth rate calculated in that census. Estimates for Bangladesh use relevant district level populations from the 2001 census and the decadal growth rates for 2001-2011 from the 2001 census. Estimates for India use district-level data from the 2001 census and assume 2011 preliminary state population growth estimates and uniform growth across districts within a state (district level population growth rates are not available.)
b. The residual basin area is in China.

[18] NCIWRDP, 1999: 129, as cited in Bandyopadhyay 2009
[19] Islam and Bari 2008.
[20] Dixit 2009.
[21] WRI 2007.
[22] World Bank 2011.
[23] Based on Uniform Recall Period consumption, in which the consumer expenditure data for all the items are collected for a 30 day recall period. Poverty lines in this case vary by state. Indian National Planning Commission.
[24] Only Delhi, Haryana, and Himachal Pradesh had lower than average proportions of the population living below the poverty line (estimated at around 14.7, 14, and 10 percent, respectively) and Rajasthan and West Bengal were near the national poverty line at 22 and 24 percent, respectively.
[25] Poverty maps produced by Bangladesh Bureau of Statistics, World Bank, World Food Programme, 2007.

Figure 14
GDP Per Capita, 2005



GDP per capita in 2005 (Nominal, in USD)

- < 250
- 250 - 500
- 500 - 700
- 700 - 1000
- 1000 - 1500
- 1500 - 2000
- > 2000

Source: Based on data from Central Statistical Organization, India and WDI 2010 (World Bank)

The basin is one of the most densely populated areas on earth. Average population density in the basin is 551 people per square kilometer, more than 10 times the global average **(Table 2 & 3 and Figure 15).** Bangladesh's total population is similar to Russia's, but its population density is 120 times greater.

In the Indian states of the basin, those districts that fall within the basin boundaries have an average population density more than five times that of the districts in the same state but outside the basin boundaries. Population density is particularly high in the eastern basin where many districts have more than twice the (already quite high) average population density for the basin as a whole.

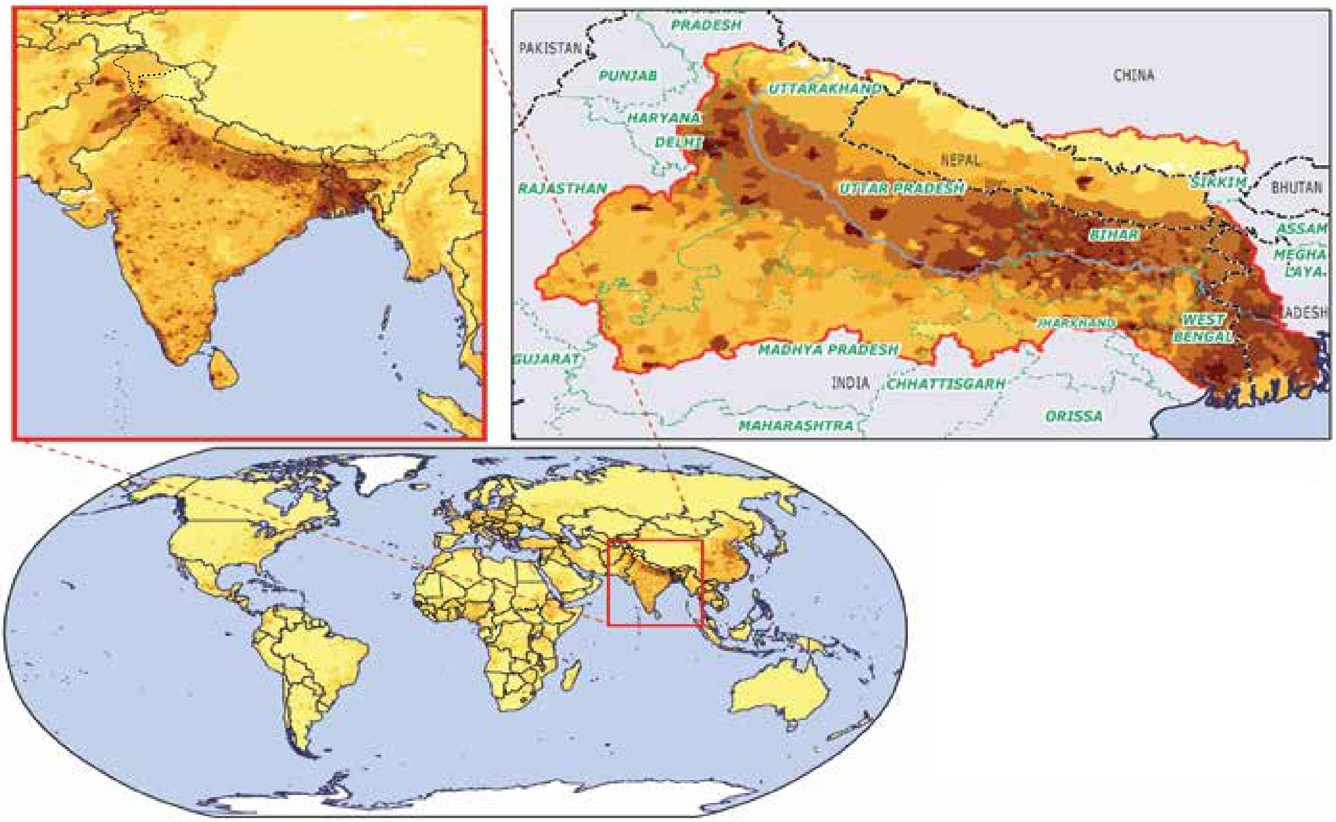
The huge population of the Basin, combined with pervasive poverty and extreme population density, mark the Ganges Basin as a unique global challenge. Population levels and poverty rates in the basin approach those of Sub-Saharan Africa. **Figure 16a** compares the total populations of the Ganges Basin and Sub-Saharan Africa. In 2005, the population of the basin was equivalent to three-quarters of the entire population of Sub-Saharan Africa.[26] Figure 16a also shows the very large

[26] The ratio for 2010/2011 remains virtually unchanged at 76 percent.

Figure 15

Population Density in the Ganges Basin

Ganges Basin - Population Density



Population Density in 2010
(persons per sq. km)

0 - 10 | 11 - 50 | 51 - 250 | 251 - 500 | 500 - 1000 | 1001- 2000 | > 2000

Source: INRM (2011).

proportion (over 70 percent) of the two populations that live on less than $2 per day. The $2 per day headcount poverty rates differ by less than 10 percent. In Sub-Saharan Africa, however, population density is very low, while in the Ganges Basin, population density is extremely high, see **Figure 16b**.

The Basin today is overwhelmingly rural, but it is growing ever more populous and urbanized.

In Nepal, 82 percent of the population is rural.[27] In India's basin districts the figure is similar, around 80 percent (which is higher than the national average of 72 percent).[28] In Bangladesh, 79 percent of the national population is classified as rural. The rural populations of all three countries face higher poverty rates, on average, than their urban counterparts. However, population growth in the basin is high and the region is rapidly urbanizing, with the growth of

[27] World Bank 2009.
[28] 2011 estimates.

Table 3

Population Density in the Ganges Basin

Country (States)	Basin Population (2011 estimates in thousands)	Population density (people/km2)
Nepal	**28,504**	**194**
Bangladesh	**50,680**	**1,285**
India	**576,344**	**575**
(Bihar)	103,681	1,101
(Chhatisgarh)	6,484	178
(Delhi)	16,677	11,245
(Haryana)	16,970	772
(Himachal Pradesh)	1,426	99
(Jharkand)	27,946	421
(Madhya Pradesh)	56,848	250
(Rajasthan)	45,402	288
(Uttar Pradesh)	199,429	828
(Uttarakhand)	10,108	189
(West Bengal)	91,372	1,030
Total	**655,528**	**551**

Figure 16a

Comparison of Population Living on Less than $2/day in the Ganges Basin and Sub-Saharan Africa

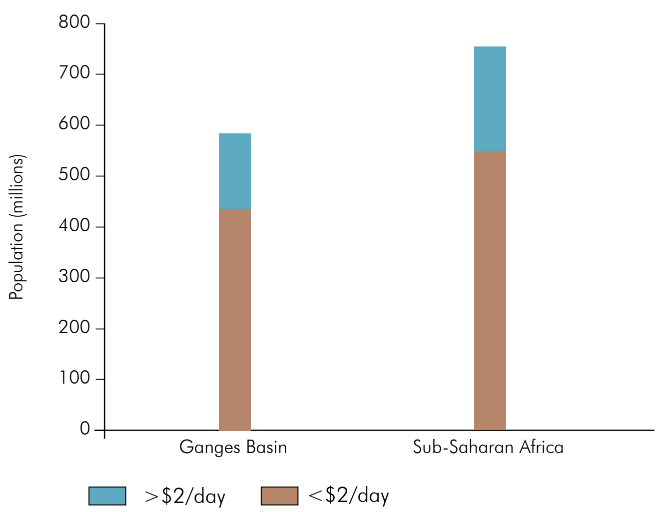
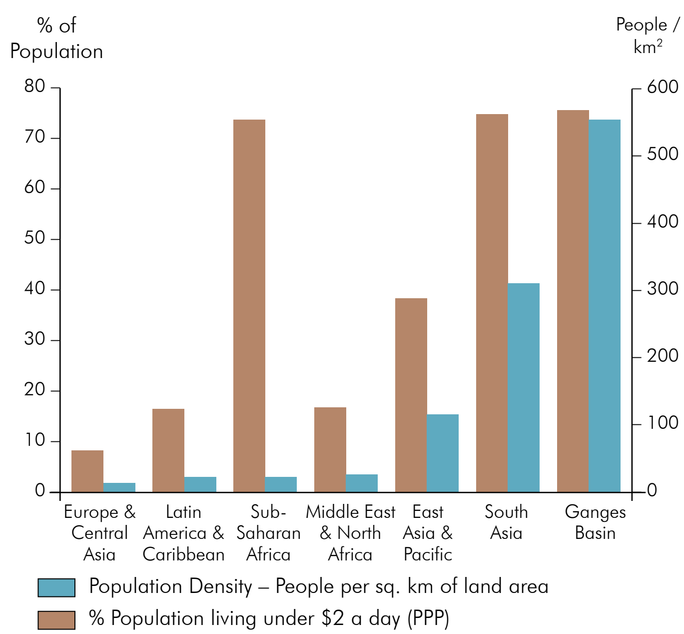


Figure 16b

Poverty rates and Population Density in the Ganges basin and Other Regions



Note: The chart is based on illustrative poverty estimates for the Ganges Basin. The estimates are for 2005. Population estimates are for all of Nepal and the Ganges Basin districts in India and Bangladesh. Population numbers for India and Bangladesh are mid-census estimates from national sources and for Nepal from the WDI. Poverty estimates use a $2 Purchasing Power Parity (PPP) poverty line for comparability across countries. Since virtually all of Nepal lies within the Ganges Basin, the poverty estimate (% of people below the $2 PPP poverty line for 2005) is taken directly from the WDI. For India and Bangladesh, however, only some districts lie within the Basin and therefore estimates were made using state-level poverty estimates ($1.03 poverty line) available from national sources (Ghani, 2010). The state level estimates were extrapolated to a $2 poverty line assuming that the national level difference between $1 and $2 PPP in poverty obtained from WDI is also a valid approximation in all the states. It was also assumed that state level poverty rates apply to the districts of that state which fall within the Basin.

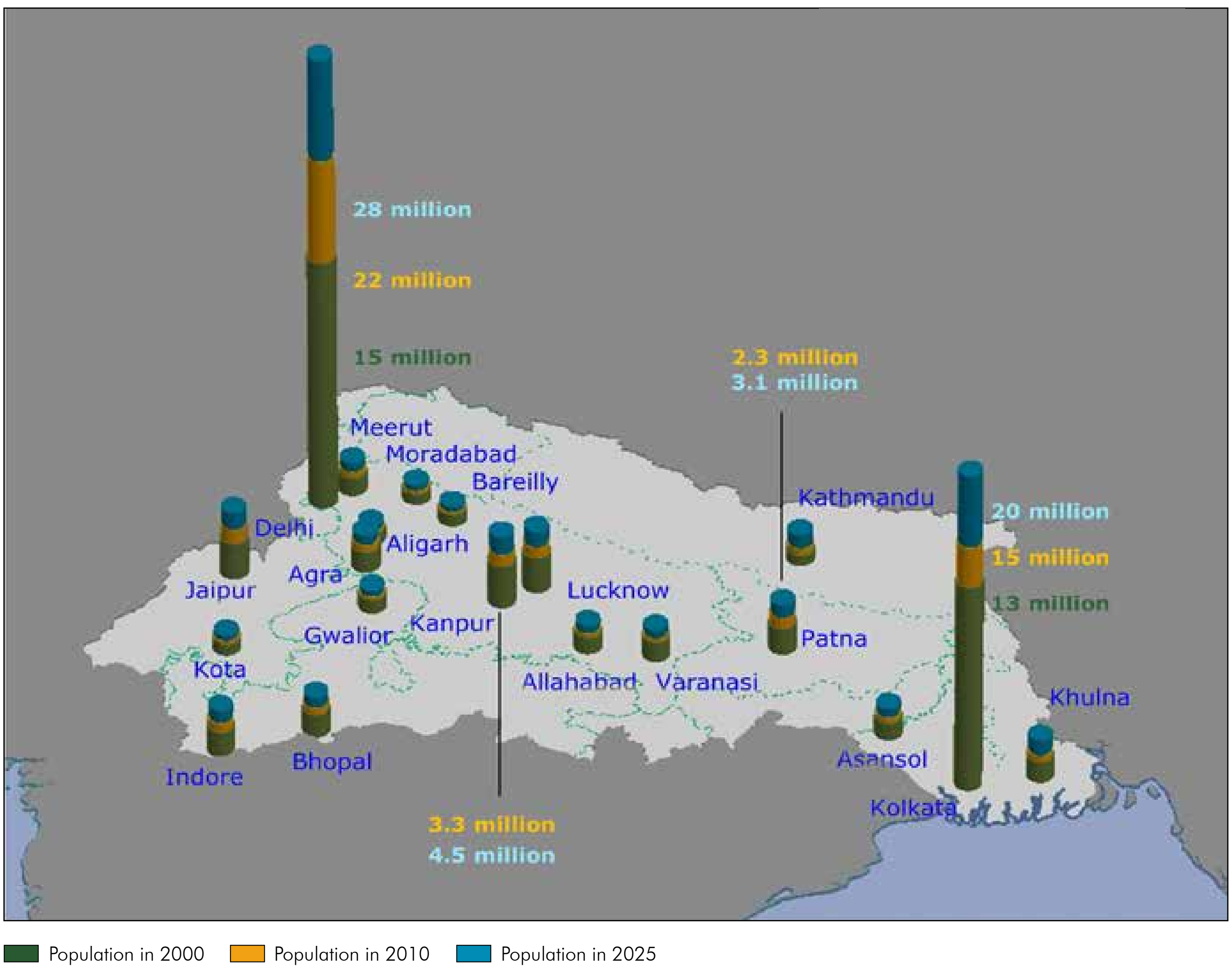
megacities such as Delhi, Kolkata, and Dhaka, and a number of secondary cities as well. By 2025, the population of Delhi alone is anticipated to be 28 million – equivalent to the total national population of Nepal today **(Figure 17)**.

Sprawling urban areas with expanding ecological footprints are becoming a dominant feature of the Ganges plain **(Figure 18)**. This trend will lead to changes in water demand and use patterns in the basin that could have significant local tradeoffs with other uses.

Population and land use changes have transformed the landscape of the basin. Forests and wetlands have all but disappeared in the plains, replaced by increasing urban areas and the expanded agricultural land needed to feed the burgeoning population **(Figure 19)**. These changes also place significant pressures on water systems as agricultural and urban/industrial water demands rise.

Pollution is a growing concern for those living in the basin. Rapid urbanization and

Figure 17
Urban Population and Growth in the Ganges Basin

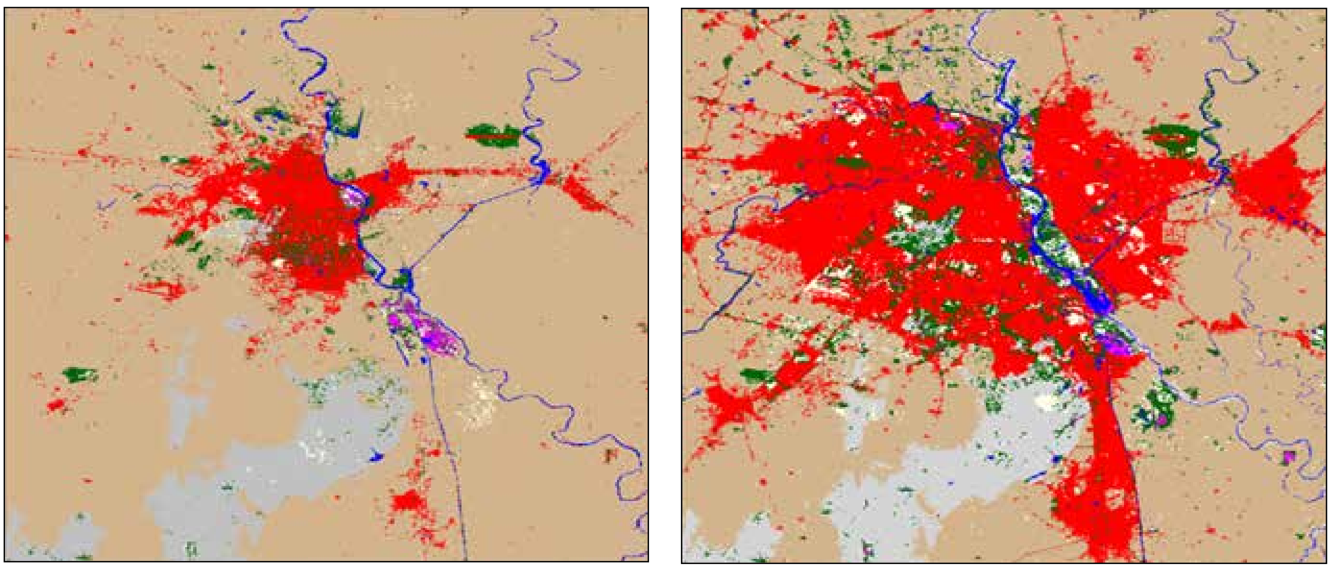


Source: Visualization based on World Urbanization Prospects 2009 update, United Nations Population Division.

Figure 18
Delhi City Expansion over 25 Years

DELHI : Increase in population of 4.2 million and 60,000 hectares of agricultural land lost

Delhi 1974 **Delhi 1999**



Land cover derived from Landsat MSS acquired May 8, 1974

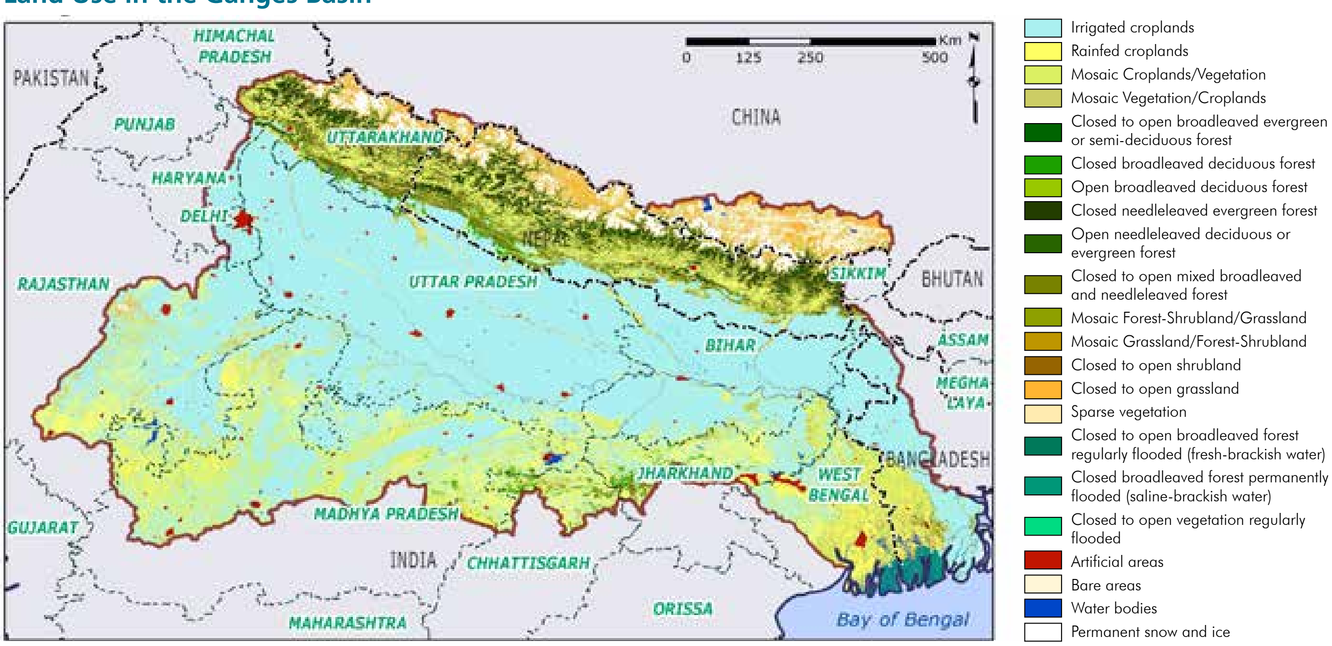
0 10 20 30 40 Km

Land cover derived from Landsat TM acquired May 21, 1999

Forest | Agricultural | Grassland | Wetland | Barren | Water | Urban

Source: Harvard University, courtesy of Professor Peter Rogers.

Figure 19
Land Use in the Ganges Basin

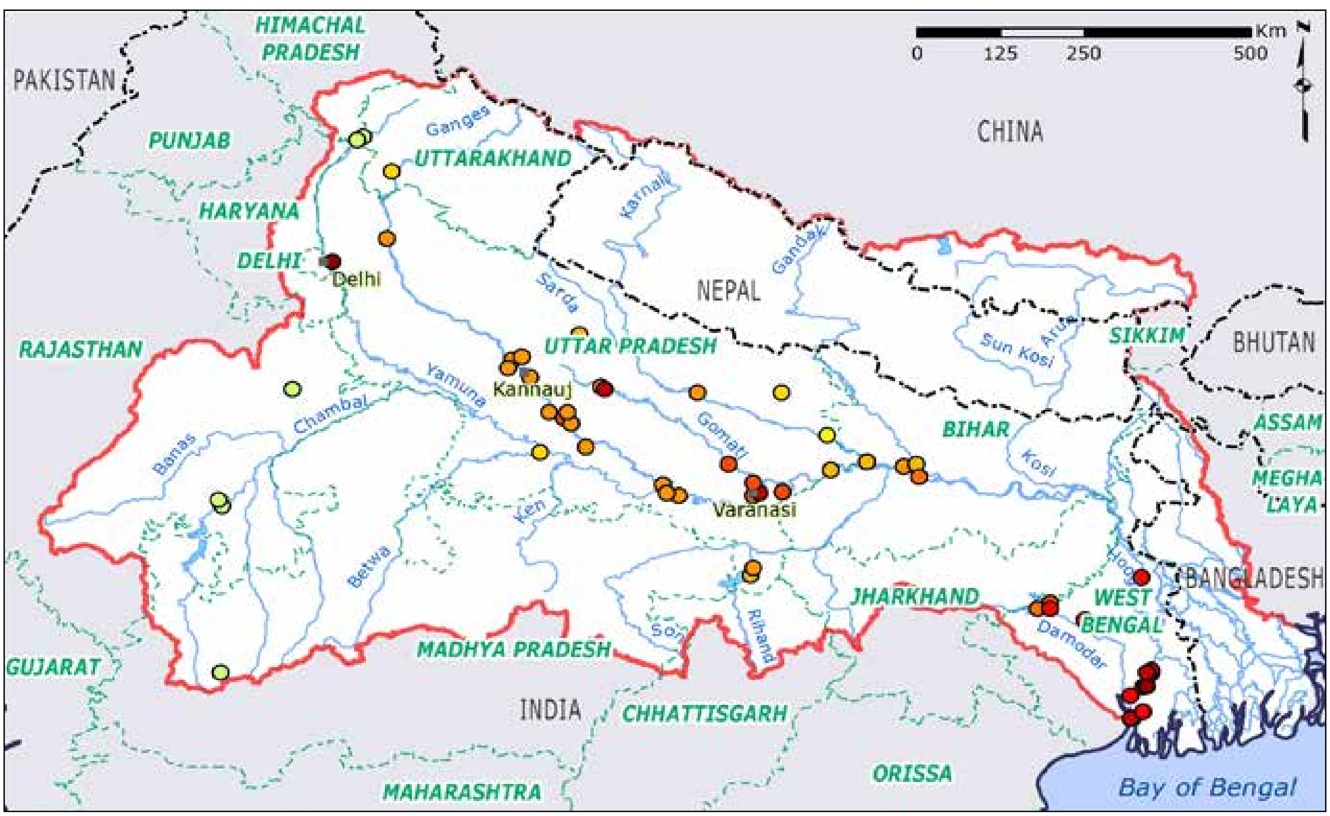


Source: ESA Globcover 2009, European Space Agency.

industrialization in recent years have caused high levels of pollution in many parts of the Ganges Basin, especially in the Yamuna near Delhi and the Ganga between Kannauj and Varanasi **(Figure 20)**. The levels of fecal coliform are some of the highest found anywhere in such a large river. Domestic sewage is the major source of contamination. Newer pollution sources such as solid waste, industrial sources (e.g. tanneries near Kanpur, distilleries, paper mills) and agricultural nonpoint sources (from the extensive agrochemical use in the agricultural areas) are increasing, adding a new dimension to this growing problem. To address this challenge, the Government of India created the National Ganga River Basin Authority (NGRBA) and has launched a major initiative with World Bank support to reduce pollution of the Ganga River. Natural arsenic in groundwater is an increasing challenge, not only in Bangladesh and West Bengal, but in many parts of the Ganges plains.

Physical exposure to water-related risks is closely linked with social vulnerabilities in the region. Poor and socially marginalized people have less access to institutions and services, limited income opportunities, and fewer assets and means to rebuild their lives after floods, droughts, and storms. These least-advantaged populations tend

Figure 20
Surface Water Quality in the Ganges Basin



Fecal Coliforms
(Count in thousands per 100 mL)

- < 50
- 0.05 - 0.1
- 0.1 - 0.5
- 0.5 - 1
- 1 - 5
- 5 - 10
- 10 - 25
- 25 - 50
- 50 - 100
- > 100

Source: Based on data from the Central Pollution Control Board (Government of India).

to live in areas with higher physical risks, while those with economic options tend to move away from the most physically insecure spaces. Typically, disadvantaged groups settle in the most drought- or flood-prone areas and occupy the least productive land. They do not have access to irrigation schemes but instead rely on unpredictable rainfall for agricultural production.

The poor and socially marginalized are often overlooked during relief and reconstruction efforts. Social prejudice against the poor, lower castes, and women may impact the way relief is distributed. Deteriorating water quality also poses particular risks for the poor. Water pollution has a disproportionate[29] impact on those, generally the poor, who rely on the Ganges for their livelihoods (fishing, agriculture, or religious tourism) as well as for their personal and domestic uses (bathing and household uses).

Skewed sex ratios in the Basin suggest that women are substantially disadvantaged. Sex ratios, the number of females per 1.000 males, are often used as an indicator of gender parity because skewed sex ratios suggest inequity in survival and longevity between genders. The sex ratios within the Ganges Basin are troubling. In Nepal, the sex ratio is estimated to be 960, and in Bangladesh, for the districts in the basin, it is 961.[30] Initial estimates from the 2011 Indian census show that while India's national sex ratio has improved (to 940 from 917 in 2001), it has worsened or stayed the same for the Indian states in the Ganges Basin.

Women in the Basin are particularly vulnerable to water- and climate-related hazards. Estimates have shown that women, the poor, and other socially marginalized groups face the highest risks from morbidity and mortality because of natural disasters. Studies in Bangladesh have shown that women and children are 14 times more likely than men to die during natural disasters.[31] Recovery can also be particularly difficult for women due to intra-family coping mechanisms. In focus group discussions undertaken for this study, women claimed that in the aftermath of a disaster, when there was limited food available to their families, they were often the last to eat.[32]

Institutions in the Basin

Treaties

The basin has a half-century history of incremental bilateral treaties, but no basinwide or multilateral treaties. Despite widespread perceptions of significant opportunities for cooperative development,[33] only a few treaties and only bilateral ones have been signed between Ganges Basin riparians.

The first treaty, on the Kosi River, was signed between India and Nepal in 1954. The treaty was developed to attenuate routine devastating floods in the Indian state of Bihar. Soon after its conclusion in 1954, however, the treaty came under criticism in Nepal where it was perceived as inequitable, in part because it called for the construction of embankments to contain the course of the Kosi, as well as the construction of the Kosi Barrage, both of which are entirely within Nepal. The land associated with the embankments and barrage (the built and inundated areas) was to be acquired by Nepal and then ceded to India. The Kosi Treaty was amended in 1966 so that the land would be leased to India rather than ceded, but many still felt the terms of that lease (199 years at a nominal annual rate) were inequitable and that it did not properly compensate the loss of fertile farmland in Nepal.

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29 Rabinowitz 2008.
30 BBS 2001.
31 Neumayer and Plumper 2007.
32 Ibid, and confirmed in Focus Group Discussions in Bihar and West Bengal and in Bangladesh (July-August 2010).
33 See, for example, Adhikari et al., 2000, Ahmad et al., 2001, Crow 1995, Dhungel and Pun 2009, Revelle and Lakshminarayan 1975, Rogers et al., 1989, Subba 2001, Verghese 1990. From the press see Rajeev Ranjan Chaturvedy and David M. Malone, 'Hydro-diplomacy: a neglected opportunity for Nepal and India,' The Hindu, June 28, 2011; Sadiq Ahmed, 'Possible gains from regional cooperation,' The Financial Express (Bangladesh), December 14, 2010; 'Nepal-B'desh to cooperate on flood control,' Kathmandu Post, November 1, 2004; 'Data sharing to reduce water induced disasters', Kathmandu Post, November 30, 2004.

The second treaty between India and Nepal, the Gandaki Treaty, was signed in 1959 with a focus on flood control, irrigation, and power. The Gandaki River, like the Kosi, brought annual floods that damaged crops and property in both Nepal and India. This treaty is considered more favorable to Nepal than the Kosi Treaty. Nevertheless, it, too, was met with strong objection in Nepal. Unlike the Kosi Treaty, the Gandaki Treaty has not been amended.

The third treaty between India and Nepal was the Mahakali Treaty that entered into force in 1997. The Mahakali River runs north to south along Nepal's western border with India. The Mahakali Treaty emphasized an integrated approach to water resources development, benefit sharing, and the need to revisit earlier activities and agreements based on present needs. It also included provision for the development of the Pancheshwar Dam (which remains unbuilt). It aimed to maximize the benefits for both countries, an approach that was absent in the Kosi and Gandaki treaties and is generally considered consistent with international good practice. But again, the treaty was met with widespread controversy in both India and Nepal.

India and Bangladesh entered into a number of successive agreements from 1975 through 1988. After prolonged negotiations, the two countries concluded a treaty on sharing the Ganges in 1996. The Ganges Treaty, whose provisions dictate inter alia the allocation of flows at Farakka Barrage (at the Indo-Bangladesh border), has also raised equity concerns in some quarters. The Ganges Treaty, allocated the low dry-season flows at Farakka between India and Bangladesh, but did not specify how much water India could withdrawn upstream from Farakka Barrage, nor did it address high-flow (flood) issues.

Although the basin's treaty history shows a progression toward good practice principles, it has been marked by contention and continues to cause some unease among the riparian countries.[34]

Outside the basin, but potentially relevant, is the history of the Indus Treaty. The 1947 partition of India and Pakistan made the Indus an international river. The dependence of both countries on its waters necessitated a cooperative resolution. After years of inconclusive bilateral negotiations, the World Bank was asked to mediate. Early progress was made in agreeing on procedures, commonalities, and on the total amount of water available and under discussion. Still, the conflicting claims of the two states created a stalemate. In 1954, the World Bank proposed allocating the western rivers (Indus, Jhelum and Chenab) to Pakistan and the eastern rivers (Ravi, Beas and Sutlej) to India. This proposal was eventually accepted by both sides. To deliver equitable shares of water to both countries, however, Pakistan had to invest heavily in link canals, diversion structures, and dams. The World Bank assisted the parties by negotiating a cost-sharing arrangement for these pivotal civil works and mobilizing the necessary finance. The Indus Waters Treaty was signed on September 19, 1960. The World Bank is a signatory, though not a guarantor, of the treaty.[35]

Institutions

Each of the Basin states has a unique institutional structure for managing transboundary waters. In Nepal, a dedicated transboundary waters office was established in 2010 under the Water and Energy Commission Secretariat (WECS)[36] to support the government's dialogue on transboundary waters. In India and Bangladesh, ministries of water resources hold the

[34] Salman and Uprety 2002.
[35] Sadoff et al., 2008
[36] The Water and Energy Commission (WEC) was established with the broad objective of developing water and energy resources in an integrated and accelerated manner. The Water and Energy Commission Secretariat (WECS) is a permanent secretariat of WEC, established in 1981 under the then Ministry of Water Resources (MOWR) and is currently under the Ministry of Energy since the 2010 split of the MOWR into the Ministry of Energy and Ministry of Irrigation. The primary responsibility of WECS is to assist the Government of Nepal in the formulation of policies and planning of projects in the water resources and energy sectors.

mandate for transboundary waters. Within India, it is notable that jurisdiction over water resources management resides with the country's 28 states. River basin management organizations are set up only for specific purposes such as constructing and managing large interstate multipurpose projects or pollution abatement. The first basin-level initiative to manage a large interstate river for water quality and environmental protection, the National Ganga River Basin Authority (NGRBA), was constituted in 2009 under the Environment Protection Act. The NGRBA was given a multi-sector mandate to ensure pollution abatement in the Ganga by addressing both water quantity and quality aspects and by adopting a river basin approach. Its powers are significant and combine regulatory and developmental functions. The Government of India intends to develop the NGRBA as a model for other rivers in the country.[37]

Bilateral commissions

Communications and cooperation on the Ganges is currently undertaken through bilateral joint commissions. Despite discussions over the years, there is no basinwide mechanism for intergovernmental communications or cooperation in the Ganges. Bilateral mechanisms, however, have been in place for decades and continue to evolve.

The Indo-Bangladesh Joint Rivers Commission (JRC) has been functioning since 1972, following a joint declaration of the Prime Ministers of Bangladesh and India. Its mandate is to ensure effective joint efforts to maximize the benefits from common river systems. It is headed by the water resource ministers of the two countries.

The current institutional mechanism between India and Nepal is the **Indo-Nepal Joint Committee on Water Resources (JCWR)**, which was formed by agreement between the Prime Ministers of Nepal and India in 2000. In order to rationalize the numerous Indo-Nepal technical committees, a three-tiered mechanism was agreed by the JCWR in 2008 comprising:

1. Joint Ministerial Level Commission on Water Resources (JMCWR) at the level of ministers of water resources of India and Nepal,
2. (continued existing) Joint Committee on Water Resources (JCWR) at the level of secretaries of India and Nepal, and
3. Joint Standing Technical Committee (JSTC) at the level of chairman, to rationalize technical committees and subcommittees under JCWR related to flood management, inundation problems, and flood forecasting.

Regional bodies

Outside of these official bilateral mechanisms, there are no organizations with a clear mandate to facilitate cooperation in transboundary waters. There are, however, several relevant regional bodies.

The **South Asian Association for Regional Cooperation (SAARC)** as it was originally conceived was not mandated to address regional water issues. In the context of climate change, SAARC has begun to consider some water issues. In the meantime SAARC has been instrumental in creating regional institutions mandated with disaster management and meteorological research. The SAARC Disaster Management Centre, established in Delhi in 2006, focuses on training and exchange of good practices, and has a mandate to serve the South Asian countries 'by providing policy advice and facilitating capacity building services including strategic learning, research, training, system development and exchange of information for effective disaster risk reduction and management.'[38] The SAARC Meteorological Centre, established in Dhaka in 1995, promotes collective research in meteorology and weather forecasting in the region.[39]

[37] World Bank 2011.
[38] SAARC Meteorological Research Centre 2011.
[39] SAARC Meteorological Research Centre 2011.

The **International Centre for Integrated Mountain Development (ICIMOD)**, established in Kathmandu in 1983, is a regional knowledge development and learning center serving eight regional member countries of the Hindu Kush–Himalayas. ICIMOD aims to help mountain people to understand changes in fragile mountain ecosystems, adapt to them, and make the most of new opportunities, while addressing upstream–downstream issues. ICIMOD promotes transboundary cooperation through partnership with regional partner institutions, facilitates the exchange of experience, and serves as a regional knowledge hub.

The **Asian Disaster Preparedness Centre (ADPC)** was established in Bangkok in 1986 at the recommendation of the United Nations office now known as UN Office for the Coordination of Humanitarian Affairs (UN-OCHA) with the aim of strengthening the national disaster risk management systems in the region. In 1999 ADPC became an independent entity, which is governed and guided by a board of trustees (21 members representing 15 countries) and advised by a regional consultative committee (32 members from 26 countries) and an advisory council (55 members from a wide range of agencies.) ADPC is active in developing and enhancing disaster risk management capacities, frameworks and mechanisms, and facilitating the dissemination and exchange of disaster risk management expertise, experience and information.

There has also been a history of 'Track 2'[40] discussions on transboundary cooperation. In the 1980s, nongovernmental groups in Nepal (Institute for Integrated Development Studies), India (Center for Policy Research), and Bangladesh (Bangladesh Unnayan Parishad) worked closely to highlight the benefits of cooperation; researching, publishing, and promoting improved regional dialogue. In the mid-1990s, the World Bank facilitated work on the 'South Asia Development Triangle/Quadrilateral' and related efforts that focused on developing analytical tools and improving regional dialogue on the Ganges-Brahmaputra Basin.

Today, the World Bank, in partnership with the governments of Australia, Norway, and the United Kingdom, supports the **South Asia Water Initiative (SAWI)**. SAWI seeks to promote improved water resources management within and among the countries of the region, with an emphasis on transboundary cooperation and climate adaptation. It facilitates the Abu Dhabi Dialogue, a Track 2 forum launched in 2006 to enable a sustained dialogue of opinion makers and decision makers from the seven countries that share the rivers rising in the greater Himalayas (Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan); complemented by a knowledge forum of more than 50 regional research institutions and a small grants fund for collaborative research. SAWI also supports knowledge development (this report is a product of SAWI) and innovative investments and actions that can enhance regional capacity and promote cooperative.

The International Union for Conservation of Nature (IUCN) recently launched the Ecosystems for Life: Bangladesh-India Initiative that uses a multi-stakeholder dialogue process to promote insights across the three major rivers systems, the Ganges, Brahmaputra, and Meghna.

Climate Context

Climate has always been a challenge in the basin. People have been living with both the positive and negative effects of water variability for centuries; these natural cycles of inundation have both beneficial and destructive aspects. On the beneficial side, short periods of inundation provide soil moisture that typically increases production in

[40] A 'Track 2' process is a nonformal process of engagement in which stakeholders such as academics, retired officials, opinion makers, and social activists engage in dialogue to further a particular agenda, resolve conflict, or build confidence.

Box 2
Defining Floods and Droughts

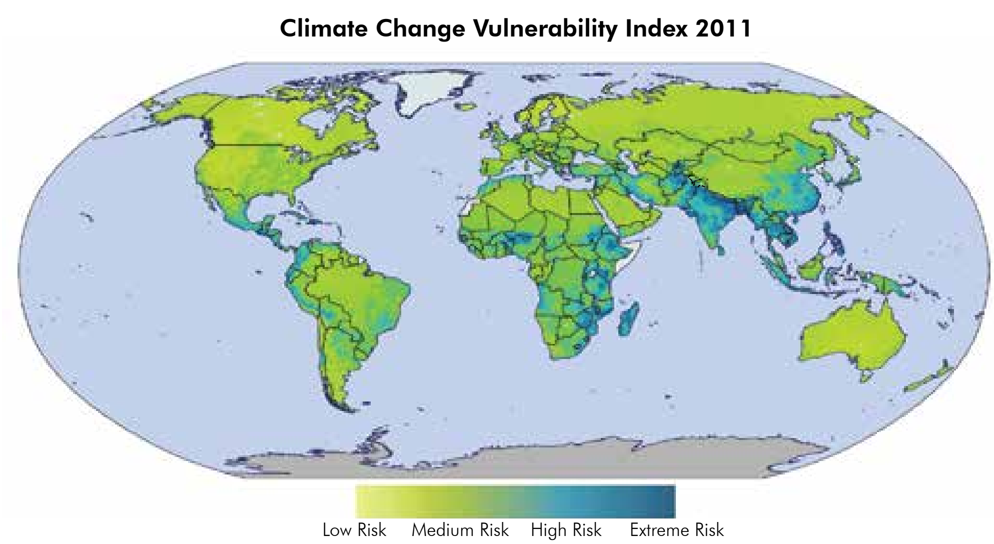
National institutions define floods and droughts based on hydrological information (i.e. the presence or lack of water), and typically measure rainfall or water levels of a particular area. On the local level, the comparison with purely hydrological flood or drought has little meaning. People use measures of floods that relate to their immediate surroundings: in a 'normal' year, flood waters would not reach the house, or would not surpass residents' knees, whereas in an 'extreme' year, water levels would submerge their houses.

Where the discrepancy between the two definitions of floods and droughts is most visible is in the distribution of relief aid. Relief and support from state and national governments is dependent primarily on the official definitions and not local definitions. Even when official droughts/floods are declared, the lag time between the actual drought/flood occurring and the declaration make it very difficult for the most vulnerable to cope.

the winter (rabi) planting season. However, peak flows also cause more extensive and devastating floods and disrupt social life and economic activity. See **Box 2** on the difficulties of defining floods and droughts.

The challenge grows with mounting population and resource pressures. While traditional societies have used a range of coping strategies to adapt to the extreme and unpredictable monsoonal climate of the Ganges Basin, many key strategies are increasingly impractical. Flood recession agriculture, for example, has been adopted by societies worldwide to turn seasonal flooding to their advantage. If an area was known to flood, communities would use it only for (supplemental) agriculture without building infrastructure or housing that would be at high risk of inundation. The extraordinary population density of the Ganges Basin, however, has led to

Figure 21
Climate Change Vulnerability Index, 2011



Rank	Country	Rating
1	Bangladesh	Extreme
2	India	Extreme
3	Madagascar	Extreme
4	Nepal	Extreme
5	Mozambique	Extreme
Rank	**Country**	**Rating**
6	Philippines	Extreme
7	Haiti	Extreme
8	Afghanistan	Extreme
9	Zimbabwe	Extreme
10	Myanmar	Extreme
Legend		
Extreme risk		
High risk		
Medium risk		
Low risk		
No Data		

Source: Maplecroft (2011).

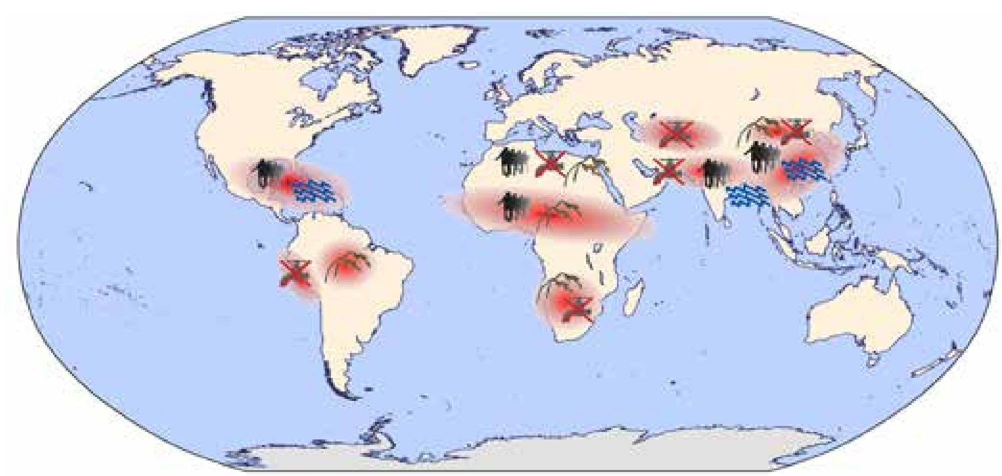
permanent habitation and commercial investments in flood plains. Today, some 2 million people live within the embankments of the Kosi River,[41] an area that in earlier generations was used only for flood recession agriculture.

The Ganges Basin today is one of the most climate vulnerable areas in the world. Melting glaciers, intensified monsoons and water-induced disasters, and sea level rise – all the ills of climate change – are expected to manifest in the basin. The countries of the basin have little capacity to deal with today's weather and hydrological variability, much less the intensification expected with climate change.

The Maplecroft 2011 rankings of vulnerability to climate change placed the Ganges' three main riparians as the first, second and fourth most climate-vulnerable countries in the world **(Figure 21).** These rankings take into account both the physical threats expected with climate change, and the countries' capacity to manage those threats. The Ganges Basin could arguably be the most climate vulnerable basin in the world.

The Ganges is a 'hot spot' for climate-induced conflicts. Climate change can exacerbate existing environmental crises and create new tensions. These dynamics can in turn lead to social destabilization and possibly conflict. Globally, conflicts related to degradation of fresh water resources, decline in food production, increased disasters, and environmentally induced migration are anticipated. Within the Ganges, India and Bangladesh are identified as hotspots, implying an increased risk for climate-induced conflicts **(Figure 22)**.[42]

Figure 22
Climate Conflict Constellations



Climate-induced increase in storm and flood disasters

Climate-induced decline in food production

Environmentally-induced migration

Climate-induced degradation of freshwater resources

Hotspot

Source: WBGU (2007).

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[41] Winrock International/ICIMOD 2010.
[42] WBGU 2007

3.

Analytical Framework

Overall Framework

This report provides an integrated basinwide perspective of future development options in the Ganges Basin. It aims to provide useful insights on critical basinwide implications of major options for water infrastructure development and related future scenarios of water use and climate. It does not provide economic, social, environmental, or technical feasibility analysis for individual projects, or try to indicate which particular piece of infrastructure (e.g. a mega-dam) is better than another one, or how these infrastructure components should be phased.

The aim of the Ganges SBA is to begin to fill a critical knowledge gap by building a nested suite of models and targeted analyses that can provide a comprehensive, interdisciplinary, and systemic understanding of the Ganges Basin. Currently, the team is not aware of any publicly available knowledge base or full basin model for the Ganges. A series of commissioned studies and original analyses were needed across a range of disciplines in order to ensure a converging picture of the basin dynamics. The three major components of this work included:

1. Water systems modeling and analysis to examine the dynamics of the Ganges Basin including: surface water system, water balance, irrigation use, water quality, climate change implications, floods and glacier melt.
2. Economics modeling and analysis to explore economic tradeoffs, distribution of benefits from new development projects in the basin, and economic benefits of additional low flows and flood mitigation strategies.
3. Social analysis through literature review, focus group discussions, and key informant interviews to understand the social impacts of and responses to water variability.

There are necessarily many constraints in undertaking such an ambitious study. Key constraints and limitations are described below.

First, much of the data used for analyses of this sort are either not collected or not accessible. For example, in India, there is no public access to critical hydrological information (especially flow data) to help calibrate the water simulation and economic optimization models. Substantial effort was required to find suitable approximations for critical data from the public domain and to resolve conflicting information. Even for other basic information, the team and its partners had to collate (and sometimes even computerize), analyze, and quality check multiple datasets in order to slowly develop what is now perhaps the most comprehensive set of relevant data for the analysis of the basin's potential in a regional context.

Second, when this work was initiated, there was no easily accessible model of the entire Ganges Basin of sufficient complexity to help answer the basin's fundamental strategic questions. The team therefore collaborated with some of the most capable institutions in the region, working closely with them to develop a new generation of water systems' modeling tools.

Finally, it would have been ideal for this work to have been carried out in a cooperative manner by empowered agencies of the riparian governments.

However, the Ganges is one of the few large international basins in the world with no permanent institutional mechanism that involves multiple riparians. The work was undertaken in partnership with regional experts and repeated consultations were held with regional stakeholders, and it is hoped that future research of this sort can be carried out by a partnership of riparian countries.

Despite these limitations, this report presents the best available evidence on the Ganges from a basinwide perspective. The knowledge base and models are considered of sufficient certainty to inform evidence-based discussions around a set of core critical issues, and provide platform for ongoing dialogue and further technical analyses.

Water Systems Modeling

The study takes a fresh, objective look at the challenges and opportunities in the Ganges Basin today. It draws upon a rich history of work on the Ganges, and presents significant original research commissioned to develop a suitable knowledge base and set of analytical tools to help answer fundamental questions about the dynamics of the water system. This new work helps us understand, in a much more nuanced manner, options that have been on the table for a long time, and points toward sustainable development paths that are important in a regional context. Some of the new work conducted for this study includes: (1) development of a knowledge base, (2) simulation modeling of basin systems, (3) a basin hydrological model, (4) a flood analyzer tool, and (5) a glacier melt analysis.

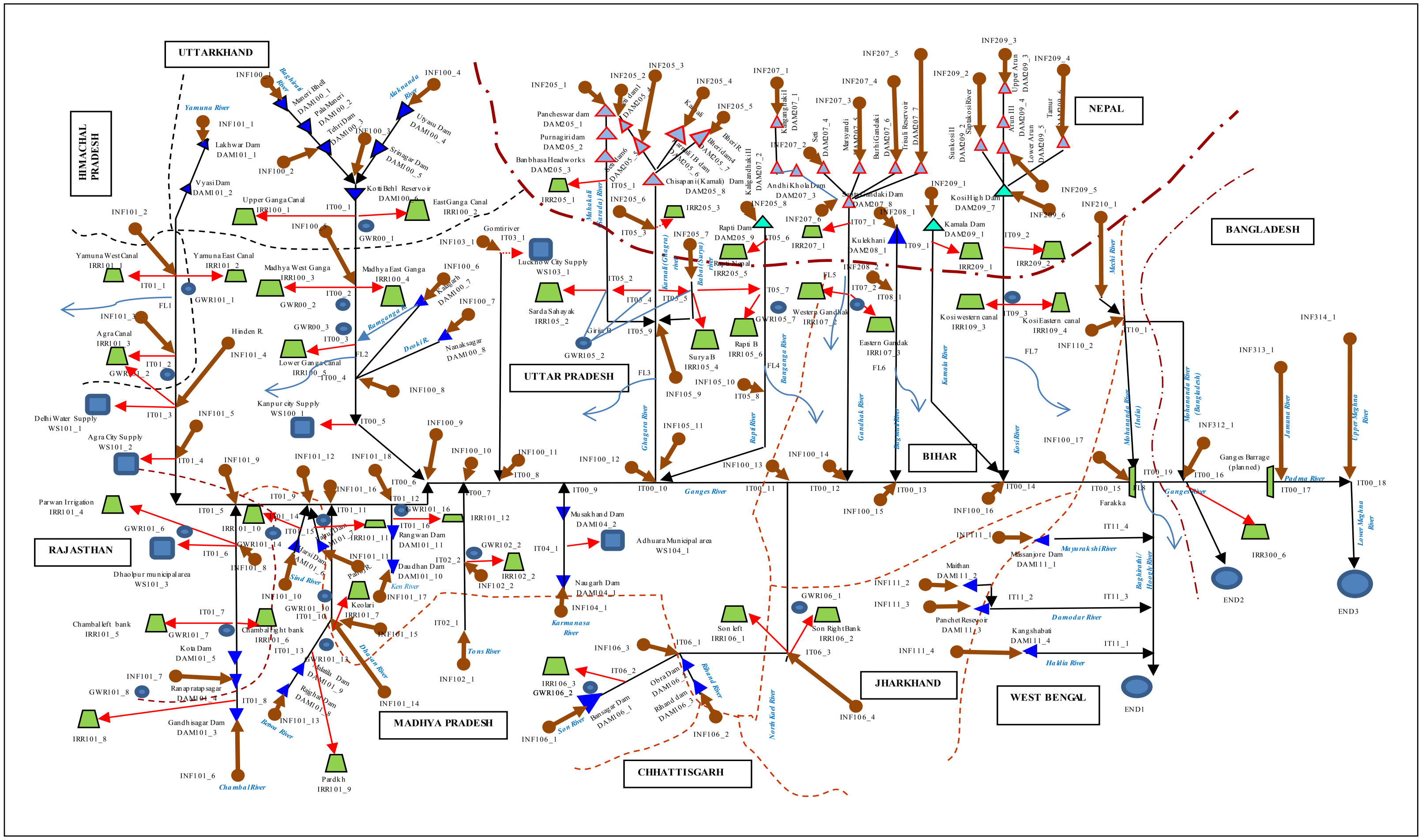
Knowledge Base Development. A geographic information system (GIS) platform was developed drawing upon publicly available global, regional, national, and subnational data on administrative units, climate, surface and ground water hydrology, irrigation, hydropower, and other water uses, wetlands, water quality, topography, soils, demography, economy, etc. These data were used to both create maps for this report and provide inputs to the analytical work conducted. A detailed literature, data, and web review was undertaken to provide useful information for this study. Key existing research drawn upon in developing the knowledge base includes a recent study by the Snowy Mountain Engineering Corporation (SMEC, 2009) on groundwater management for the Ghagra-Gomti Basin.

Basin Systems Simulation Modeling. To better understand systems linkages and to explore the implications of a number of development and climate scenarios in the basin, a MIKE BASIN simulation model was developed by the Institute for Water Modeling in Bangladesh along with associated models such as a MIKE 11 hydrodynamic model and MIKE 21 salinity model (IWM, 2010). **Figure 23** shows a schematic of the primary network representation used in both the basin simulation and economic optimization models. It indicates the complexity of the hydrologic network of the Ganges Basin system and supports the conclusion that modern basinwide modeling approaches are needed to capture the interrelationships among development options under consideration, and hence fully inform basin development decisions.

Basin Hydrological Model (Soil and Water Assessment Tool - SWAT). The INRM (Integrated Natural Resource Management Consultants) consortium based in New Delhi (from the Indian Institute of Technology IIT-Delhi and Texas A&M University) developed the SWAT model for this study (INRM, 2011). It was used to analyze the water balance, irrigation use, water quality, and climate change implications on hydrology in a more detailed spatial perspective. As **Figure 24** indicates, the SWAT model provided greater detail of specific catchments in the basin. The model was also used to examine the water quality implications of various scenarios **(Figure 25)**.

Figure 23

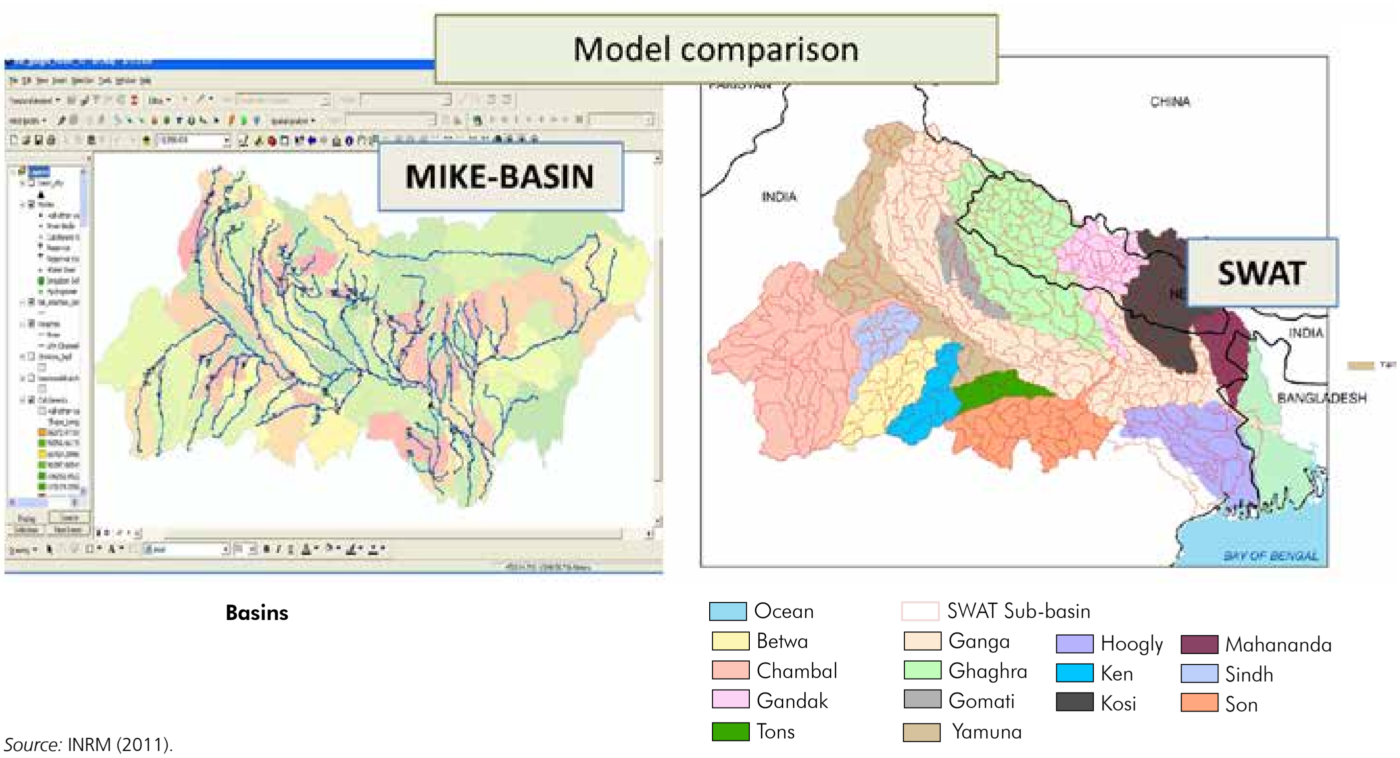
'Simplified' Schematic of the Ganges Basin Water Systems and Economic Optimization Models



River
Diversion
Dam (Planned)
Dam (Existing)
Irrigation
International Boundary
State Boundary

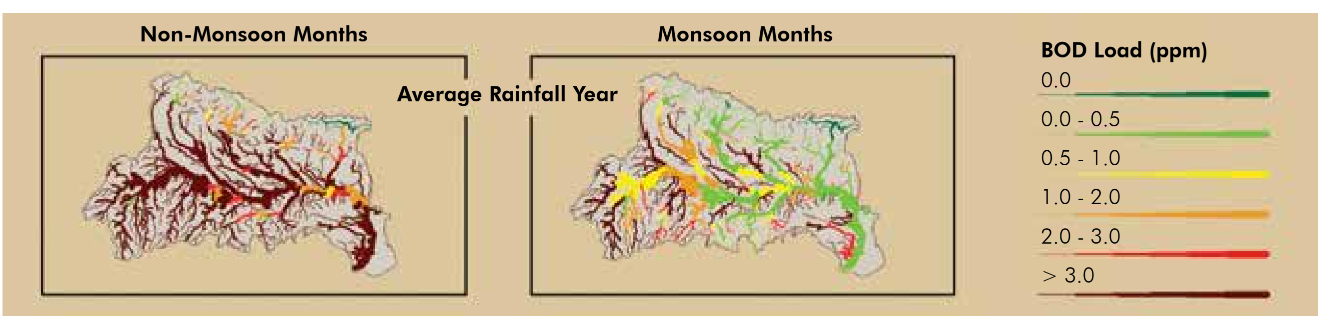
Source: IWM (2010).

Figure 24
Catchments in the MIKE BASIN Model (left) and SWAT Model (right)



Source: INRM (2011).

Figure 25
Water Quality Modeling in SWAT



Source: INRM (2011).

Flood Analyzer Tool. This model was developed by RMSI, Pvt. Ltd., New Delhi, to better understand the history and nature of floods in the Basin and the losses from various flood scenarios **(Figure 26)**.

Glacier Melt Analysis. This This analysis, carried out by Professor (emeritus) Don Alford, Professor Richard Armstrong, and Dr. Adina Racovitaneu, estimated glacial melt contribution and climate change-induced glacier melt enhancement in the Ganges Basin.

In addition, the authors of this study undertook a number of further analyses relating to knowledge-base development, climate change, and use of the new tools described above.

Water Systems Modeling Scenarios

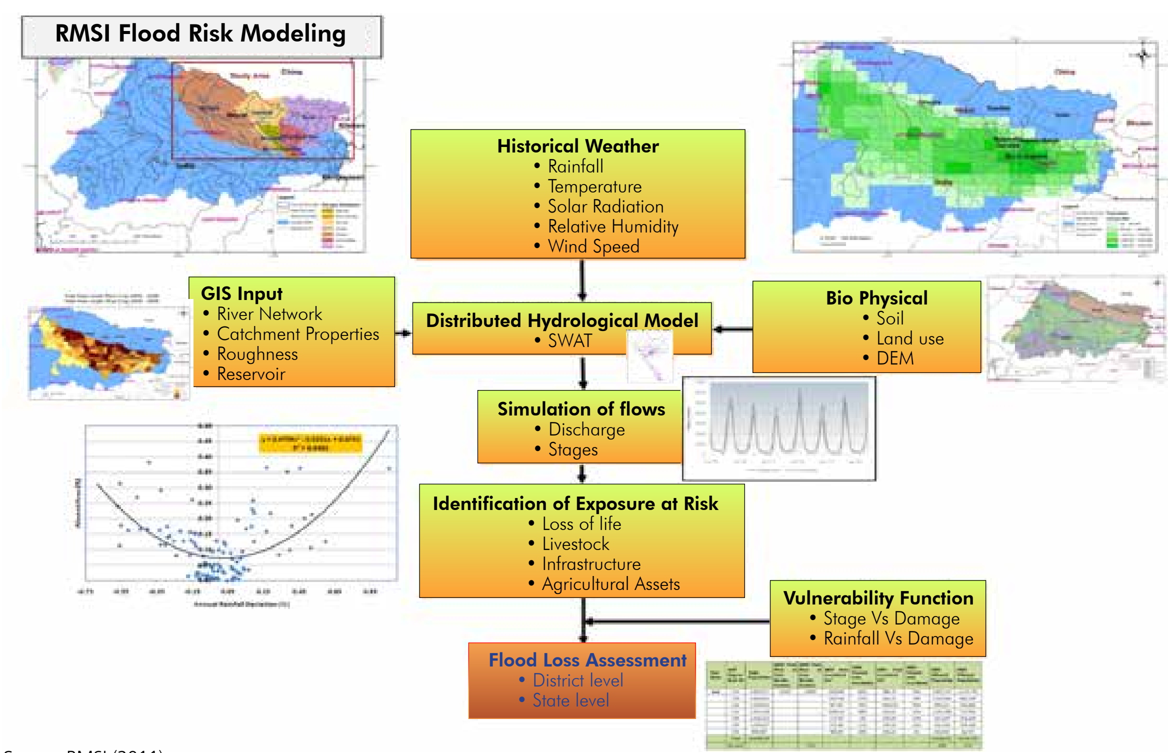
A number of scenarios for the future of the Ganges Basin were considered in this analysis. It is important to note that these scenarios were not chosen based on their likelihood, rather they were chosen to help represent the range of possible future developments and to provide insights regarding some fundamental questions about the dynamics of development in the basin.

The scenarios in **Table 4** explore the role of additional infrastructure in providing systemwide benefits in the Ganges Basin. Some of the key storage scenarios considered in the systems simulation modeling are summarized in **Table 4** and **Figure 27**. These results also present insights regarding the role climate change may play in infrastructure investment decisions.

Water System Model Criteria and Indicators

Impacts of the various development options were examined at particular locations. In any system model, just as it is possible to analyze many

Figure 26
Flood Risk Management Analytical Framework



Source: RMSI (2011).

scenarios, it is also possible to examine an extensive set of output results (e.g., flows at various sites and time periods). To keep the study manageable, results were examined at particular locations of interest. In **Figure 28**, the yellow circles indicate where flows were analyzed for the potential impact of major upstream dam development.

The water systems modeling work focused on a cluster of key biophysical criteria and indicators (Table 5), which present the 'backbone' of new information in this study. Complemented by socioeconomic information, they form a picture of alternative futures in the Ganges.

Water Systems Model Calibration and Testing

Models are a simplification of reality. Despite many data challenges, the models on which the insights presented in this report are based have been reasonably calibrated and tested (IWM, 2010). Good flow calibration results were obtained by IWM's MIKE BASIN model for the available observed flow data upstream at the proposed Chisapani[43] dam site in Nepal, and also at Hardinge Bridge near the end of the system in Bangladesh. Additional data (especially in India) would enable improved calibration of the models. However, this analysis should be adequate for the scale of the river system and the level of the strategic questions posed.

The model is not always able to accurately characterize the flood peaks, possibly due to reliance on sparse rainfall data (as many of the remote catchments of the rugged Himalaya have neither meteorological stations nor gauges). Hence, the model does not fully reflect the heterogeneous nature of variability in the many mountain catchments and subcatchments in the system. This issue could be partially addressed by improved monitoring and integration of increasingly reliable modern satellite information into the available hydrometeorological data systems.

Simulated flows in India could not be calibrated or validated due to the lack of publicly available daily

Table 4
Water System Modeling Scenarios

Scenaio		Year	Infrastructure
A	Current Baseline	April 1998-June 2008	Existing
B	Business as Usual	2025	Gorai River Restoration
C	(B+Gorai RRP)		
D	(C+Ganges Barrage)		Ganges Barrage (and Gorai Restoration)
E	(B+Kosi)		Kosi High Dam
F	(B+Mahakali)		Mahakali Dam
G	(B+25 GW installed)		Mahakali, Kosi and Chisapani, + KaliGand I&II+Dams
H	(G+other major storages in Nepal)		All major Storages in Nepal built
I	(B+Br-Gan .link)		Brahmaputra-Ganges link in Bgd
J	([B; H] Climate Change	2050	J1: Existing
			J2: All major storages

Source: IWM (2010).

[43] The Chisapani Dam site on the Karnali River is shown here for illustrative purposes. Similar results were achieved for all other major Nepali basins.

Figure 27 (a)
Schematic Representation of Storage Options

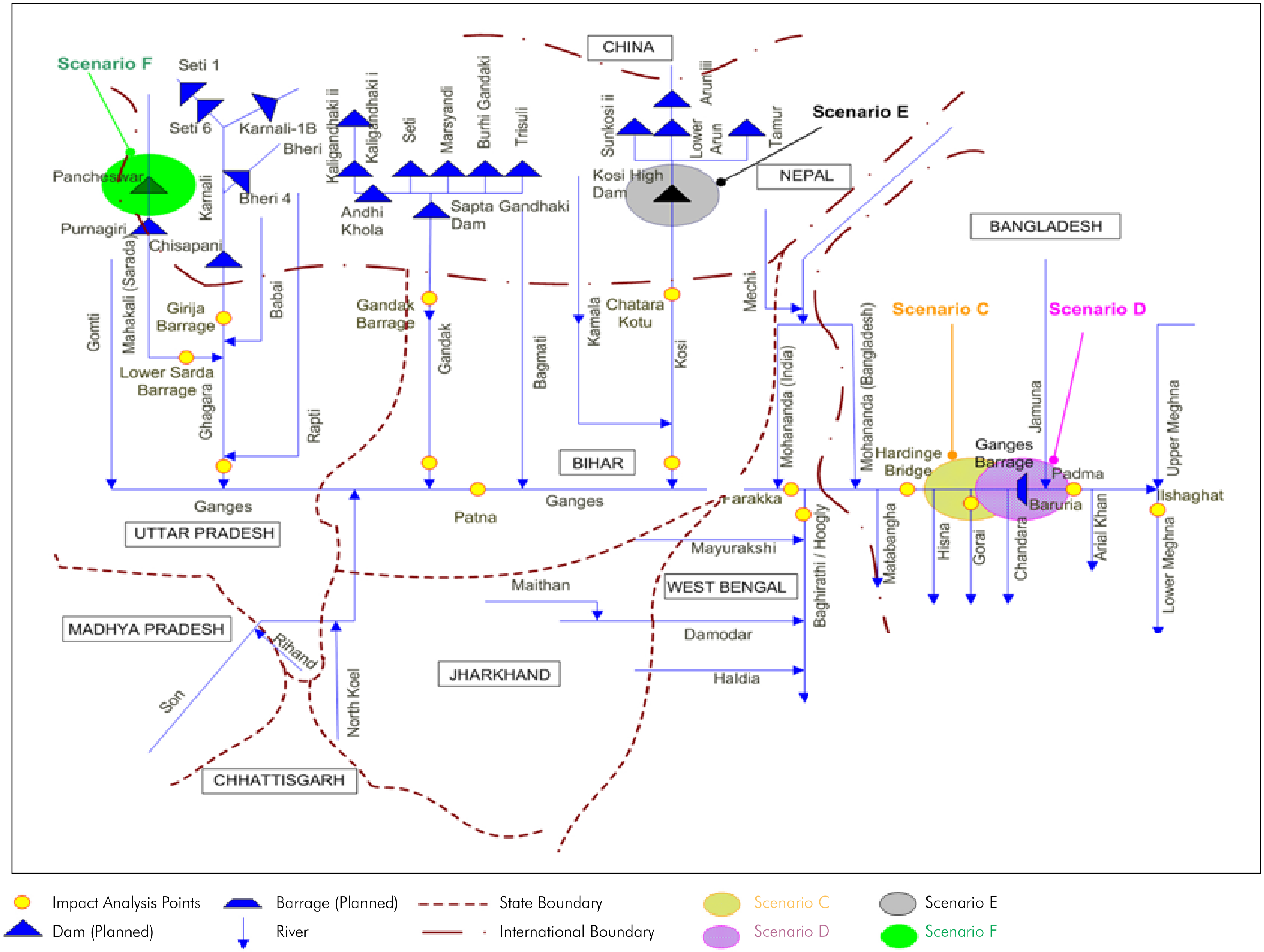
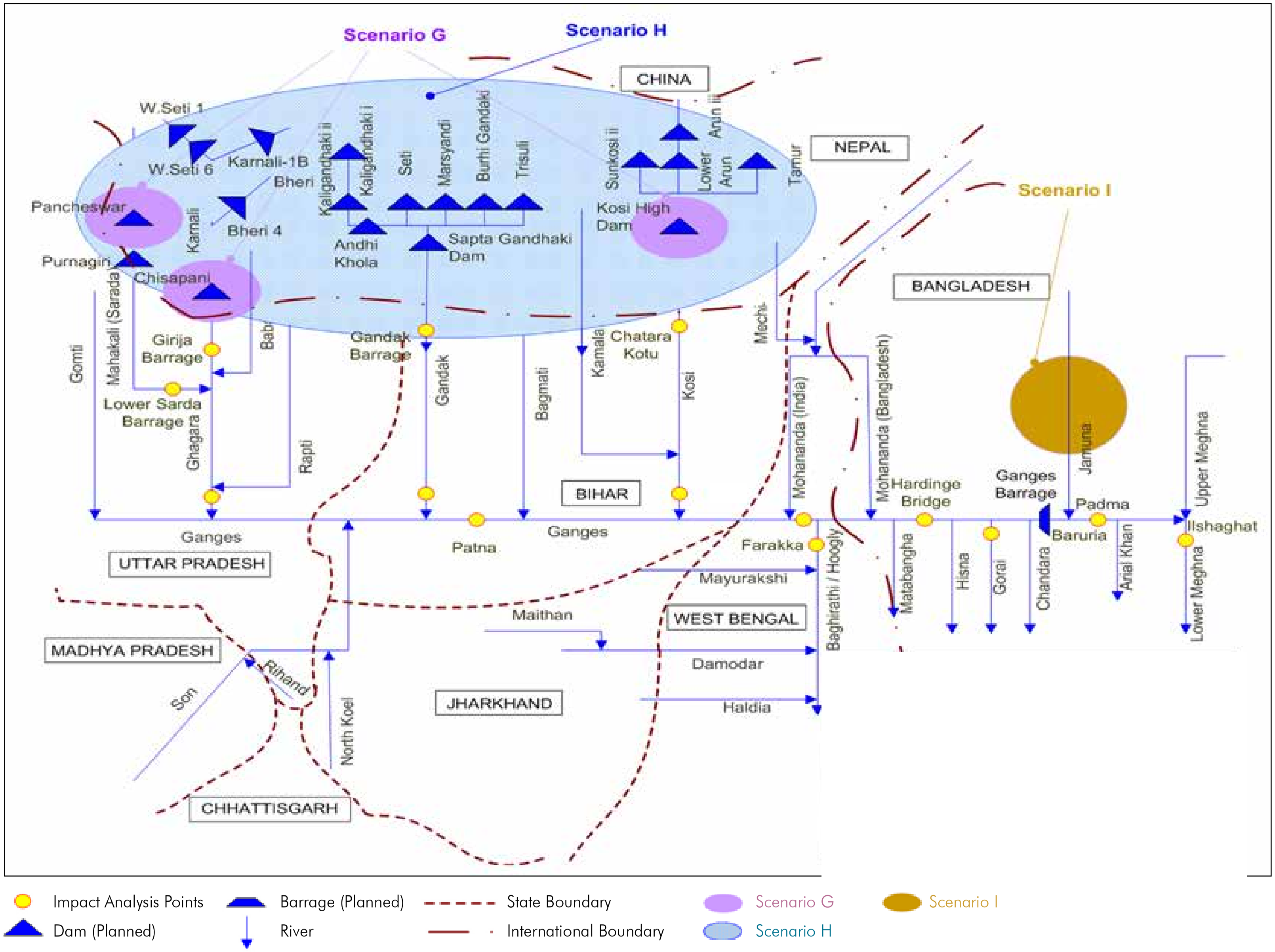


Figure 27 (b)
Schematic Representation of Storage Options

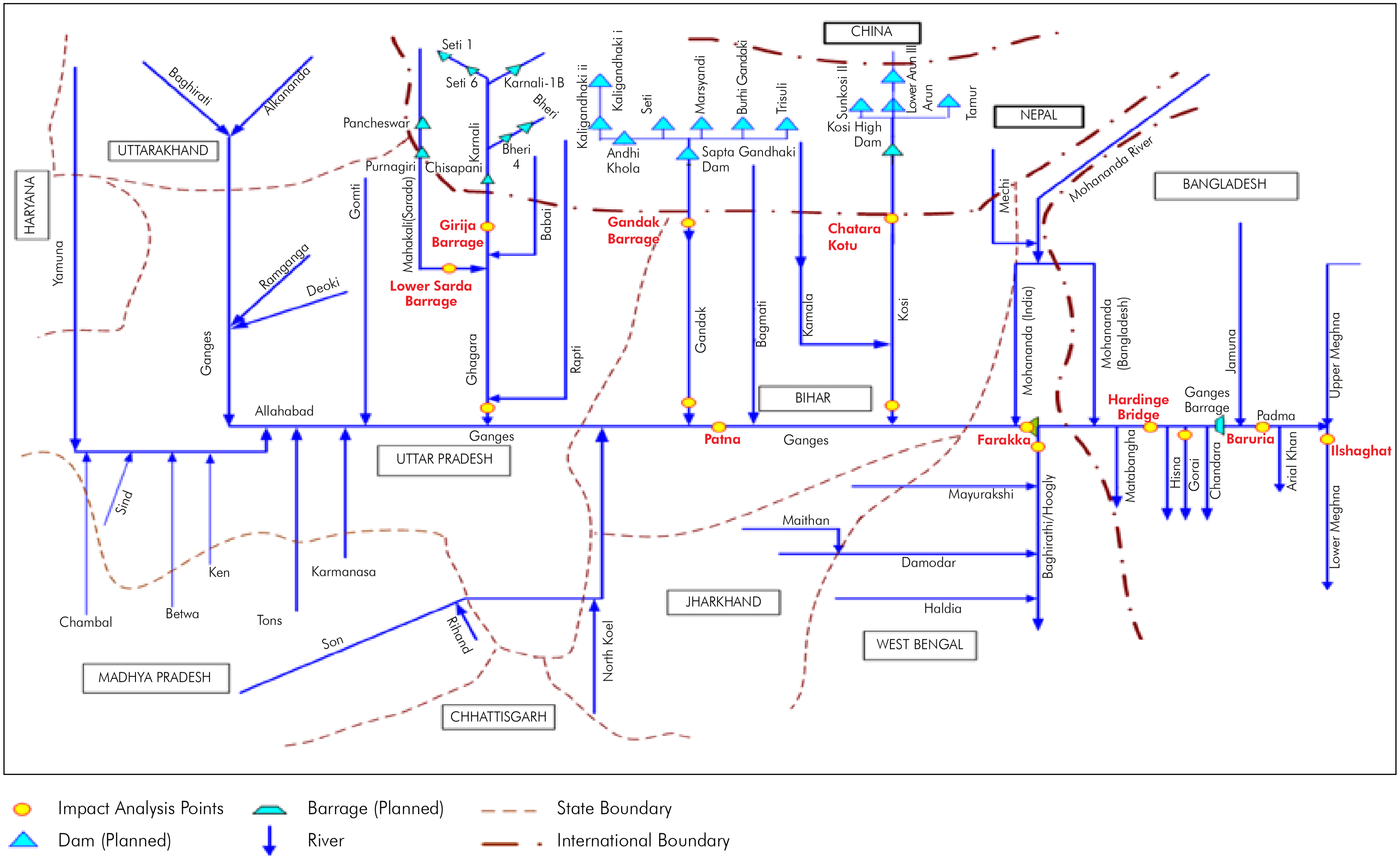


Source: IWM (2010).

Note: Scenario C considers dredging in the Gorai River, Scenario D considers the Ganges Barrage in Bangladesh, Scenario E considers the Kosi Dam, Scenario F considers the Pancheswar Dam, Scenario G considers large dams with 19gigawatt total capacity, Scenario H considers all planned dams in Nepal, Scenario I considers the Jamuna-Ganges link in Bangladesh, and Scenario J considers climate change scenarios.

Figure 28

Major Impact Locations for the Water Systems Model



Source: IWM (2010).

Table 5
Key Criteria and Indicators for the Water Systems Models

Criteria	Indicator
Hydrology	Flows in major rivers (monthly hydrographs, by year and average) Descriptive statistics (average, changes) Schematics Flooded areas (in Bangladesh)
Energy	Basin hydropower production (by site and total)
Environment	Salinity intrusion (maps, values at key locations) Key pollution levels at key locations (e.g., BOD, DO)
Navigation	Navigability of key reaches
Demands	Key water demands for urban and irrigation (annual and monthly)

flow datasets; however, they seem to be consistent with other proxy data (e.g. results of other models such as the SWAT model, monthly averages from the literature) and the good calibration obtained further downstream (e.g. as shown at the Hardinge Bridge in Bangladesh) also provides a certain degree of confidence in the accuracy of the models.

The other models used were also calibrated successfully. For example, the MIKE 11 hydrodynamic model, developed over many years at the IWM, was able to reproduce observed data within Bangladesh. The MIKE 21 advection-dispersion salinity model, developed in 2008 at IWM, also shows reasonable calibration. The SWAT models show very good calibration as well for the catchments modeled. The calibration of these models is illustrated in **Figures 29-33.**

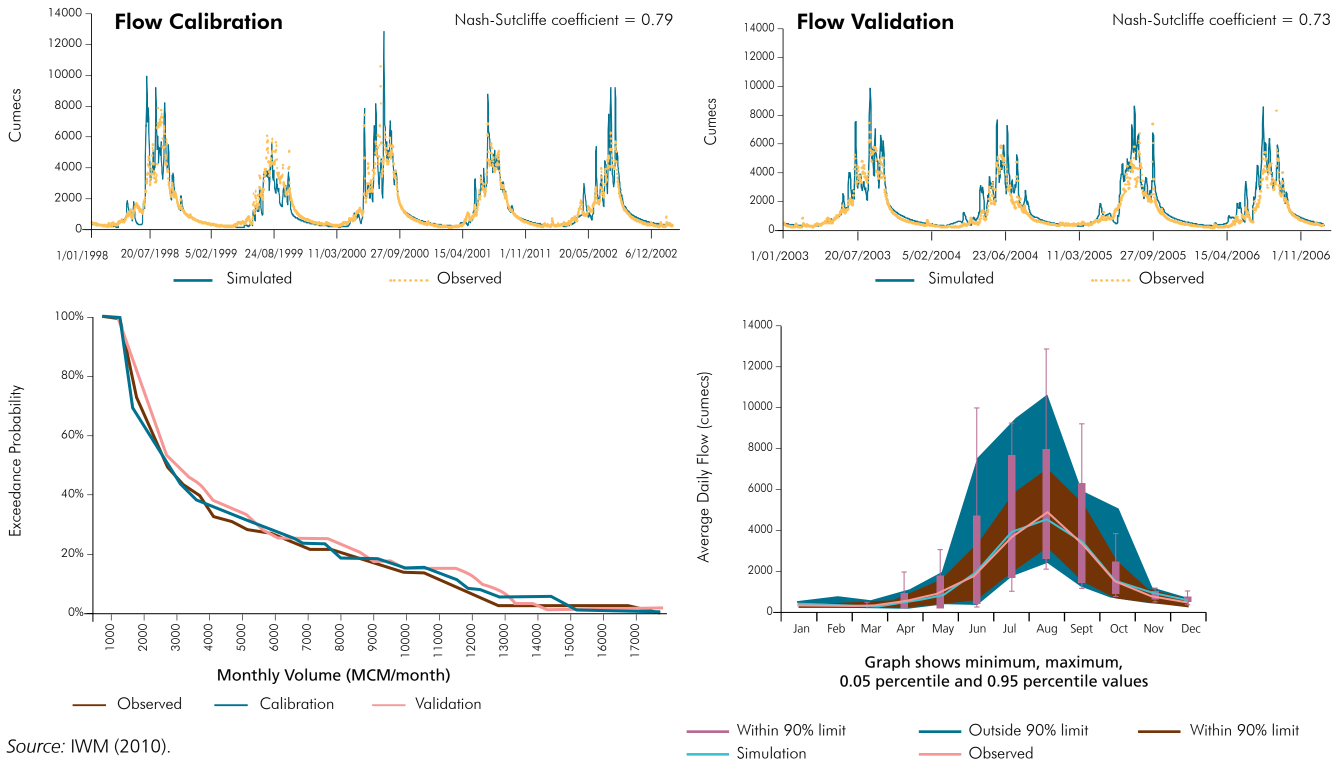
Figure 29 shows good calibration of the MIKE BASIN Model at the Chisapani Dam site in Nepal's Karnali Basin. The basin simulations show good agreement based on daily, monthly, and annual comparisons with observed data. Calibration of the basin model was done using daily discharge data from Naryanghat on the Gandak River, Chisapani on the Karnali (Ghaghara) River, Banga near Belgaon on the West Seti River, Jamu on the Bheri River, and Chatara Kotu on the Kosi River in Nepal; as well as at Hardinge Bridge on the Ganges in Bangladesh. The Nash-Sutcliffe coefficients[44] for calibration and validation of daily flows are greater than 0.74 and 0.73, respectively, in all the calibration points of the model. The simulated monthly volumes in the monsoon consistently show good agreement for calibration years; they are generally within 10 percent and always within 14 percent of observed values. The simulated monthly volumes for low-flow conditions (excluding Hardinge Bridge where there are inadequate observed values for the dry season) are within 35 percent of observed values. Discharge data of stations situated within the Ganges Basin are essential to increase the calibration points and thereby improve performance of the model. Overall, the model can be considered adequate and acceptable for making relative comparisons at the basin level.

Figure 30 shows similarly good model fits for the MIKE BASIN model near the end of the river system,

[44] Nash-Sutcliffe efficiency coefficients (R squared) are model accuracy statistics used to assess the predictive power of hydrological models. A coefficient of 1 means a perfect fit between modeled discharge and observed data.

Figure 29

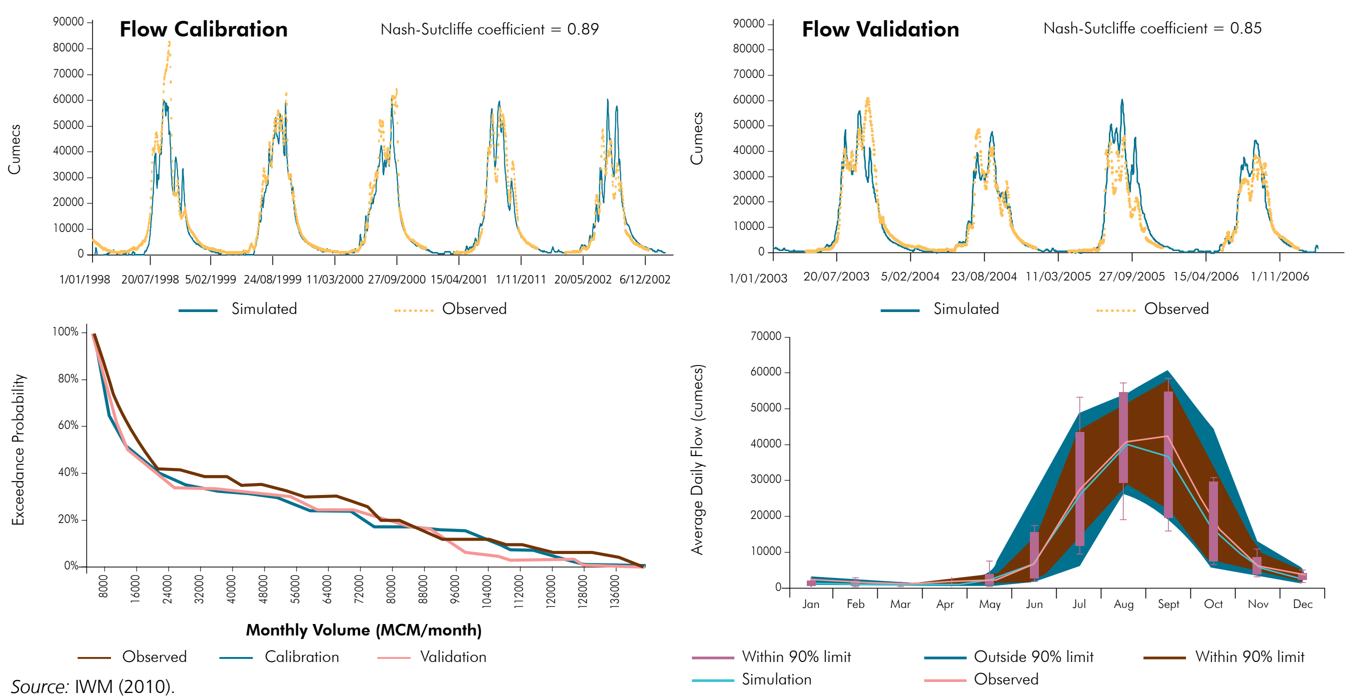
Calibration and Validation of the MIKE BASIN Model (Karnali Basin in Nepal)



Source: IWM (2010).

Figure 30

Calibration and Validation of the MIKE BASIN Model at Hardinge Bridge in Bangladesh



Source: IWM (2010).

measured on the Ganges River at Hardinge Bridge in Bangladesh.

Figure 31 shows excellent calibration of the MIKE 11 hydrodynamic model in Bangladesh, measured at Hardinge Bridge in Bangladesh.

Acceptable calibration of the MIKE 21 salinity model, measured at Khulna on the Pussur River in Bangladesh, is shown in **Figure 32**.

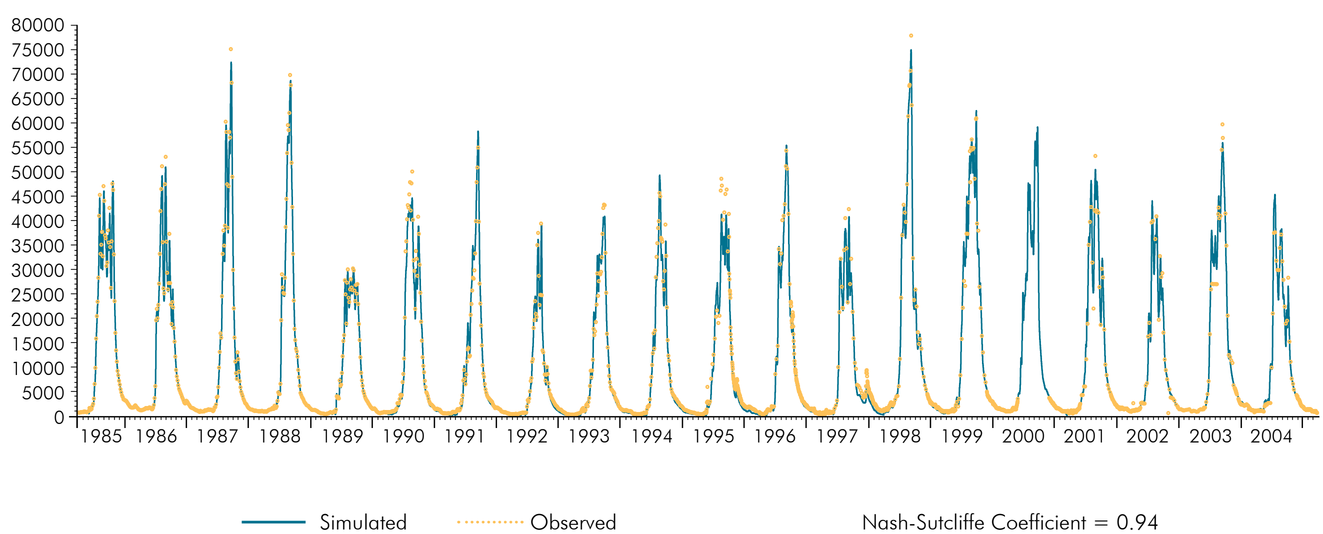
Economic Optimization Modeling

The Ganges economic optimization model attempts to maximize total annual economic benefits by varying releases of water from a set of assumed infrastructure facilities. The total annual economic benefits are the sum of the economic value of four components: (1) hydropower production from new and existing dams; (2) irrigation water for the cultivation of agricultural crops; (3) reducing flood damages; and (4) incremental low flows to Bangladesh above the minimum legally required at Farakka Barrage.

Although this model focuses exclusively on these economic values, it does not suggest that these are the only values to be considered in the development of multipurpose infrastructure in the basin. The Ganges is a river of enormous cultural, religious, and social significance, and these types of values also must be a central consideration. Ecosystem sustainability, recreation and tourism, navigation, municipal and industrial water supplies, and equity concerns within and across borders should all be factors in development decisions. Economics is just one important part of the decision calculus.

The model is formulated as an annual, nonlinear, constrained-optimization problem with a monthly time step. The model determines the annual pattern of water allocations that maximize the systemwide economic benefits from hydropower, agriculture, flood reduction, and downstream low flows. It calculates the economic benefits by water use and by country. Minimum flows in specific upstream reaches of the river and at the Farakka Barrage are imposed in the model as constraints on river

Figure 31
Calibration of the MIKE 11 Hydrodynamic Model at Hardinge Bridge in Bangladesh



Source: IWM (2010).

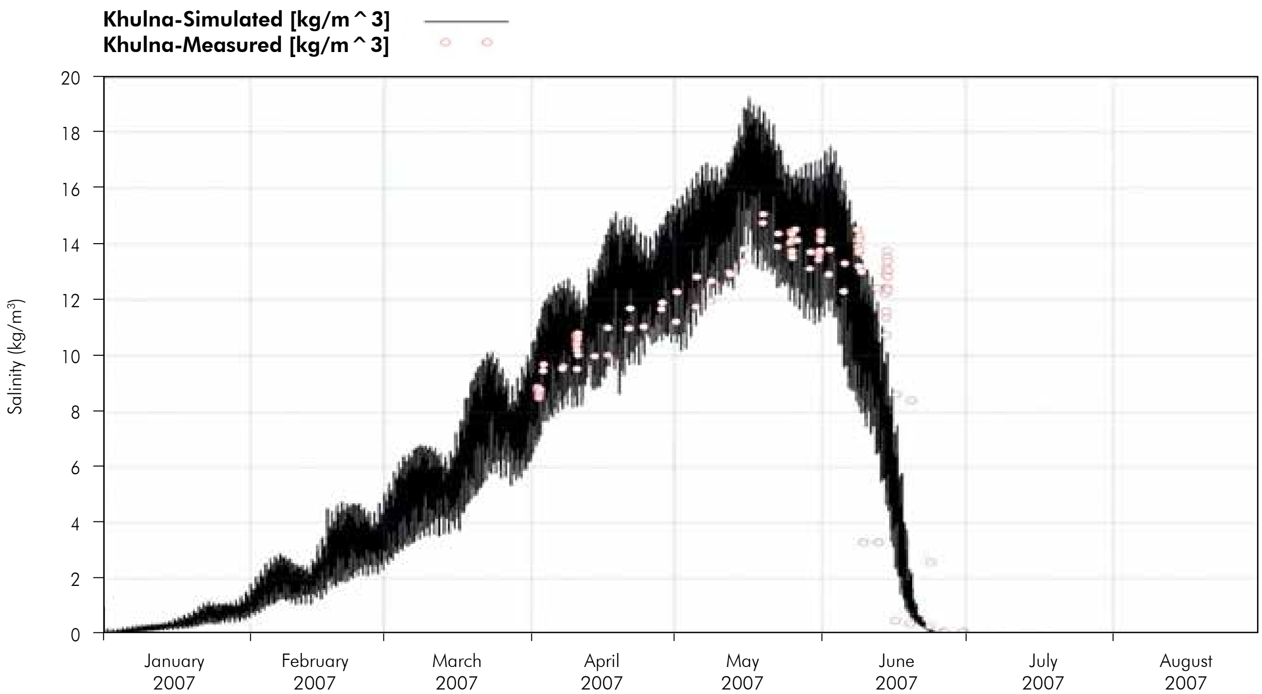
Figure 32

MIKE 21 Salinity Model: Modeled River System of the South West

Source: IWM (2010).

Figure 33

MIKE 21 Salinity Model: Comparison of Simulated and Measured Salinity in the Pussur River



Source: IWM (2010).

flow. In the analyses presented here, for example, upstream minimum flows must be sufficient to satisfy all municipal demands, and downstream flows must at least be in accordance with the minimum flow specified in the Ganges Treaty between India and Bangladesh.

The economic optimization model schematic **(Figure 23)** shows how the model characterizes the Ganges system as a network of nodes and links. There are five basic types of nodes: reservoirs, irrigation withdrawals, flood outflows, flood returns, and intermediate nodes. The model includes 29 major existing storage reservoirs (all but one of which are in India), plus 23 potential new dams. All of these new dams and the reservoirs behind them are in Nepal, with the exception of the proposed Pancheshwar Dam site on the Mahakali River, which is a border river shared by India and Nepal.[45] Most of these reservoir nodes allow storage of inflows up to reservoir capacity, beyond which flows spill downstream (three of these new dams are run-of-the-river hydropower projects without water storage). Reservoir releases determine hydropower production and the amount of water available for downstream irrigation.

There are 34 irrigation nodes in the optimization model, some of which, in reality, correspond to very large command areas served by irrigation canals. Some of these command areas currently are only partially irrigated with surface water due

[45] The Mahakali River runs north to south, with the right (western) bank in Indian territory and the left (eastern) bank in Nepal. The international border runs down the center of the river so half the Pancheshwar Dam and reservoir would be in each country.

to constraints on water delivery during the low-flow period. At these nodes, the model removes water from the river system and partitions it into four components. The first portion of this water is used to satisfy irrigation water demands for crops grown in the command areas (the amount of water required in different areas is estimated based on crop water requirements obtained from the United Nations Food and Agriculture Organization (FAO) crop water model, CROPWAT). The second component accounts for losses to nonproductive evapotranspiration from canals and fields; our analysis assumes this portion to be equal to 60 percent of the water actually used by crops (the first component), or 30 percent of the water diverted to irrigation areas. The third portion of diversions – 20 percent overall, or 40 percent of the crop water requirement – is assumed to flow back into the Ganges system via return flows. Finally, the model allows additional diversion of water into groundwater recharge when the canal capacity is not fully utilized. This recharge water is not lost to the system; the model adds it to storage in groundwater reservoirs beneath each irrigation node. This stored groundwater can then be pumped (at a cost) and used throughout the year to help meet irrigation water demands when surface flows are insufficient. The water balance for groundwater reservoirs only incorporates flows out of the modeled surface water system and does not include recharge from 'green water' (water stored in the soil) or from local precipitation and infiltration.

There are also eight flood outflow nodes. Seven are located on the northern Ganges tributaries (Yamuna, Upper Ganga, Ghagara, Rapti, Gandak, Bagmati, and Kosi) and one is on the main Ganges. At these nodes, monthly flows in excess of natural river channel capacities leave the river network and cause flood damage. A fraction of these river spills are then assumed to return to the river at the flood return nodes, which are located just downstream of the flood outflow nodes. The other intermediate nodes in the Ganges economic optimization model account for inflow (i.e. where runoff enters the system); confluence (where multiple rivers meet); and distribution (where a river splits). In total, 77 of the model nodes receive inflows from local catchments.

The mathematical model's objective function is expressed as:

$$\boldsymbol{Maximize\ Z} = \sum_k \boldsymbol{p^h} \cdot \boldsymbol{H_k^m} + \sum_j \boldsymbol{p^{irr}} \cdot \boldsymbol{I_j^m} + \boldsymbol{p^l} \cdot \boldsymbol{L^b} - \sum_k \boldsymbol{F_k^m} - \sum_j \boldsymbol{c^g} \cdot \boldsymbol{G_j^m},$$

where:

Z total economic benefits (in millions of US$);

p^h economic value of hydropower (US$/kW-hr);

H_k^m annual hydropower generated in project at node k (in GW-hr/yr);

p^{irr} economic value of irrigation water (US$/m^3);

I_j^m volume of irrigation water delivered to area j, in state/country m (in millions of m^3);

p^l economic value of low flows (US$/m^3);

L^b volume of low flows to Bangladesh during the lean season (January – May), above the Farakka treaty minimum (in millions of m^3);

F_k^m economic cost of exceeding channel capacity at node k, in state/country m (in millions of US$);

c^g cost of pumping recharged groundwater (US$/m^3); and

G_j^m volume of recharged groundwater pumped to area j, in state/country m (in millions of m^3).

The model uses a monthly time step t and determines the value of the decision variables that yield the highest outcome of the objective function Z. This model-determined pattern of water releases and allocations to water users is subject to constraints on flow continuity in the river, water balance and partitioning at irrigation nodes, river channel capacity, low flow and municipal/industrial water requirements, groundwater and surface water storage capacity, installed hydropower capacity, irrigation water requirements, and land availability. There is also a requirement that all reservoirs (including those for groundwater) end the year at the same level at which they began, though optimal initial levels are determined by the model.

In addition to these modeling efforts, a short study was commissioned on the economics of 'hard' versus 'soft' flood mitigation strategies.

There are a number of important limitations of the Ganges optimization model formulation. First, and perhaps most important, the model does not incorporate hydrological uncertainty. It assumes that managers of the system know the pattern of inflows a year in advance and can adapt monthly operation ahead of time to optimize water allocations for the year. Second, an annual model cannot describe the consequences of a sequence of years of abnormally low or high flows. However, because there is little physical opportunity for over-year storage in the existing or potential infrastructure projects on the Ganges, decisions on optimal releases from reservoirs will be made without consideration of multiyear consequences. Third, estimates of annualized capital costs were made separately using old cost data inflated to present values. Capital costs of dam construction and new and expanded canals for irrigation were not directly included in the model itself.[46] Fourth, upstream water quality concerns have been included only through the minimum flow constraints. Fifth, the Ganges economic optimization model cannot precisely replicate the provisions of the Farakka Treaty (established in 1996) for allocation of water between India and Bangladesh.

Economics Optimization Model Data and Scenario Analysis

A user of this economic optimization model assumes that a particular set of infrastructure projects is in place; the model does not solve for the optimal set of projects. A user can explore the consequences of building different sets of new dam projects, and test the sensitivity of results to different hydrological flows (using low, average, and high flow years). He/she can impose minimum flow restrictions or prioritize demands along critical stretches of the river (for example diversions to Kolkata). Finally, a model user can alter river channel capacities to reflect changes in river geomorphology or the effects of enhanced embankment protection (assuming there are no breaches).

The consequences of constructing different sets of upstream storage infrastructure are measured relative to a baseline that closely resembles current conditions. It is not possible to precisely characterize the present situation of Ganges water management because the amount and precise pattern of surface water withdrawals for different basin irrigation schemes in India are unknown. Instead, we estimated overall crop water requirements in different irrigation schemes based on state-level data for the major crops in the existing mix, accounting for local climatic conditions and the differing cropping intensities in irrigated areas within Bangladesh, India, and Nepal.[47] Thus, instead of constraining irrigation water withdrawals according to existing surface water demands in the basin, the model solves for the theoretical area of land that should be irrigable given existing cropping patterns, yields, market prices, and water use at the field level according to the irrigation water partitioning parameters discussed above.

The economic optimization model was used to examine the impacts of four options for new infrastructure projects. The hydrological year used in the base case is the year 2000, for which the overall runoff into the Ganges was 502 billion cubic meters (compared with an average of 508 billion cubic meters over the 10-year period 1999–2008; range 460–545 billion cubic meters). None of the major river tributaries had exceptional hydrology in 2000.

The four options examined are:

1. Existing storage and flow regulation projects (status quo, baseline case)

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[46] The purpose of these models is to look at basinwide dynamics, not to assess the costs and benefits of specific projects. Project-level analysis would require significant additional economic, social, and environmental analysis.

[47] Japan International Cooperation Agency 1985; BBS (Bangladesh Bureau of Statistics) 2004; Indiastat 2005.

2. Three proposed mega-dams in Nepal (Similar to Scenario G for the water systems models): Pancheshwar Dam on the Mahakali/Sarda River, Chisapani Dam on the Karnali River, and the Kosi High Dam on the Kosi River
3. Only building smaller dams and run-of-the-river projects in Nepal, of which we include 20 (we include only the largest dams among many on a long list of possible projects)
4. All major proposed storage in Nepal built (similar to Scenario H for the water systems models)

Sensitivity analysis was conducted to explore the effects of several modeling assumptions on the results: (1) varying the relative economic value of low flows to the delta; (2) varying the economic value of irrigation water; and (3) testing the effects of low, average, and high years of flow on both physical and economic outcomes in different portions of the basin. Sensitivity analyses were combined on the first two assumptions by constructing nine cases representing all low, medium, and high combinations of the economic value of water to irrigation and downstream low flow augmentation. These assumptions are shown in **Table 6**.

Social Analysis

The social analysis complements the hydrological and economic modeling sections by providing a demographic overview of the Ganges Basin, and insights on the community-based flood management strategies and the role of embankments in the basin. This analysis complements a literature review with new qualitative research, including focus group discussions, semi-structured household-level questionnaires, and open-ended interviews with local and regional key informants and experts. In total, 68 focus group discussions were conducted with men and women in communities facing a variety of water management issues, including biodiversity loss, salinity intrusion, water quality, floods, and droughts. **Figure 34** shows the sites for the focus group discussions.

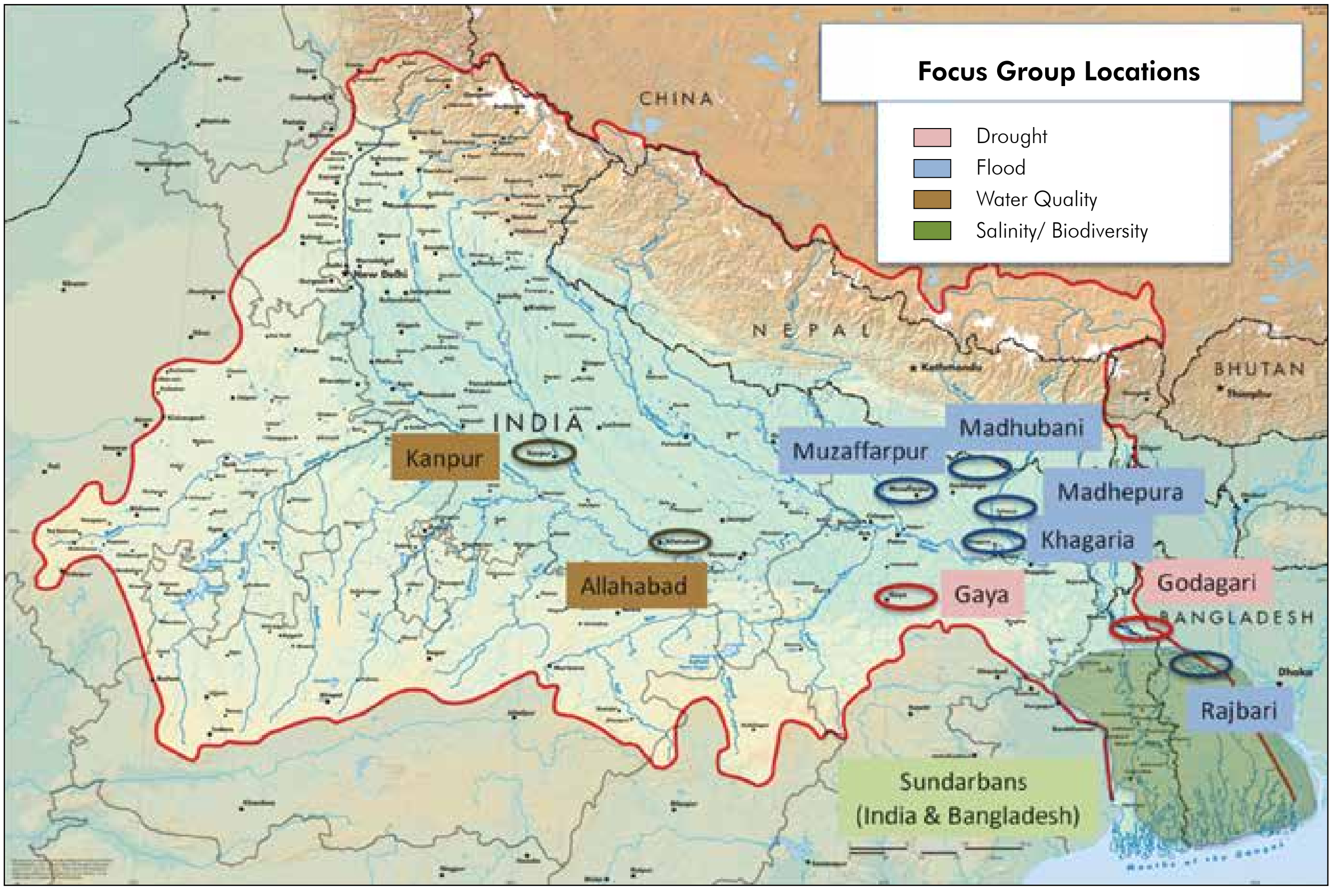
The key challenge was that the diversity of populations in the Ganges Basin makes it difficult to ascertain impacts that can be generalized for the entire basin. The social analysis aims to address this challenge by investigating key areas to better understand localized views and responses to flooding and to generate key themes around flood management from the local level. It does not attempt to draw a representative sample of the basin.

Focus group discussions were organized in sites that face problems of (1) chronic flooding, (2) drought, (3) water quality issues, and (4) salinity intrusion. Focus group discussions were conducted with men and women in about 20 districts across India and Bangladesh in coastal areas and the lower plains.

Table 6
Assumptions of Irrigation and Low-Flow Values in the Economic Optimization Model

Economic value	Low (US$/m^3)	Medium	High
Value of low flows to the delta above Farakka Barrage minimum for Jan-May	0.00	0.05	0.10
Value of water in irrigation	0.01	0.05	0.10

Figure 34
Site Map of Focus Group Discussions



4.

Ten Fundamental Questions

Fundamental environmental, economic, and social questions must be answered to guide informed decisions on the sustainable management and development of the Ganges Basin's resources. This section asks key questions that can help focus future efforts to explore the potential and limitations of water resources development in the Ganges Basin. We pose ten fundamental questions, describe the commonly held perceptions[48] on the answers to these questions, and then provide answers and insights based on the new information obtained from our modeling and analysis. The ten questions are:

1. Is there substantial potential for upstream reservoir storage in the Himalayan headwaters of the basin?
2. Can upstream water storage control basinwide flooding?
3. Can upstream water storage augment low flows downstream?
4. Are there good alternatives or complements to reservoir storage?
5. Is there substantial untapped hydropower potential in the Ganges Basin?
6. What is the magnitude of potential economic benefits from multipurpose water infrastructure, and what are the tradeoffs among different water uses?
7. What are the cost- and benefit-sharing dynamics of upstream water storage development?
8. Is infrastructure the best strategy for protecting communities from floods?
9. Is it possible to control sediment in the Ganges?
10. What will climate change mean for the basin?

This list is not an exhaustive set of questions about the dynamics of and development options for the Ganges Basin. Instead, it was created to stimulate discussion of some of the most critical issues with which riparian countries will need to grapple as they manage and develop their shared water resources.

Question 1.
Is there Substantial Potential for Upstream Reservoir Storage in the Himalayan Headwaters of the Basin?

Perception: Yes

Much has been written about the potential for large water storage structures in the Himalaya. It is generally assumed that this potential could be harnessed through large multipurpose dams to produce hydropower, deliver more timely irrigation water, and regulate the extreme flows of the Ganges River.

Findings: Not Really

Although many sites are attractive for the development of multipurpose water storage infrastructure, the steep terrain and deep gorges allow surprisingly little water to be stored behind even very tall dams. Developing the full range of structures under consideration in this report would provide additional active system storage equivalent to only about 18 percent of annual average flow, which is not very significant on a basinwide scale.

Even if every one of the 23 large dam sites identified in Nepal were developed, the aggregate active storage on the river system would be only about 130–145 billion cubic meters, of which about one third already exists. This amount of storage is quite small compared with the 500 billion-cubic-meter average annual flow of the Ganges River

[48] By necessity, these summarized perceptions are broad generalizations that do not represent the range of perspectives and insights offered by researchers, journalists, and government officials in the region and abroad. Many have written on these issues and come to conclusions that are similar as those reached in this report.

49

(Figure 35). For comparison, storage capacity on many rivers is 100–200 percent of the mean annual flow. For example, the Colorado River's storage capacity is roughly 250 percent of mean annual flow. Storage on the Nile is about 300 percent.

The topography of the Ganges system simply does not allow for storage of large volumes of water. Furthermore, developing even the modest 130–145 billion-cubic-meter storage potential on the Ganges would be very expensive; the 23 large infrastructures proposed would require capital investment of roughly US$35 billion (2010 dollars) and likely take at least 30 years to construct.[49] Why is there so little storage capacity when there are so many dam sites? The Himalaya offer many opportunities for the development of multipurpose storage dams that could produce hydropower and provide water for drinking, industrial supplies, and irrigation. However, the rugged topography and steep mountains (**Figure 36**: Gradients of Selected Himalayan Rivers) do not allow for large reservoirs, thus Himalayan dams do not create the substantial storage that is generally available behind tall dams in less steep areas.

Figure 35
Current and Potential Surface Water Storage in the Ganges Basin

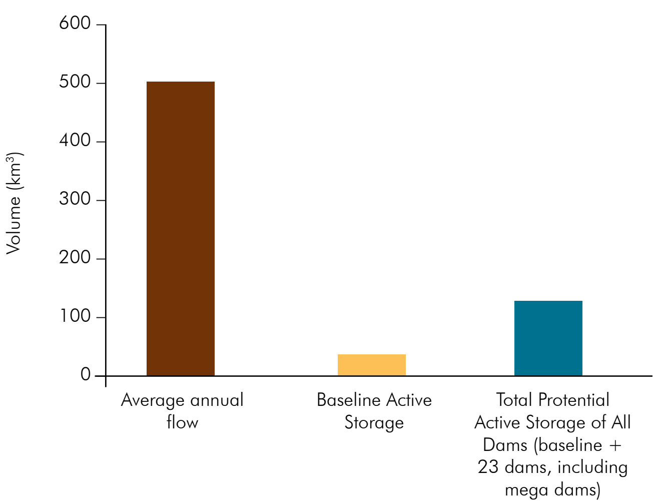


Table 7 presents the major existing and proposed dams in the Ganges system with heights of more than 100 meters. Even though many of these dams would be among the tallest in the world, they would provide surprisingly little storage. In Egypt's flat terrain, the Aswan High Dam, with a height of 111 meters, can store 162 billion cubic meters of water, whereas the Andhi Khola Dam site on the Kali Gandaki River in Nepal, with a comparable height of 110 meters, would store only 0.9 billion cubic meters.

A distinction is made between a dam's active (live) storage and its gross (or total) storage. Most dams are designed to have only a portion of their storage actually accessible every year while the remaining (dead) storage is reserved for sediment storage. To understand the potential of system storage to regulate flows, one must compare the active storage with the mean annual flow or high flows of the river. For example, as shown in Table 7, the Chisapani Dam on the Karnali River in Nepal has the highest proposed storage in the Ganges system at 28.2 billion cubic meters of gross storage; however, its usable live capacity is only 16.2 billion cubic meters. Since the average annual flow of the Karnali River at the Chisapani site is approximately 44 billion cubic meters (with monsoon flows alone ranging from 22 to 47 billion cubic meters depending on the year), even this dam, with the largest storage capacity of any identified dam site in the Ganges Basin, would not be able to provide over-year storage or store the full monsoon flow.

Despite often polarized views on this debate, dams are not good or bad per se. As the following questions indicate, in addition to detailed individual project-level analyses, it is critical to

[49] Dams could arguably be built in the middle and lower reaches of the river basin, but alluvial plains are not generally favorable for dam construction, and the combination of high temperatures and flat reservoirs with high surface area-to-volume ratios would lead to large evaporation losses. Plus, because of the very high population density in the Ganges plain, dams with large surface area would have great impacts in terms of resettlement.

understand the systemwide implications of, and alternatives to, dams.

Question 2.
Can Upstream Water Storage Control Basin Wide Flooding?

Perception: Yes

Himalayan storage reservoirs are commonly seen as the answer to the flooding that plagues the Ganges plains and delta, especially in areas of Bangladesh, Bihar, and eastern Uttar Pradesh.

Findings: Not Really

Although a moderate amount of flow could be stored at the subbasin level, this storage is unlikely to significantly reduce flooding because it is generally not the level of peak flows in major (usually embanked) tributaries that causes flooding, but rather localized rainfall, high flows in smaller tributaries, and embankment failures.

At the basinwide level, the storage potential is simply too small to meaningfully regulate the full river system. The modest scale of potential active

Figure 36
Gradients of Selected Himalayan Rivers

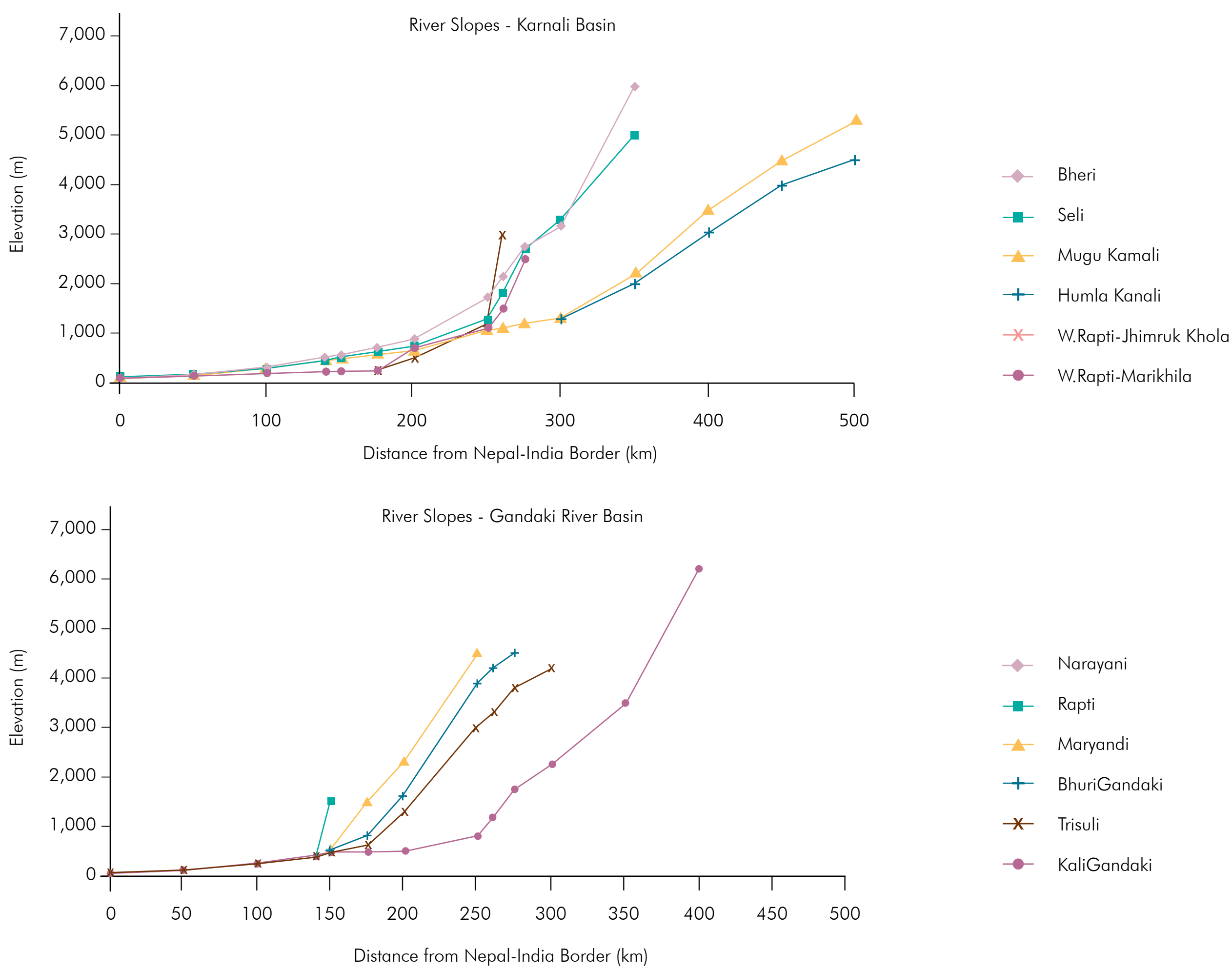


Table 7

Existing and Proposed Dams in the Ganges Basin over 100m High, with Global Comparators

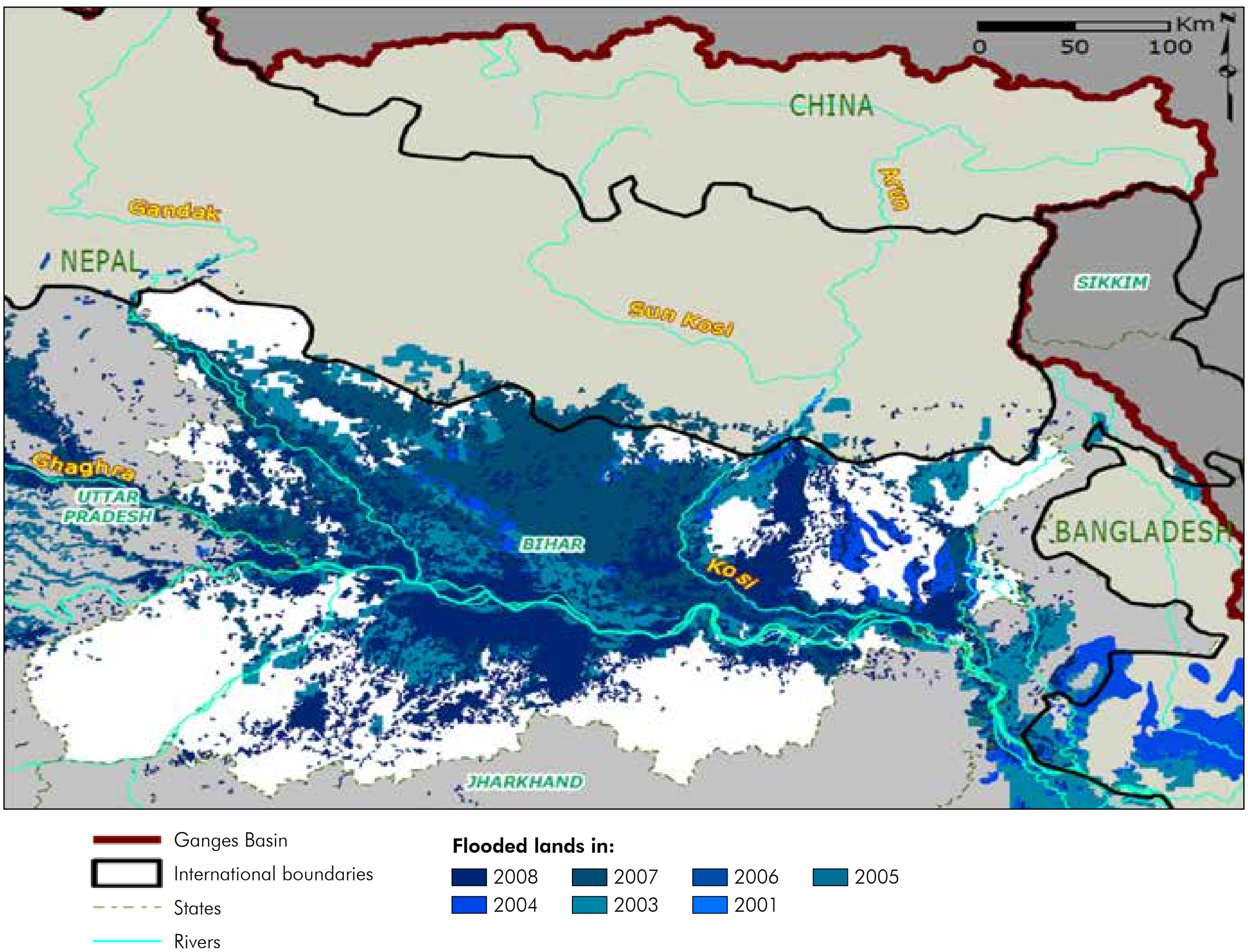
Dam	River	Total height (m)	Gross Storage Capacity (BCM)
Existing			
Tehri	Bhagirathi	261	3.5
Marsyangdi	Marsyangdi	240	6
Lakhwar *(Under construction)*	Yamuna	204	0.6
Utyasu *(Under construction)*	Alaknanda	175	3.7
Kalagadh	Ramganga	128	0.3
Kulekhani	Bagmati	107	0.1
Proposed			
Budhi Gandaki	Budhi Gandaki	300	3.2
Upper Karnali	Karnali	260	7
Bheri 4	Bheri	260	15.8
Kali Gandaki A	Kali Gandaki	260	6.9
Pancheshwar	Sarda	250	6.8
West Seti (Seti 6)	West Seti	240	3.1
Chisapani	Karnali	240	28.2
Sapta Koshi High	Koshi	220	13.5
Seti 1	West Seti	195	1.5
Sun Khosi	Sunkoshi	180	1.5
Kali Gandaki 2	Kaligandaki	160	5.1
Purnagiri	Sarda	150	3.4
Tamur Mewa	Tamur	150	1.9
Seti	Seti	145	4
Trisuli	Trisuli	140	11.0
Andhi Khola	Kali Gandaki	110	0.9
International Dams	**River**	**Total height (m)**	**Gross Storage Capacity (BCM)**
Nurek[1]	Vakhsh, Tajikistan	300 [a]	10.5
Hoover[2]	Colorado, USA	221	35.2
Three Gorges[3]	Yangtze, China	175	39.3
Aswan[4]	Nile, Egypt	111	169

Sources: This table was compiled from a variety of sources and expert interviews to reflect the range of large dams under discussion by governments and stakeholders. It is not an official list of planned investments.
1. Ghasimi 1994, p. 138.
2. Cech 2010, p. 223.
3. Chinese National Committee on Large Dams, 2011.
4. Abu-Zeid and El-Shibini 1997, pp. 209-217.
Note: a. the tallest dam in the world.

storage severely limits riparians' ability to ever truly regulate this river system, even assuming an aggressive development of storage infrastructure. On the positive side, fewer dams will preserve a more natural hydrology in the river system, which provides a wide variety of services.

Flooding across the Ganges Basin is extensive and devastating, but so routine that it often receives little attention. **Figure 37** shows flooded areas over the years throughout the Ganges plains and delta. Upstream storage has long been considered a promising way to control these floods.[50] Given the

Figure 37
Flooded Areas in the Ganges Basin



Source: Based on data from RMSI Pvt. Ltd. and Dartmouth Flood Observatory.

[50] For example: Sanjeev K. Verma, 'Dams in Nepal Only Way to Check Floods,' The Times of India (Patna Edition), August 27, 2008; 'India and Nepal Negotiate Dam Construction Project', NDTV News, May 26, 2011, http://english.ntdtv.com/ntdtv_en/news_asia/2011-05-26/india-and-nepal-negotiate-dam-construction-project.html (Accessed September 6, 2011); 'India-Nepal to Talk on Building Dams to Stop Floods,' Webindia123.com, May 25, 2011, http://news.webindia123.com/news/articles/India/20110525/1757253.html (accessed September 2, 2011); and 'Nepal-India Meet on Inundation in Progress,' Kathmandu Post, October 8, 2002. Opposing views are fewer, but also expressed, see Surendra Phuyal, 'Dams Do Not Solve Flood Problems of Bihar,' March 1, 2001; Navin Singh Khadka, 'The Mother of All Floods,' The Nepali Times, August 8-14, 2003.

flat topography of the plains and delta, attention has focused on dams in the upstream mountainous regions. The floods in the Ganges plains and delta, however, are the result of several phenomena: (1) heavy rainfall and overland flow outside the main stem of the rivers, (2) breaches in embankments, (3) rising rivers that are not fully embanked, or (4) overtopping of embankments. Upstream storage and improved embankment construction and management may help in some cases. However, many floods are caused by rising waters on rivers that do not have significant upstream dam sites, or by heavy rains that find no drainage. In these cases, flood preparedness and early warning systems, along with land zoning and insurance, are essential flood-protection strategies.

Over the years, because of the particularly devastating nature of the regular floods in eastern Bihar near the Kosi River (also known as the 'Sorrow of Bihar' because of these destructive events), special attention has been given to the potential of the Kosi High Dam for reducing flood impacts. The dam site is in Nepal approximately 40 kilometers north of the Nepal-India border. **Box 3** gives an idea of the causes, frequency, and severity

Box 3

A Chronology of Recent Floods in Bihar

1998: High river discharges in most rivers in North Bihar in the first week of July cause embankments of Burhi Gandak, Bagmati, Adhwara and Kosi to be partially damaged.

1999: Unexpectedly heavy rains in October threaten the Kamla Balan river system and Kosi spurs.

2000: Kamla Balan and Bhutahi Balan catchments receive heavy rainfall in first and last week of July, causing flooding. In first week of August, Eastern Kosi embankment punctured.

2001: North Bihar is very flood affected. Western Kosi embankment, Bhutahi Balan right embankment, Bagmati left embankment and Burhi Gandak left embankment are partially damaged.

2002: North Bihar again experiences serious flooding caused by overtopping of Kamla Balan left embankment and Khiroi right embankment.

2003: Flood levels at Patna breaks 1994 record in Ganga and downstream. Bhagalpur breaks 1978 record. Status in rivers other than Ganga and Gandak is normal.

2004: Initial monsoon rains in the first week of July break previous three years' flood record and surpass the 1987 flood in north Bihar. Bagmati, Burhi Gandak, Kamla Balan, Bhutahi Balan, and Adhwara group of rivers set new flood level records. Embankments breach in 53 locations, inundating a vast area of north Bihar and causing widespread damage and loss of life. Kosi remains normal.

2005, 2006: Normal floods.

2007: Very serious flooding in north Bihar. Heavy rainfall at beginning of flood season, with regular continuing rainfall in July and August, keep the Burhi Gandak and Bagmati rising. About 28 embankment breaches occur, affecting nearly the whole of north Bihar with floods and consequent heavy losses of life and livelihoods.

2008: Kosi embankment breached on August 18 at Kusha in Nepal causing the entire river to divert to an old channel, flooding areas that had not been flooded in hundreds of years.

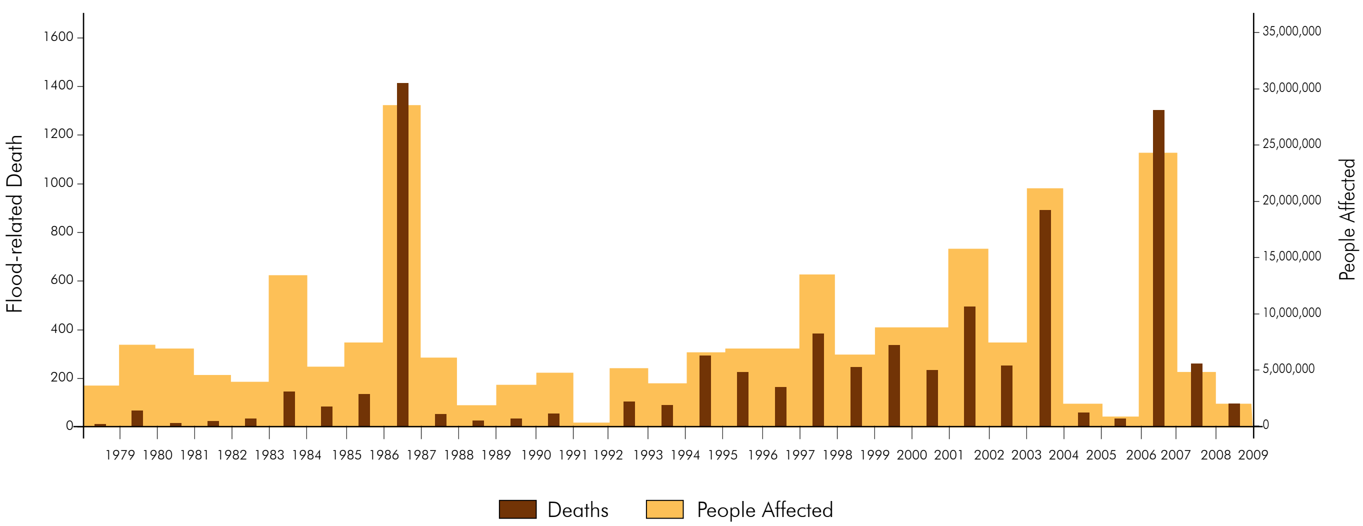
Source: Primarily from Bihar Flood Management Information System (FMIS) of these floods. **Figure 38**: Flood-Related Deaths and Flood-Affected People in Bihar demonstrates how Bihar has always been impacted by floods, with hundreds dying and tens of millions of people affected year after year.

It is often assumed that if a large dam, such as the proposed Kosi High Dam, were built upstream of Bihar, these devastating floods could be controlled. To examine this question, the simulation models were run with various operating rules. The rules were chosen to balance the often-competing uses of storage – to control floods, generate hydropower, and meet irrigation and other demands. Flows were simulated on the Kosi River near the proposed Kosi High Dam site for four infrastructure options: (1) existing infrastructure, (2) with the proposed Kosi Dam, (3) with the three proposed mega-dams, and (4) with all major planned dams in Nepal. **Figure 39** presents the results.

The models indicate that in many years, current flood peaks in the Kosi River (in red) can be brought down by building such a dam (in blue) and by leaving a substantial 'flood cushion'[51] when operating the dam. The exceptions are years such as 2003 when a closely occurring 'second peak' event occurs. Even if the dam reservoir is empty at the beginning of the monsoon, it would be completely filled after capturing the first flood peak. It could not be re-emptied in time to hold back the second flood peak.

Even the very large proposed Kosi High Dam, however, cannot eliminate flood peaks and spread the hydrograph smoothly throughout the year because the dam, which provides only 9.5 billion cubic meters of live storage, would be built on a river with an average annual flow of 55 billion cubic meters (much higher in many years). The dam could thus regulate only a small part of the monsoon flows, even in low-flow years.

Figure 38
Flood-Related Deaths and Flood-Affected People in Bihar

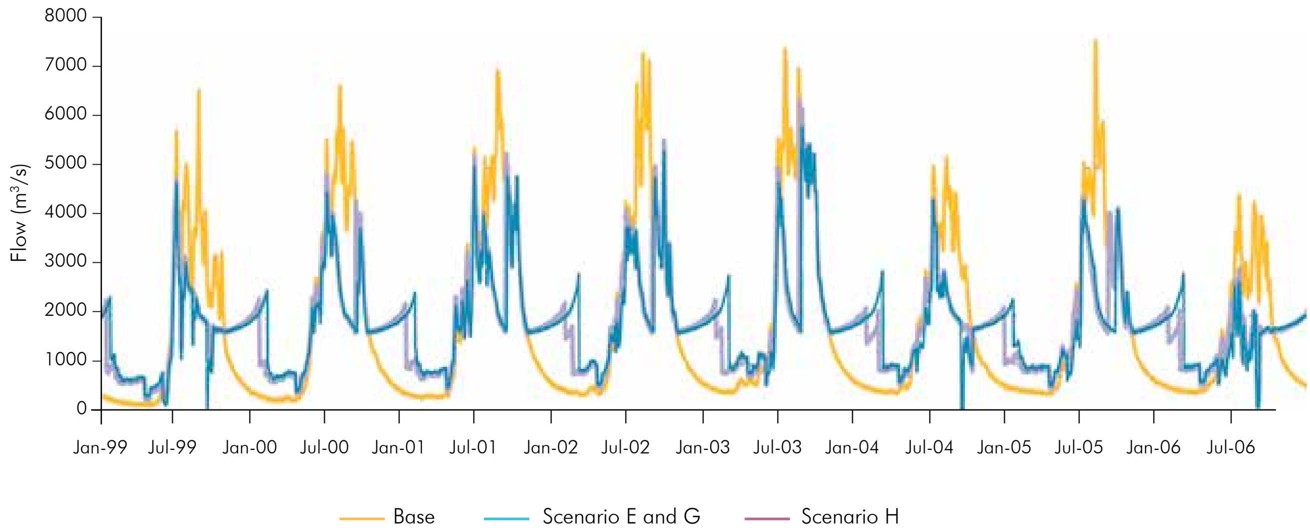


Source: Disaster Management Department, Government of Bihar.

[51] A flood cushion is created by lowering the water level in a dam reservoir to make space to capture anticipated flood waters. Lowering dam reservoir levels, however, creates tradeoffs with hydropower and irrigation uses where higher levels are generally more productive.

Figure 39

Flood Peaks on the Kosi River under Different Infrastructure Scenarios



Scenario E = Kosi Dam, Scenario G = Megadams (Kosi, Pancheswar, and Chisapani) and Scenario H = all major planned dams in Nepal
Note: The shape of the flows downstream of the Kosi High Dam in this graph is an artifact of the modeled operating rules considered in this MIKE-BASIN simulation model run. In reality, these flows are much smoother.

The important question, however, is not whether the Kosi High Dam can reduce flood peaks in the Kosi River; but whether reducing flood peaks in the river will diminish flooding events in Nepal and Bihar. The answer, unfortunately, is 'not really' – for the following reasons:

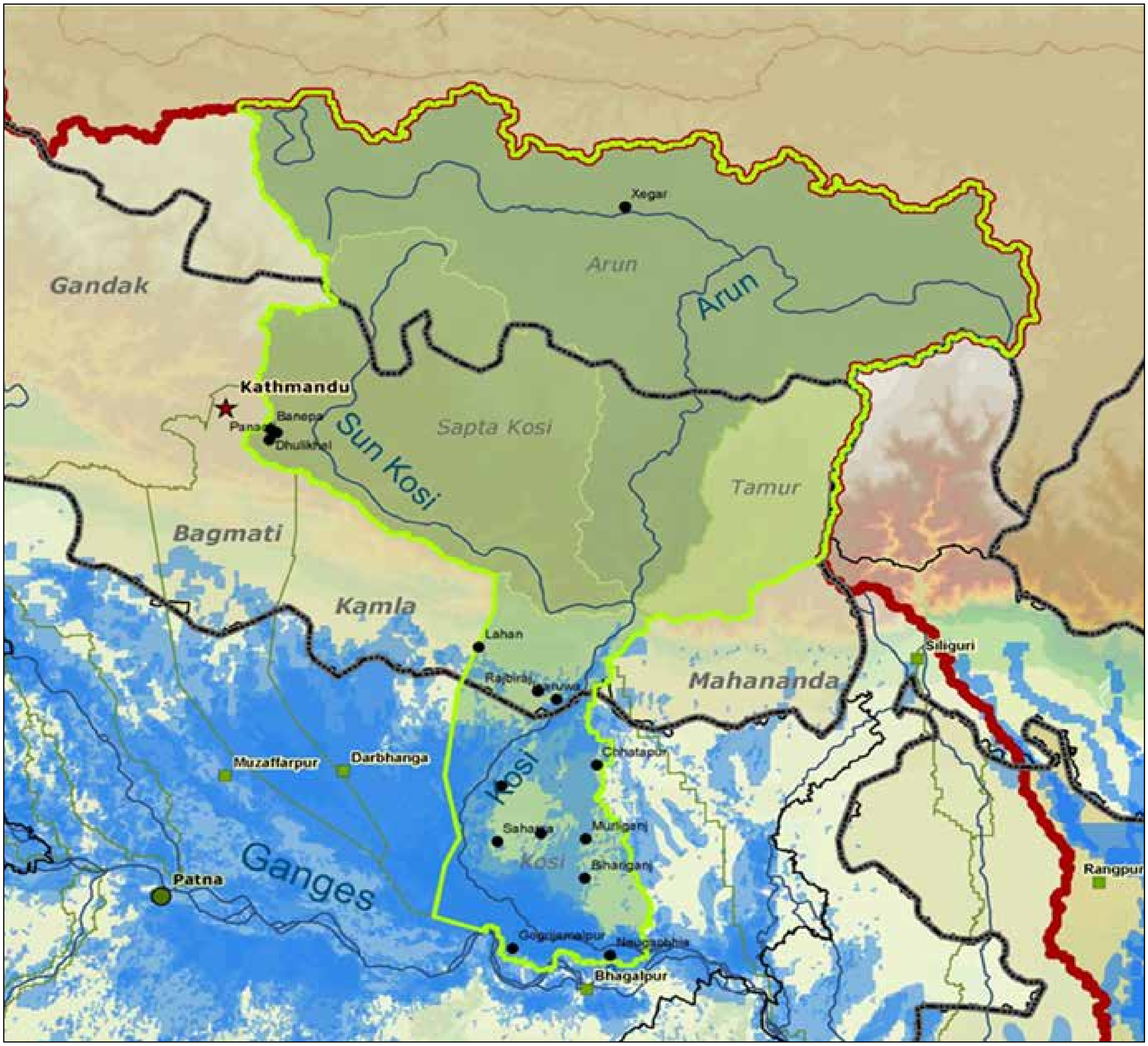
Figure 40 superimposes basin boundaries over the areas that were impacted by floods over the past decade. The image shows that ***most of the flooding in Nepal and Bihar lies outside the Kosi subbasin***. The development of the Kosi High Dam or any other flood-control infrastructure upstream in the Kosi River will impact only a small part of the flood-affected areas downstream. The majority of floods are a consequence of intense local rainfall and/or high flows in other river systems that would not be affected by building the Kosi High Dam.

The role of embankments (levees): The Kosi River, like other major tributaries of the Ganges flowing from Nepal to India, is fully embanked. Moreover, the Kosi embankments have never been overtopped. ***Bringing down the flood peaks within the Kosi embankments is unlikely to affect the lands outside the embankments, and it is unlikely to make much of a difference inside the embankments where people expect flooding***. Embankments are generally oversized to allow for river movement and extremely high flood flows. Therefore, in theory, flood flows in embanked rivers (even without an upstream dam) should not overflow and cause flooding damage.

However, people cultivate land and even live within the embankments in this poor, densely populated area. In fact, some 2 million people live in 380 villages within the Kosi embankment.[52] In addition,

[52] Singh et al., 2009.

Figure 40
Flooded Areas and Kosi Basin Boundaries



Major rivers | Ganges Basin | International boundaries | Kosi Basin | Indian States | Sub-basins

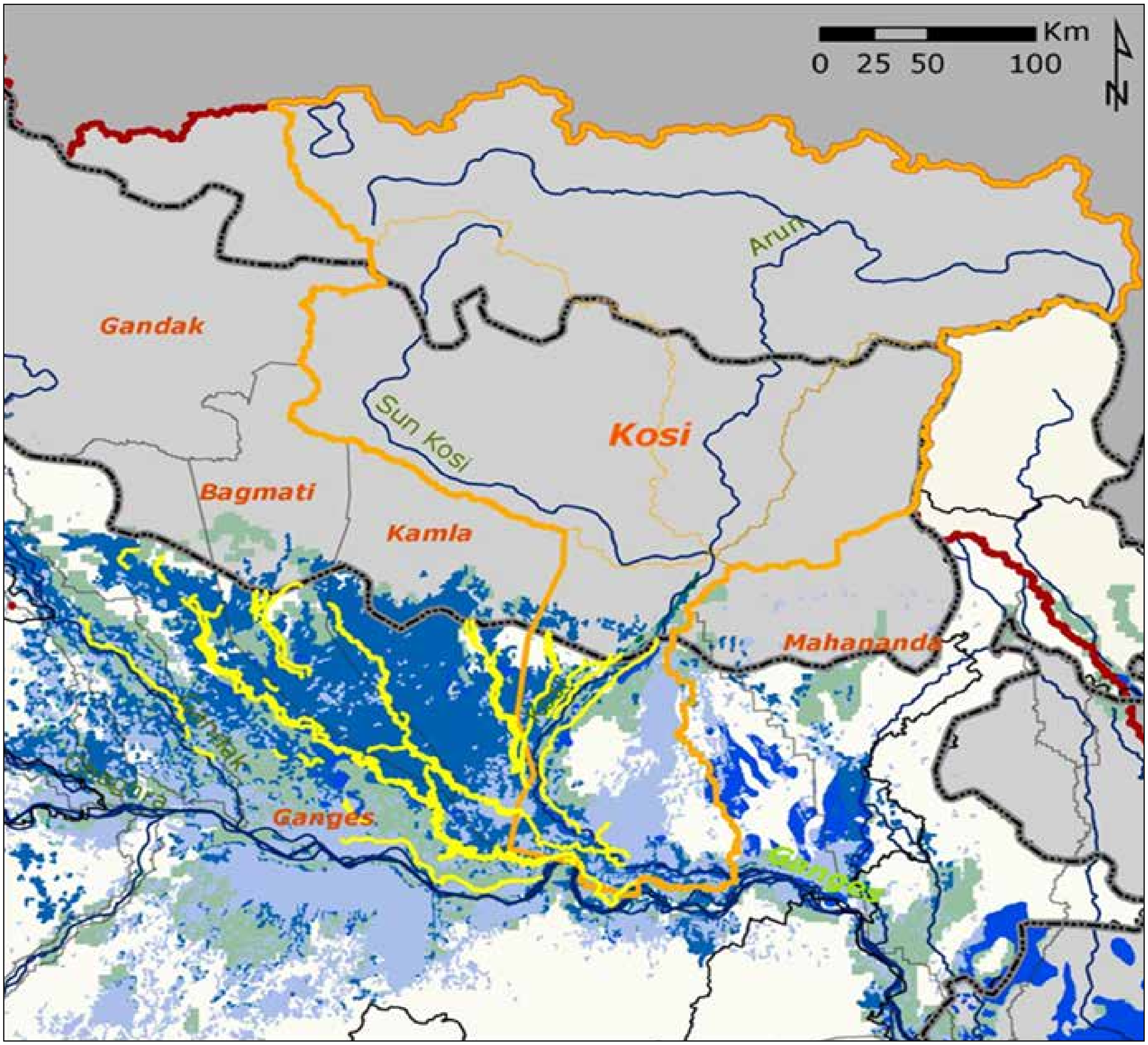
Flood Intensity (past decade)

Low | High | Very High

Capital cities | Major cities | Cities and towns in Kosi Basin | Other cities

Source: Based on data from RMSI Pvt. Ltd. and Dartmouth Flood Observatory.

Figure 41
Embankments in the Ganges Basin



Flooded lands in:

2008 | 2007 | 2006 | 2005 | 2004 | 2003 | 2001

Major rivers | Ganges Basin | Embankments | International boundaries | Kosi | States

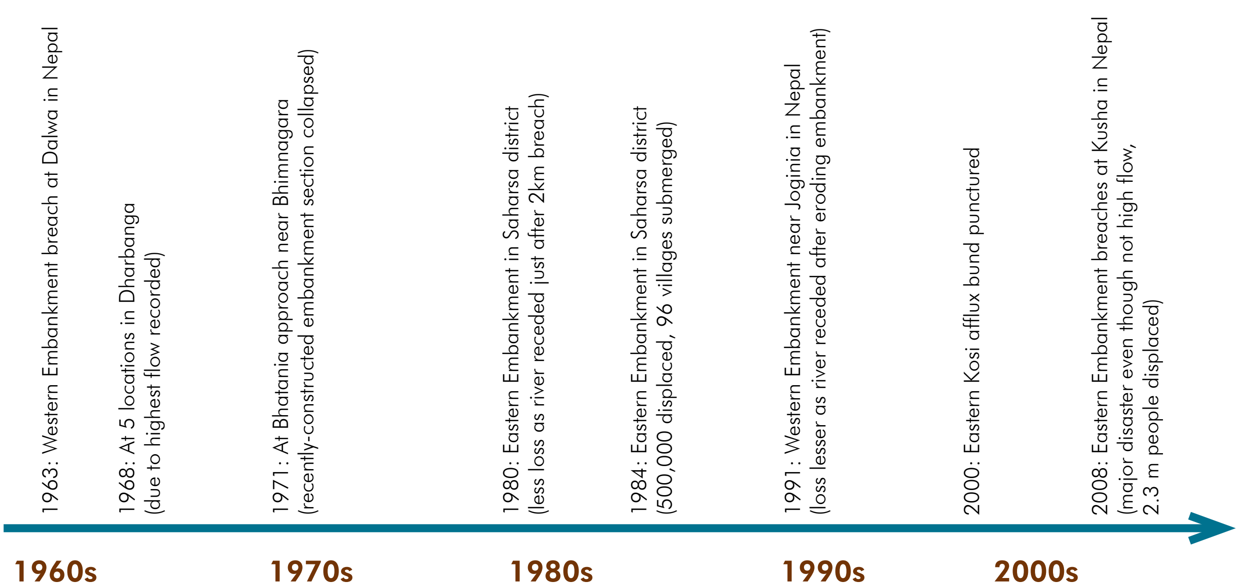
Source: Based on data from RMSI Pvt. Ltd. and Dartmouth Flood Observatory.

many embankments in the basin were poorly constructed and are generally poorly maintained (Figure 41). The Kosi 'floods' of 2008 were caused by a breach in the Kosi embankment in Nepal (which is maintained by the Government of Bihar under the Kosi Treaty). This breach made more than 3 million people homeless as the Kosi burst out of its embankments and moved to an old river channel abandoned a few centuries ago. The event led to a major six-month engineering effort to guide the river back within its embankments. Further illustrating the disconnect between peak river flows and flood events, the 2008 breach actually occurred when flows were quite low, nowhere near flood levels, which indicates an urgent need to improve embankment maintenance systems Any intensification of flows, for example as a consequence of climate change, would reinforce the need for robust embankment maintenance systems coupled with 'soft' flood-management systems. (See Question 8.)

Embankments have a mixed history in Bihar. In 1952, there were only 160 kilometers of embankments in Bihar. The 'Kosi Project,' inspired by a 1953 visit of high-level officials to the Hwang-Ho embankments of the Yellow River in China, was a massive embankment-building campaign beginning in 1955. Bihar now has about 3,500 kilometers of embankments, mostly in flood-prone north Bihar **(Figure 42)**.[53] Still, large areas of the state remain flood prone despite (or, some contend, partly because of) the embankments. The longstanding debate over the value of embankments is discussed later in this section.

A single infrastructure project like the Kosi High Dam cannot eliminate floods in Bihar. A balanced approach examining all possible structural and nonstructural interventions is needed. Investments in real-time hydromet systems and modernization of forecasting and warning systems may be the

Figure 42
Timeline of Major Damage to the Kosi Embankments



Source: Bihar Flood Management Information System (FMIS)

[53] Singh et al., 2009 and Mishra 2008.

best strategy in the short run, and possibly even in the longer run. Co-benefits of such investments include enhanced information for farmers to time their planting and fertilizing, and the collection of time series hydromet data needed for climate change monitoring and modeling.

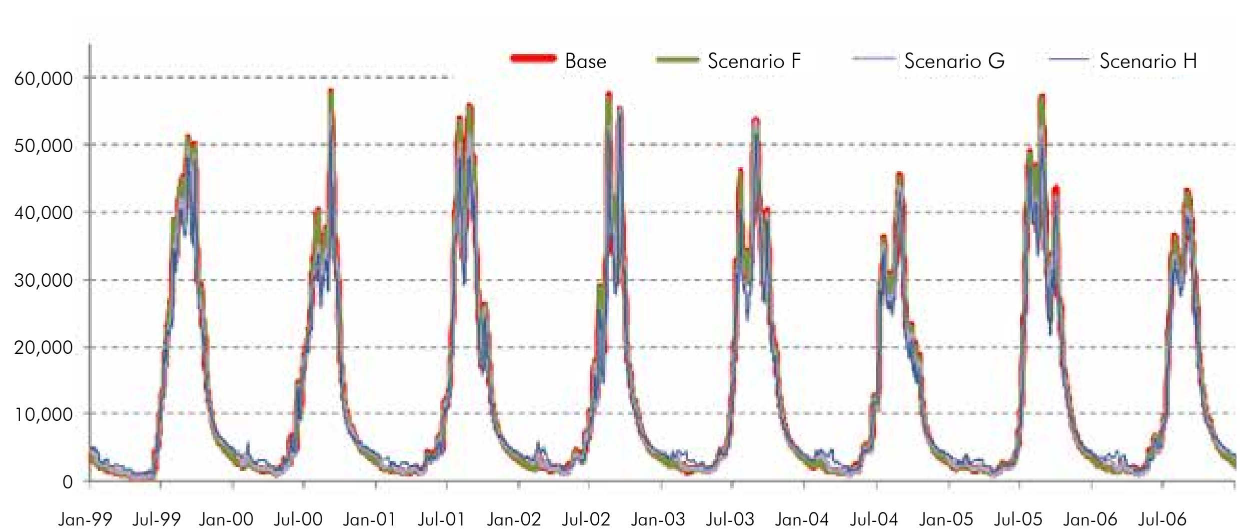
The broader, basinwide question is unequivocally answered by our analysis. Can Himalayan dams control floods in the main-stem Ganges as far downstream as Bangladesh? No.

The models were run to simulate changes in flow measured on the Ganges main-stem at Hardinge Bridge in Bangladesh (near the India-Bangladesh border). The simulation hydrographs under the base-case scenario and a few scenarios with all 23 major Nepal dams (including the three megadams) show that the flood peaks are virtually indistinguishable **(Figure 43).** There is no change in the flood peaks because the system storage is insufficient to make any notable difference in the monsoon flows in the main river channel near the India-Bangladesh border.

Similarly, the models produced flood maps for the Ganges delta in Bangladesh corresponding to two infrastructure options: (1) the base case and (2) with all potential dams built. The maps (**Figure 44**) show that there is no perceptible difference on the area flooded in the Ganges-dependent parts of Bangladesh even when the full suite of dams is built in Nepal.

The storage capacity of Himalayan dams is so small compared with the full flow of the river that once the modified flows of a dammed tributary reach the main-stem, the river's 'memory' of that storage is lost. The flow in any given tributary is only a fraction of the peak monsoon flow in the main-stem of the Ganges. Even if several tributaries are dammed, the effect is insignificant because there is so much water in the main-stem. This is particularly true in the years with highest flows.

Figure 43
Flood Peaks at the India-Bangladesh Border under Different Infrastructure Options



Source: IWM (2010).
Note: The different scenarios relate to which dams were considered operational as follows: Scenario E = Kosi Dam, Scenario F = Pancheswar Dam on the Sarda, Scenario G = Mega Dams (Kosi, Pancheswar, and Chisapani), Scenario H = All planned major dams in Nepal

Question 3.
Can Upstream Water Storage Augment Low Flows Downstream?

Perception: Yes

In addition to holding back floods, these reservoirs are expected to release water stored during the wet season for use in the dry season. This release would augment low flows for ecosystems, agriculture, and other uses across the basin, especially in the dry months preceding the monsoon.

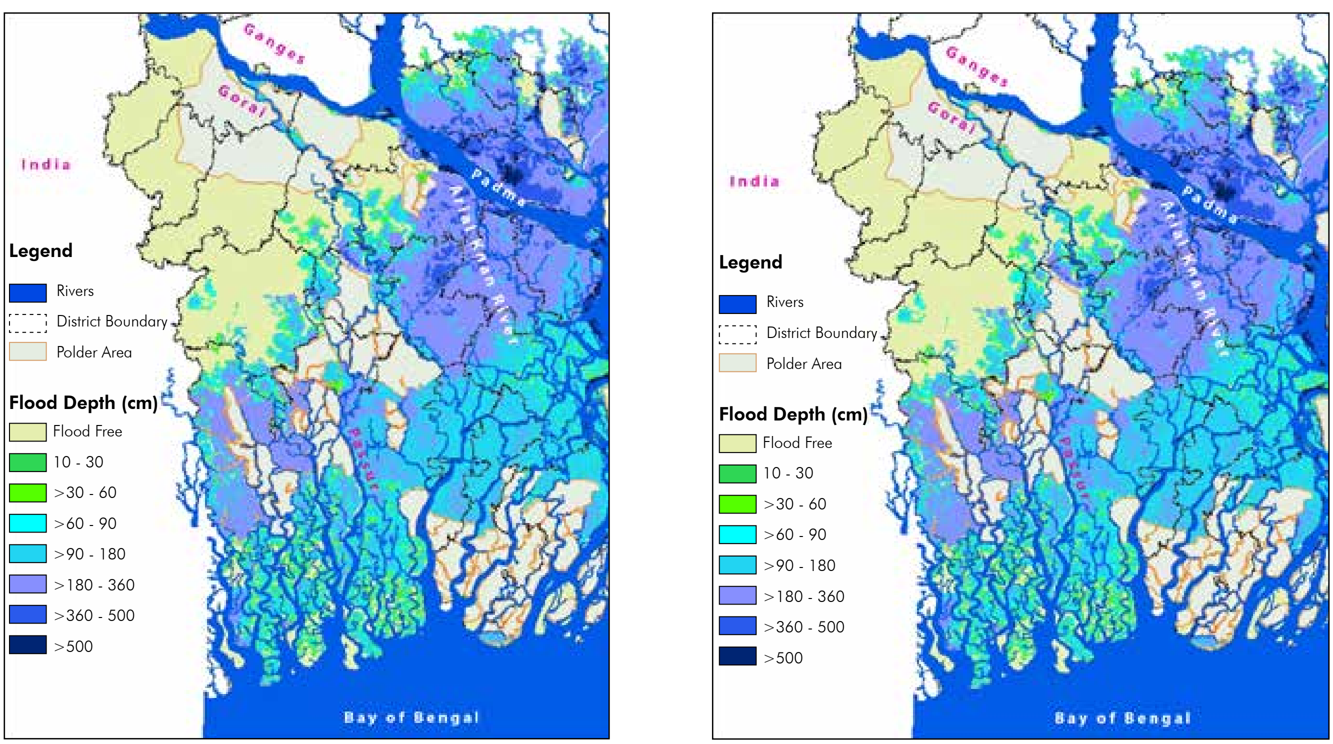
Findings: Yes, But...

In physical terms, the modeling results confirm this expectation. Low-flow augmentation could indeed be significant if all the large dams under consideration were built, approximately doubling low flows in the driest months. Shifting even a minor portion of the flood flows to the dry season could significantly increase low flows especially in a very dry years. Low-flow augmentation may be large relative to current low flow, but it is negligible compared with peak flow, so the integrity of the hydrological system as it currently stands is unlikely to be threatened by infrastructure development.

However, the economic value of this additional low-flow augmentation is unclear because of soil waterlogging and low agricultural productivity in India and Bangladesh. Water is not currently the crucial constraint to agricultural productivity in the specific parts of the Ganges Basin that could receive

Figure 44
Flood-Impacted Areas in the Ganges Delta under Different Infrastructure Options

Negligible impact on the main-stem Ganges



Base Case | **All Potential Dams Built**

Simulated Extent of Flood Area for 2004 Peak Flows in Bangladesh Coastal Region

Source: IWM (2010).

additional flows. Even if these dams were built (at high costs and likely over decades), increased productivity would require agricultural modernization that would be beneficial regardless of upstream dam construction.

The effects of increased low flows may make important contributions to enhancing ecosystem and navigation services in the Sundarbans, an important issue that requires additional research.

Nepal's rivers contribute about 70 percent of low flows to the Ganges. Most of these low flows are sustained by groundwater base flow and snow or glacier melt, since current storage in the system is limited. Furthermore, much of this low flow is currently used in India. Barrages in Uttar Pradesh and Bihar divert water from the Himalayan tributaries that provide most of the system's low flows for use in large irrigation systems. Increased storage capacity upstream would allow for delayed releases of modest amounts of monsoon water that ordinarily flow through the system with the flood. Even a minor portion of the massive flood peaks can make a sizeable difference in increasing the minimal low flows in the Ganges today.

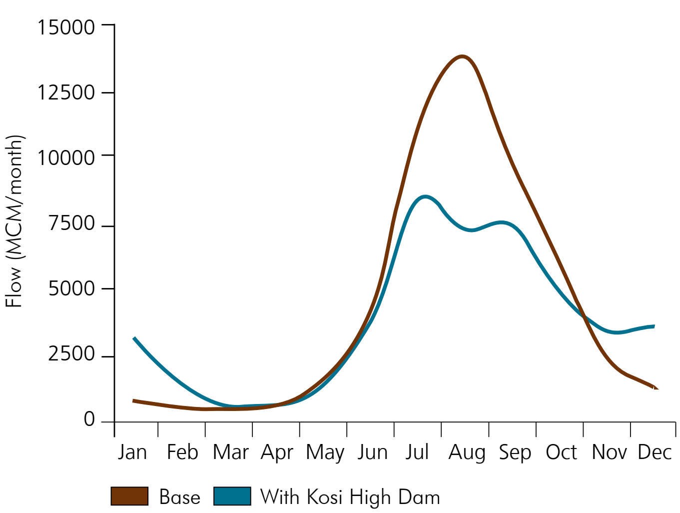
Figure 39 shows the transfer of water from the wet to the dry season in the Kosi tributary system that would be possible under different development scenarios. The 'with dams' options (blue and purple lines) are much smoother than the base-case option (red line), meaning the dams would lessen flood peaks and raise low flows. In particular, note that in the dry months of November through March the scenarios with upstream regulation have significantly higher flows than the base case **(Figure 45)**.

In the main-stem Ganges River, the scenario with all Nepal dams built shows that low flows in most of the dry months could be doubled, even allowing for some additional water withdrawals upstream **(Figure 46)**. However, the distribution and use of these additional low flows (which could reach about 54 billion cubic meters per year) would depend on the outcome of negotiations among the riparian countries.

The three mega-dams together would add about 33 billion cubic meters per year to dry season flow, and the smaller Himalayan projects together would add about 22 billion cubic meters. The Kosi High Dam by itself would provide only a marginal amount of low-flow augmentation. The volume of potential low-flow augmentation varies only slightly with annual hydrological variability.

Figure 45

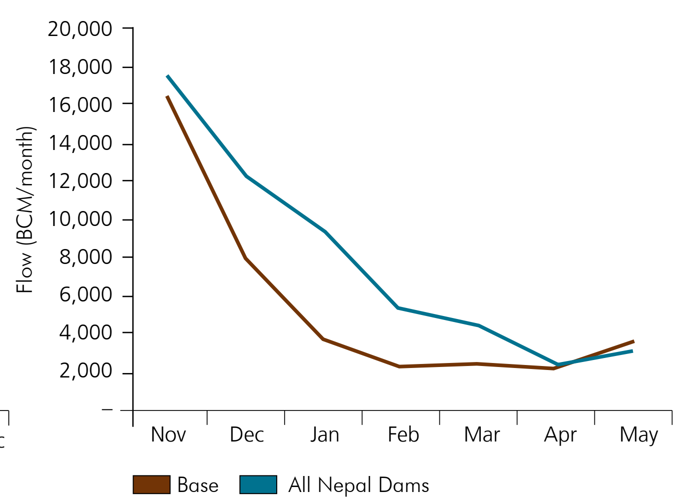
Low Flows on the Kosi River under Different Infrastructure Options, 1998–2007



Source: MIKE BASIN Model, IWM (2010).

Figure 46

Low Flows on the Ganges at Hardinge Bridge



Source: IWM (2010).

The economic model suggests that the optimal allocation of this low-flow augmentation is sensitive to assumptions about the value of water. If the economic productivity of water in India and Nepal is high relative to its value in Bangladesh, upstream irrigation schemes (potential new ones in Nepal, and existing ones in India) could use these additional flows **(Table 8)**. Thus, if new Nepalese irrigation schemes were developed alongside the dam projects, the economic model would allocate them up to 32 percent of the additional water in the dry season, while Indian irrigation schemes would be allocated the balance.[54] If the value of water downstream were higher for irrigation or ecosystem uses, then the economic optimization model would allocate a larger share of water to flow downstream. In reality, the distribution and use of these additional low flows would likely depend on the outcome of negotiations among the riparian countries.

It is essential to interpret these low-flow augmentation results carefully because there are alternative strategies for obtaining many of the non-power co-benefits of these dams, and the best uses and values of enhanced low flows are uncertain. Although these models do indicate that upstream storage can substantially increase low flows, it is not clear how valuable this would be in economic terms or how best to allocate the water. The water could be used for a variety of purposes: to increase surface water irrigation in Nepal and/or India, to increase diversions to Kolkata through the Hooghly River, or to increase low flows into the delta and the Gorai region. The best option is not obvious given that evidence suggests the productivity of irrigation water in the Ganges plains is low,[55] and given the uncertain impacts or benefits of low-flow augmentation in the Ganges delta (e.g. for salinity intrusion management). All of these options need to be investigated further.[56]

One important issue associated with low flows is the health of the Gorai distributary system in southwest Bangladesh. The Gorai, home to tens of millions of people and a fragile mangrove ecosystem, is believed to have once been the main outlet of the Ganges. But the Ganges has meandered eastward and now bypasses the Gorai and joins the Brahmaputra to form the primary Ganges-Brahmaputra-Meghna outlet east of the Gorai. Over time, sediment from the Ganges' enormous sediment load was deposited in the main river creating a sand bar at the mouth of the Gorai. Today, a flow of 925 cubic meters is needed at Hardinge Bridge to overtop this sand bar that otherwise cuts off the supply of Ganges main-stem water to the Gorai River distributaries. If all the Nepal dams are built, the number of days when flows are less than the critical 925 cubic meters could in theory be halved (if dry-season abstractions did not increase upstream), substantially enhancing flow into the Gorai

Table 8

Low Flow Augmentation in Irrigation, as Allocated by the Economic Optimization Model

Low Flow Augmentation in Irrigation	3 Mega-dams in Nepal	+20 Smaller Dams in Nepal	All Major Storages in Nepal
Volume of additional water for upstream irrigation (BCM/year)	28 (23-28)	33 (28-33)	38 (32-38)
Volume of additional water flowing to Bangladesh (BCM/year)	5 (2-5)	9 (5-9)	16 (12-16)

Source: This table is derived from the Ganges SBA economic optimization model and assumes the marginal value of low-flow augmentation in all three countries is US$0.05 per cubic meter. For sensitivity analyses on these values, see Table 11.
Note: The first number indicates the average year, with numbers in the bracket indicating the range.

[54] The distribution of this water is sensitive to assumptions about the net economic benefits from irrigated agriculture in India and Nepal, and from low-flow augmentation in Bangladesh.
[55] Sharma 2008.
[56] Chowdhury 2005, Molden et al., 2001, and Rogers et al., 1998.

during the dry season. But even with the development of these large dams, significant sustained dredging efforts, requiring both capital investments and institutional strengthening, would likely be needed. In contrast, modest river-training works combined with a program of regular dredging at the mouth of the Gorai, could potentially sustain the Gorai even in the absence of upstream dam development.

Surprisingly, augmented low flows could actually reduce the productivity of some land. Many parts of India's eastern Uttar Pradesh and Bihar have high groundwater levels even in the pre-monsoon (lowest flow) season, which has led to significant waterlogging of the soil. In Uttar Pradesh alone, about 5 million hectares are waterlogged and a million hectares are saline (sodic) because of secondary salinization due to high water tables and blocked drainage. Many of these areas recover slowly during the dry season as they drain and soil moisture evaporates.

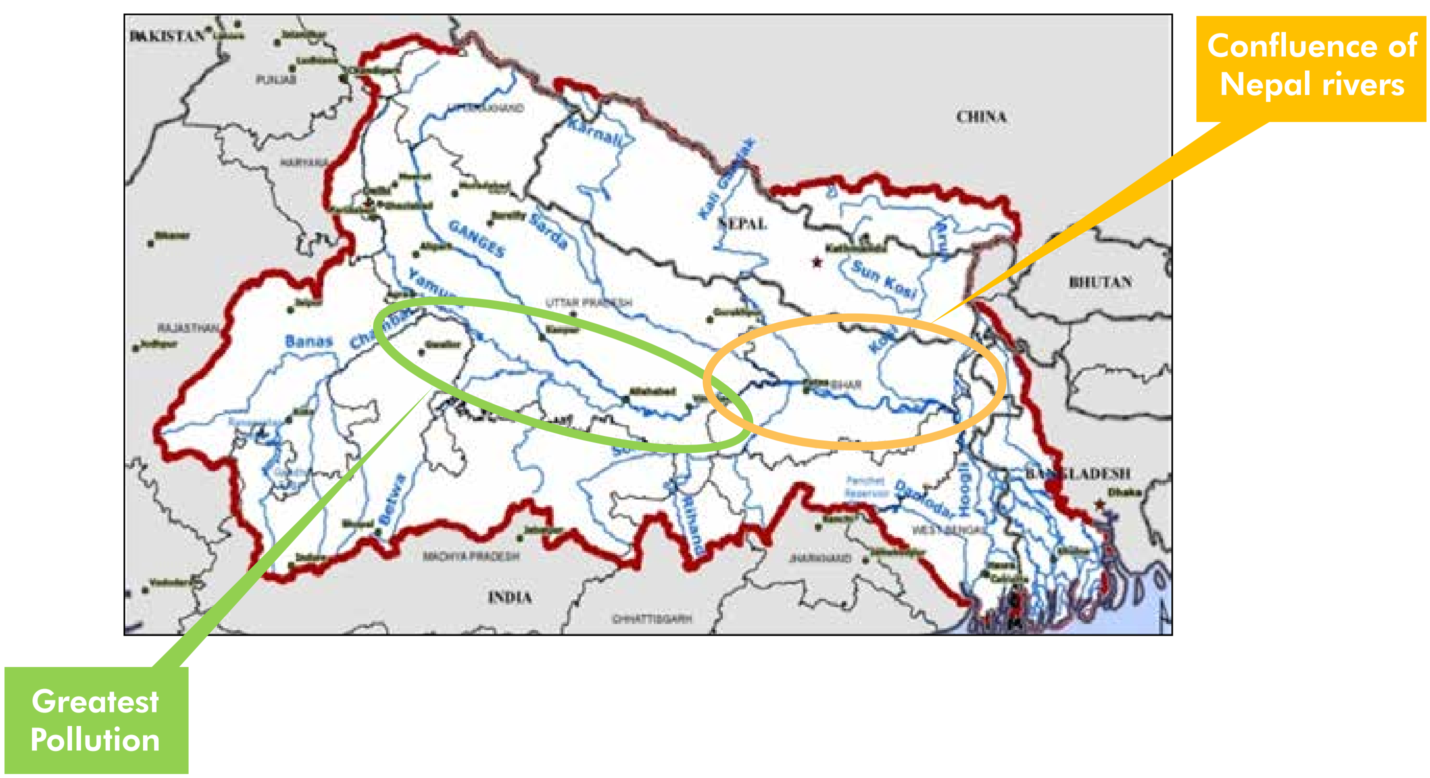
Augmenting low flows in some areas may actually cause harm by increasing marginal waterlogged areas and reducing productivity.

The net economic benefits of augmenting low flows in a systemwide context are unclear.

Could augmented low flows from upstream storage help manage water quality in India? Not really.

In recent years, rapid urbanization and industrialization have produced more sewage and industrial pollutants, which flow directly into the Ganges. The Ganges Basin is highly polluted, especially in the Yamuna near Delhi, in the Kannauj- to-Varanasi stretch in eastern Uttar Pradesh, and also in the Ramganga-Kali tributaries in western Uttar Pradesh. Would upstream storage in Nepal help improve the water quality downstream by increasing flows to dilute pollutants in the dry season?

Figure 47
Ganges Water Quality in Critical Stretches



Unfortunately, it does not appear promising. The Himalayan rivers join the Ganges downstream of Varanasi and therefore would not provide dilution benefits to the critical stretches, which are all upstream **(Figure 47)**. There might be water-quality benefits along the Ganges in Bihar, assuming low flows were passed through the system and not abstracted for irrigation, but they would be very modest relative the water quality challenge in this stretch of the Ganges. It is also possible that water-quality benefits could be derived from judicious operation of existing Indian reservoirs, particularly the Tehri Dam.

Salinity could be affected by upstream storage dams. However, salinity levels in Bangladesh do not appear very sensitive to the different dam options. There may be more complex and far reaching implications of salinity changes near the Bangladesh coast if the relative flows of the Ganges distributaries and the Padma/Jamuna/Meghna River change. In the extreme, changes in these distributaries could potentially affect the direction of freshwater currents in the Bay of Bengal that serve as a buffer against salinity increases in the Ganges-dependent coastal area. There is a clear need to better understand how changes in water quality in the Gorai (southwest Bangladesh) might affect ecosystems and communities in this fragile delta region.

Question 4.
Are there Good Alternatives or Complements to Reservoir Storage?

Perception: No

Many believe that large human-created storage (dams) is the only option of adequate scale to meet the basin's needs, given the region's growing populations and economies. Although underground aquifers, lakes, glaciers, snow, ice, and even soils are all forms of natural water storage, it is widely believed that these storages are relatively small, that the basin's groundwater is being drastically overexploited, and that its glaciers are melting rapidly.

Findings: Yes, underground

Vast, aquifers in the central and lower reaches of the Ganges Basin hold water in natural storage and can be sustainably used. Increased strategic and sustainable use of this groundwater, within an appropriate policy and energy-pricing environment, and in conjunction with a well-managed surface water system, could provide water-supply benefits on a scale comparable to the full suite of dams considered in this report, and it could possibly do so more immediately, at national, state, or local levels, and at lower financial, social, and environmental cost. Moreover a conjunctive-use strategy could be designed that would also help manage waterlogging in the basin, and enhance the reliability of water supplies to tail-end users in surface irrigation schemes and/or irrigators in the eastern reaches of the Ganges plain.

This study has shown that surface water can be augmented during low-flow seasons if large-scale multipurpose water infrastructure is developed, and that irrigation is one possible use of the enhanced low flows. Additional irrigation water could be used to extend the area covered by the winter (rabi) crops and improve the summer (kharif) crop by enabling moderately improved flood management in the tributaries on which dams were built.

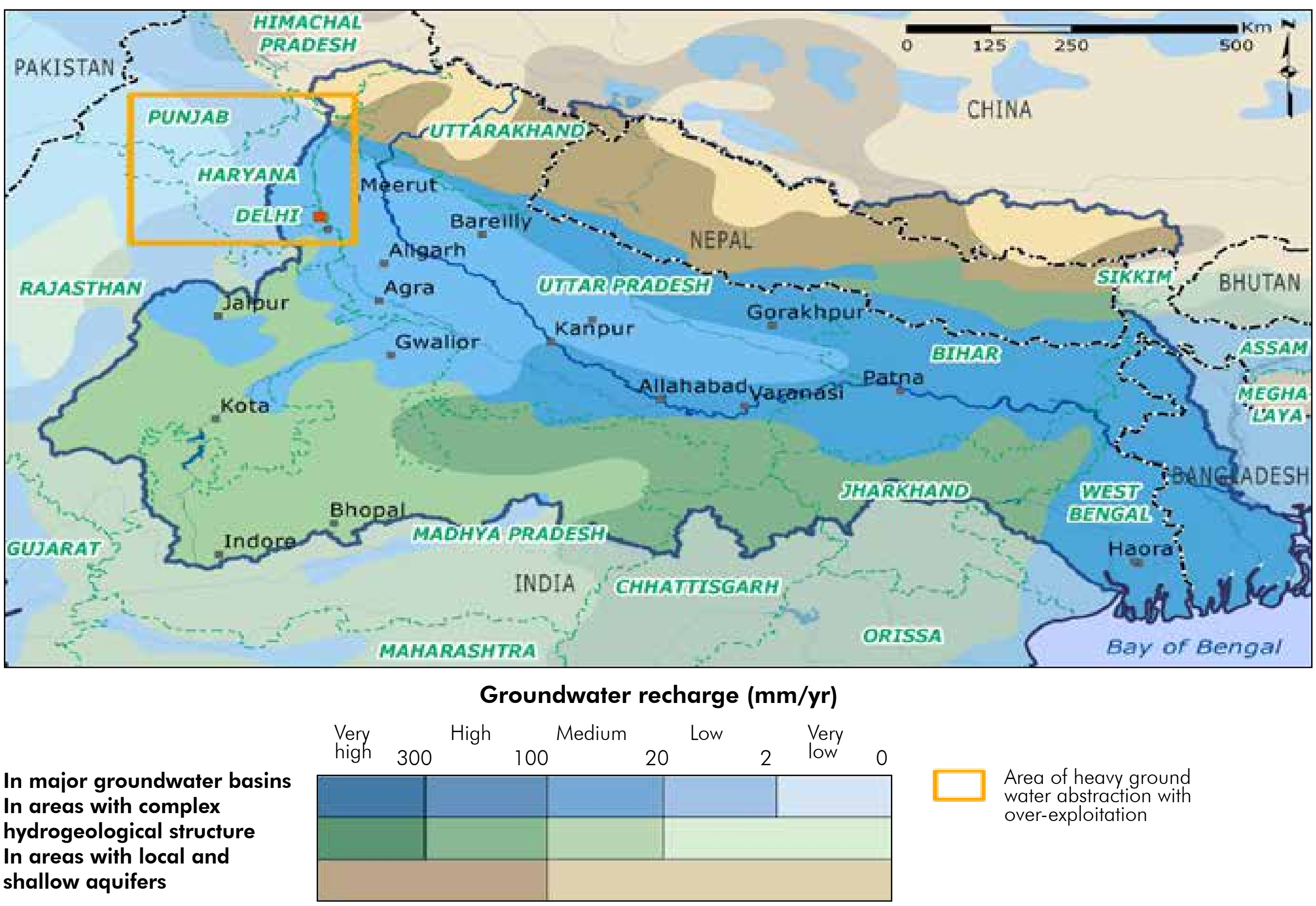
The time and costs (financial, social, and environmental) involved in building 23 large dams, however, would be high, and similar agricultural gains and/or low-flow enhancements could be achieved by other means.

Most agricultural yields in the Ganges Basin are just a fraction of Asian and global benchmarks, and even of other areas in India. Increasing agricultural productivity is a continual challenge. **Investments to enhance productivity could yield dramatic gains even in the absence of additional water from upstream storage**. Enhancing the productivity of existing agriculture would be much more efficient than expanding the irrigated area because it would not necessarily require additional land or water resources. Investments in market infrastructure, cropping patterns, seeds, fertilizers and agrometeorological information could probably raise farmer productivity at less cost. Such investments would then enhance the economic value of any additional water, and hence the economic benefits of upstream storage if it were built.

The real strategic story, however, lies further below the surface – the Ganges Basin has one of the world's greatest aquifer storages. The basin was formed by alluvial deposits from the Himalaya, resulting in an aquifer that is several kilometers deep in some areas. It is a complex, multilayered system interspersed with clay layers and perched aquifers and possibly an extensive deep aquifer as well, though this has not yet been explored **(Figure 48)**. Although groundwater overexploitation is a challenge across much of India, groundwater development in the Ganges Basin is estimated at just 33.5 percent (as compared with development in the Indus of 77.7 percent).[57]

The storage available in the shallow alluvial aquifers of eastern Uttar Pradesh and Bihar is approximately 30– 50 billion cubic meters, comparable to the low-flow augmentation (approximately 40–60 billion cubic meters, see **Table 11) that could be achieved with construction of 23 large and mega dams in the Himalaya**. Moreover, the water from upstream dams would suffer evaporative and leakage losses

Figure 48
Ganges Basin Groundwater Potential



Source: Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and UNESCO. http://www.whymap.org/whymap/EN/Products/products_node_en.html as it traveled downstream, and the timing of water availability could not be targeted as precisely as the pumping of groundwater directly by a farmer onto his or her own fields.

The untapped potential of groundwater storage was recognized most notably in a 1975 Science article, 'The Ganges Water Machine.'[57] The authors envisaged a massive program of targeted groundwater pumping in the dry season to irrigate winter crops. In the wet season the groundwater would naturally recharge from the monsoon rains and the extensive 'leaky' surface-water canal systems, with additional artificial recharge (pumping) of wet season flows into the aquifer. If this proposal proved practical, an enormous amount of water storage could be utilized.

This seasonal use of the groundwater aquifer for water storage deserves careful economic comparison with Himalaya storage options. Groundwater storage and pumping could prove to be a low-cost means of providing additional irrigation water during the dry season and preventing waterlogging. Large dams in the Himalaya could provide supplemental irrigation water during the dry season, but they would not reduce waterlogging (and might exacerbate it); would take longer to plan and build; and would entail social and environmental disruptions and hazards. The main economic benefit of large dams in the Himalaya would be hydropower generation, not irrigation. Groundwater storage and pumping would consume large amounts of electricity, so there could in fact be important complementarities between groundwater and Himalayan hydropower.

Our findings suggest that the basic construct of the Ganges Water Machine – although not necessarily at the full scale envisaged in the paper – is sound. **Ambitious, well-managed conjunctive use programs in targeted parts of the Ganges Basin could deliver substantial water storage, additional dry-season water, and a response to the extensive waterlogging and sodicity problems of the basin**. Conjunctive use is being undertaken today, but not in a planned manner. In response to erratic supplies of surface water, many farmers have already started exploiting the plentiful good-quality groundwater to irrigate crops and/or to provide supplementary irrigation conjunctively with surface water. Surface water supplies are especially unreliable at the tail ends of large, over-designed irrigation systems. These systems were intended to spread the available water out over large areas rather than meet demands reliably. For example, in the Sarda-Sahayak canal system in eastern Uttar Pradesh, the designed performance covers 64 percent irrigation intensity in kharif season (wet/summer) and only 36 percent in rabi season (dry/winter).

A well-managed scheme of conjunctive surface and groundwater use could be designed to diminish waterlogging and better manage the water table. Waterlogging is most common at the head of large surface irrigation schemes. The leakage from these schemes, combined with rainfall and the inability of the water to drain back into canals, has caused extensive waterlogging often up to a kilometer away from major irrigation canals (**Figure 49**). If farmers at the

Figure 49
Waterlogging Along the Sarda-Sahayak Canal System in India

Source: Nagaraja Harshadeep Rao (2010).

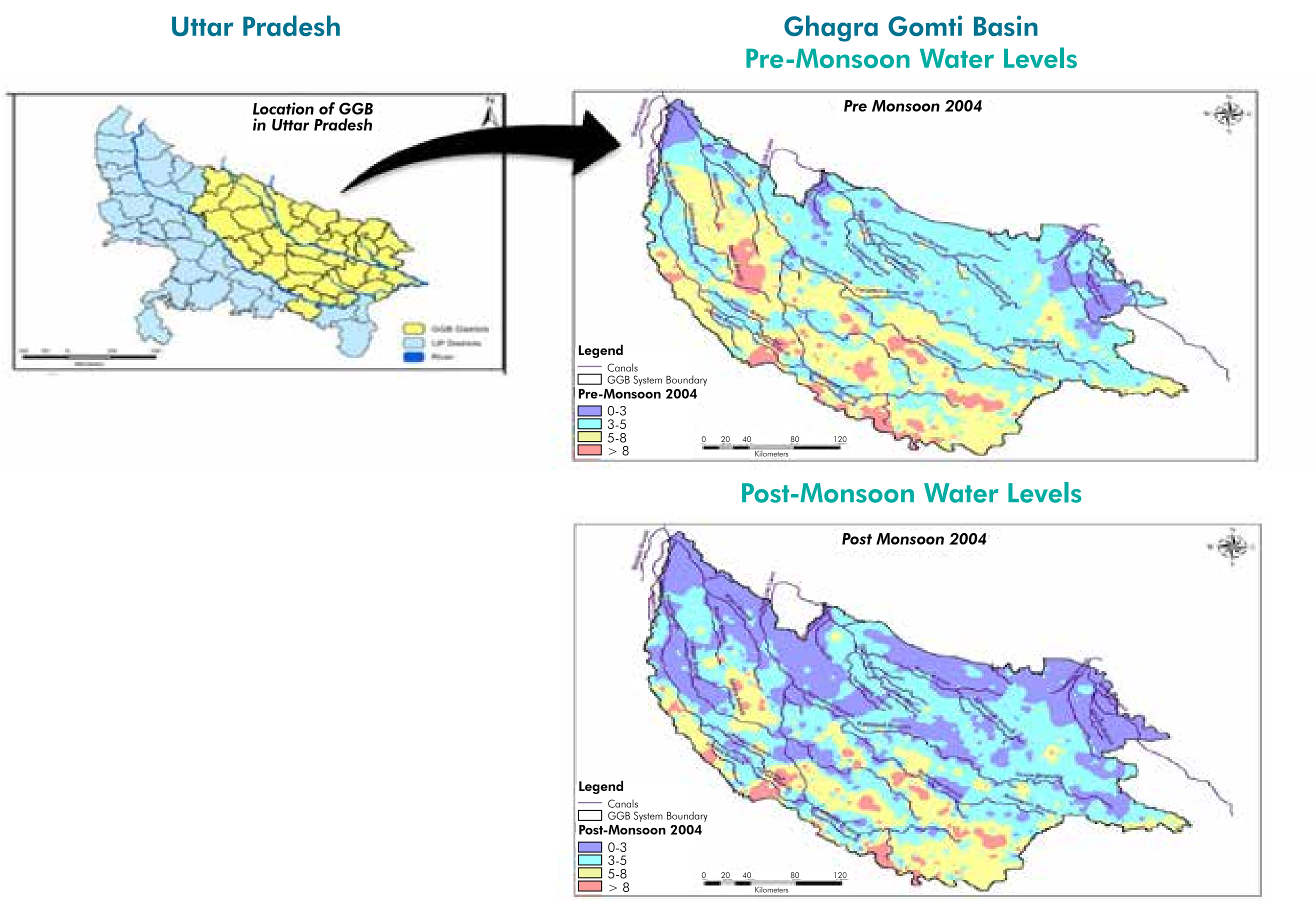
[57] Revelle and Lakshminarayan 1975.

head of these canals irrigated their winter crops with pumped groundwater, waterlogging could be better controlled and the productivity of their land could be enhanced. The surface water they would otherwise have used could then be sent down to tail-end users or left in the river for downstream/eastern farmers, or for other uses such as municipal supplies or ecosystem and navigational services.

The policy environment needed to convince these farmers to use groundwater rather than surface water in the dry season would admittedly be challenging, but tools are available. For example, the rosters dictating water delivery from surface canals could be adjusted to encourage groundwater use where groundwater levels were high and/or land is becoming waterlogged. Groundwater use could be discouraged where water tables are falling. Energy pricing policies could be used to incentivize changes in groundwater usage. Sophisticated groundwater mapping and monitoring would be needed.

An immediate opportunity to implement this approach exists in Uttar Pradesh. Figure 50 shows high groundwater levels throughout the dry season in the Ghaghra-Gomti Basin, a subbasin of the Ganges in the eastern part of Uttar Pradesh, which has significant potential for enhanced groundwater

Figure 50
High Groundwater Tables in Ghaghra-Gomti Basin in Uttar Pradesh, India



Legend

Canals | GGB System Boundary | 0 - 3 m deep | 3 - 5 m deep | 5 - 8 m deep | > 8 m deep

Source: SMEC (2009).

irrigation. If supported by a well-designed conjunctive-use program, additional groundwater use could significantly enhance land, water, and agricultural productivity. A detailed study[58] suggests that **in this subbasin, 2.5 million tubewells (in addition to the 1.75 million now in place) could sustainably pump more than 20 billion cubic meters of additional groundwater, a scale of lean-season water supply augmentation roughly comparable to that provided by the full suite of large dams currently under consideration in the Ganges Himalaya**.[59]

These findings do not suggest that upstream dams are necessarily a poor investment, nor do they suggest that downstream benefits should be ignored. This section explores just a subset of the benefits those structures could potentially provide. **If upstream multipurpose dams are found to be economically, socially, and environmentally justified by the bundle of benefits they can produce (predominantly hydropower, as will be discussed later), then additional dry-season water could be an important co-benefit**. Although upstream storage is probably not the best option for delivering increased dry-season irrigation water, it could be an attractive complementary investment to more immediate interventions in conjunctive use. For example, immediate investments to improve the conjunctive use of groundwater and surface water could enhance agricultural productivity, which, in turn, would raise the value of any additional low-season agricultural water that might eventually be delivered by upstream dams. Alternatively, if the productivity of agriculture were strengthened to the extent that demand for irrigation water was diminished, enhanced low flows could be readily allocated to a range of other important in-stream uses including ecosystems and navigational services.[60]

Question 5.
Is there Substantial Untapped Hydropower Potential in the Ganges Basin?

Perception: Yes

The Himalaya have enormous hydropower potential. This power is seen as a source of domestic energy supplies as well as a source of export revenues for Nepal where potential supplies far outstrip potential demand. It is also seen as an important source of clean energy in a region that is experiencing high growth.

Finding: Yes

In Nepal alone, it is estimated that more than 40,000 megawatts of economically feasible potential hydropower exists in the Himalayan headwaters of the Ganges. Less than 2 percent has been developed. The suite of dams examined in this report, the largest 23 in Nepal, would have an installed capacity of about 25,000 megawatts, producing an estimated 65-70 terrawatt hours of power annually (and saving up to 52,000–56,000 tonnes of carbon equivalent per year.) The net value of this potential hydropower is estimated at some $5 billion annually, quite significant relative to Nepal's 2011 gross domestic product (GDP) of $18.9 billion (current US $).[61]

To answer this question, a number of modeling runs (with both the water simulation and economic optimization models) were carried out to represent the current baseline condition and scenarios with combinations of the three often-discussed mega-dams in Nepal (Pancheshwar Dam on the Mahakali/Sarda River; Chisapani Dam on Karnali/Ghagara River; and Kosi High Dam on the Kosi River), as well as for 20 smaller dams in Nepal. The results were not surprising.

Yes, there is substantial hydropower potential in Nepal. Just the three mega-dams with

[58] SMEC 2009.
[59] In comparison, the 23 dams under consideration could yield some 38 billion cubic meters of additional water for irrigation (Table 8). Evaporative losses and leakages, however, can be anticipated to approach 50 percent before the water would arrive on farms downstream. Add to this the inefficiency of farmers being unable to control surface water timing as effectively as they can control groundwater application, and the productivity gains of the two scenarios become roughly comparable.
[60] This is not to imply that ecosystems and navigational services should be subordinated to agricultural water uses. It is only to note that there should be little concern that investments focused on the productivity of irrigation water would lead to a situation in which the water that was saved would have no other use or value.
[61] World Bank 2009, World Development Indicators.

19,000 megawatts of installed capacity could produce 35–45 terawatt hours of electricity annually. The remaining 11 dams in the water systems model, representing 4,600 megawatts of installed capacity, could generate at least 18 terawatt hours annually. Including the 20 smaller dams in the economic model yields another 26–30 terawatt hours per year. Current hydropower production in the entire Ganges Basin is about 12 terawatt hours annually and the current installed hydropower capacity in Nepal is only about 644 megawatts.[62] The new dams considered in this study are all located in Nepal (Pancheshwar is on a border river with India), where domestic demand is much less than the magnitudes of potential production discussed here. Nepal's peak demand is projected to grow to 1,733 megawatts by 2019–2020.[63]

The Government of India has repeatedly stated its interest in importing Nepal's surplus, hydropower. This could slow the growth in greenhouse gas emissions in India and be beneficial for the India-Nepal trade balance. If this power were sold in India, where a conversion factor of 0.8 kilograms per kilowatt hour is used to reflect the power mix and calculate carbon savings, 65–70 terawatt hours of hydropower would save more than 52,000–56,000 tonnes per year of carbon equivalent. Additionally, power exports from Nepal to India could help correct Nepal's persistent balance-of-payments deficit with India. Today, Nepal imports power from India.

Although it would take many years to design and build large hydropower in Nepal, particularly if transboundary negotiations are required, it is clear that this is a region with rising energy demand in the medium term. India alone has a projected shortfall of about 100,000 megawatts by 2017.[64] A range of cross-border transmission projects are now being implemented and explored. India and Nepal have agreed to build a cross-border transmission line. Discussions are underway regarding a similar investment between India and Bangladesh.

Whereas most observers tend to focus on the installed capacity of a power plant (in megawatts) when discussing hydropower potential, which is important for high-value peak load potential, the actual power generation (e.g. in megawatt-hours) from the system is critical for assessing economic benefits.[65] Power generation reflects the hydrology of the river and the size of the reservoir. For example, as shown by the modeling analysis, the Kosi High Dam has an installed capacity of only 3,500 megawatts, but can produce more power than the Chisapani Dam with an installed capacity of more than 10,000 megawatts. Similarly, the 20 smaller dams have just over a quarter of the installed capacity of the three mega-dams, but they can generate more than half the power of the full suite of dams (**Figure 51**) indicates that seasonal variations in hydropower production from storage dams in the Ganges Basin would probably be considerable, given the limited storage available and the short monsoon season. This is even more so in the case for run-of-the-river projects that have no storage dams, unless they are regulated by a significant storage upstream that can provide a more consistent flow throughout the year. Thus, rather than delivering power consistent with full installed capacity (megawatts) of these dams throughout the year, actual power generated will be lower and marked by seasonal fluctuations (**Figure 52**).

In addition to intra-annual (seasonal) variability, it is important to recognize that these flows are highly variable from year to year. Hydropower production will therefore display strong inter-annual fluctuations since the system has no over-year storage.

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[62] Nepal Electricity Authority 2010.
[63] Nepal Electricity Authority 2011.
[64] Karki 2007.
[65] Installed capacity is the theoretical capacity of all of the turbines in a power plant if they were run at full design capacity year round. In a monsoonal climate like the Ganges in the absence of very large-scale storage, there will be many months each year without adequate river flows to run all turbines at their full capacity.

Our results indicate that there is indeed substantial potential for regionally significant hydropower generation in Nepal. Importantly, however, this report does not provide analysis of specific projects. The development of any specific project would require financial, environmental, social, and technical (i.e., engineering, seismic, sediment) analyses before a statement could be made about its feasibility. Constructing large dams in the difficult Himalayan terrain and building transmission lines from isolated and inaccessible areas could be very costly and could result in significant environmental and social impacts that would need to be mitigated. It should also be possible to significantly benefit isolated communities

Figure 51
Hydropower Potential in the Ganges Basin

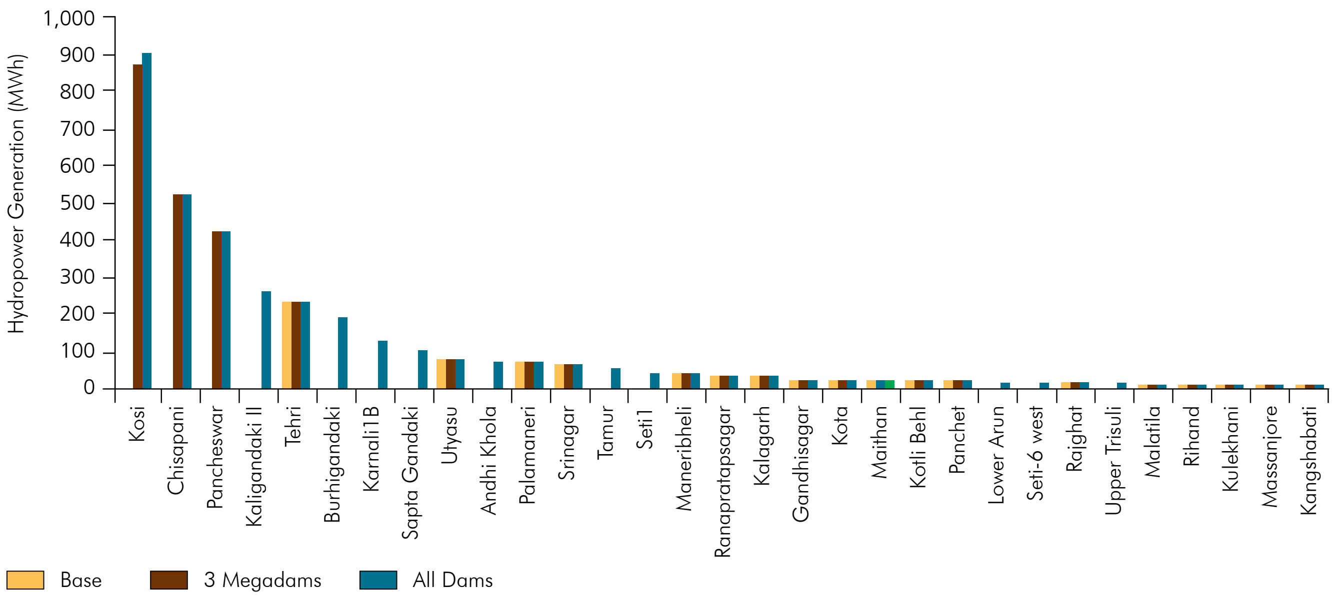
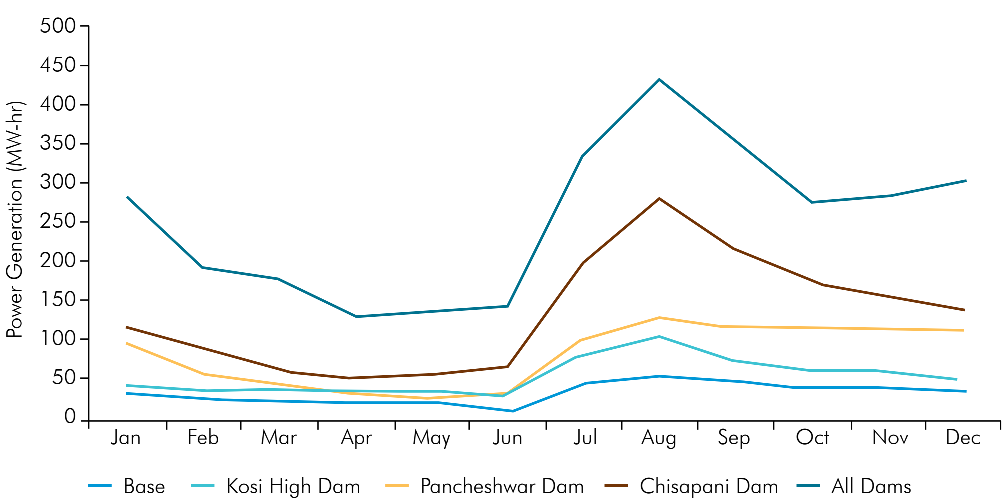


Figure 52
Monthly Generated Hydropower (Based on Model Results)



in project areas by enhancing connectivity of roads, telecommunications, and power.

Question 6. What is the Magnitude of Potential Economic Benefits from Multipurpose Water Infrastructure, and What are the Tradeoffs Among Different Water uses?

Perceptions: Big gains, big tradeoffs

There is a general sense that development of multipurpose infrastructure will bring significant economic benefits, but no common perception about the relative values of hydropower, flood control, and low-flow augmentation.

It is widely believed that the design and operation of multipurpose dams will significantly skew the distribution of benefits among different water uses (and hence users.) The tradeoffs are believed to be very large and, therefore, a matter of concern and contention.

Findings: Big gains, but modest tradeoffs

The gross economic benefits of additional hydropower from the 23 new dam projects considered in this report were estimated to range from US$3–8 billion per year (depending on the infrastructure scenario and assuming that 25 percent could be sold as peaking power in India to yield an average power value of $0.1 per kilowatt hour). Since these 23 projects are estimated to cost about US$2 billion per year, the total net value of hydropower would likely be about US$5 billion per year. Benefits from additional irrigation and ecosystems water are difficult to predict but in the range of US$1–2.5 billion.

For the most part, the economic tradeoffs among hydropower, irrigation, and flood control objectives are small. This is because there is little difference in the optimal water releases for power production versus those for downstream water supply (since the objective for both is to store peak flows to achieve steadier dry-season releases), and because flood control is limited, regardless of how operating rules are designed. There is a tradeoff in the quantity of water used for irrigation in the Ganges plains versus low-flow augmentation in delta.

The potential economic benefits from new hydropower generation associated with developing the full suite of hydropower investments described in this report was estimated to gross US$7–8 billion annually (roughly US$5 billion net) above the current hydropower benefits produced in the basin (about US$2.5 billion). This estimate assumes that 25 percent of the power will be sold at peaking tariffs in India. If the energy from these dams were not used for peaking purposes, anticipated benefits would be reduced by about 25 percent. Conversely, if the dams could be operated to supply greater than 25 percent peaking power, the benefits would be higher. **Table 9** presents the economic optimization model outcomes for various infrastructure options in an average year.

While flood damages in the Ganges Basin are significant, the report's findings suggest that the construction of upstream multipurpose water storage would not have a large effect on flooding events. Impacts on peak flows in the main-stem Ganges, particularly in wet years, would be relatively small. Thus, the economic value of flood savings associated with these infrastructure development options would be small **(Table 10).** On the tributaries, and particularly in the Gandak and Kosi Rivers, the reduction in peak flows would be larger. But these major tributaries, on which the large dams would be built, are extensively embanked. Along the Kosi, for example, embankments have never been overtopped by floods. Flooding events on embanked tributaries result more from embankment failures and localized heavy monsoon rainfall that cannot be quickly drained due to these embankments and the raised river beds they have created. The evidence in this

Table 9

Range of Economic Optimization Model Outcomes for Different Infrastructure Options

	Status Quo	3 Proposed Mega dams	20 Proposed Smaller Dams	All Dams (Existing & Proposed)
1. Hydropower production (amounts above status quo shown in parentheses)				
a. Production (TW-hr/yr)	25.3	70.8 (+45.5)	51.7 (+26.4)	101 (+75.7)
b. Value (billions of US$/yr)	2.5	7.1 (+4.6)	5.2 (+2.7)	10.1 (+7.6)
2. Low flows for irrigation (amounts above status quo shown in parentheses)				
a. Volume of water (BCM/yr)	83	111 (+28)	117 (+34)	121 (+38)
b. Incremental value above status quo (billions of US$/yr)	N/A	+1.4	+1.7	+2.0
3. Low-flows augmentation in the delta				
a. Volume of water (BCM/yr)	N/A	+4.8	+9.0	+15.4
b. Incremental value above status quo (billions of US$/yr)	N/A	+0.24	+0.45	+0.77
4. Change in monsoon season flows (%)				
a. Ganges at Farakka	-	-7	-8	-12
b. Kosi at Chatra	-	-7	-	-14
c. Ghagara downstream of the Rapti inflow	-	-11	-6	-17
d. Gandak at India/Nepal border	-	-1	-22	-20
5. Infrastructure costs				
a. Capital cost (billions of $US)	-	15.3	19.1	34.4
b. Annualized capital cost (billions of $US/yr)	-	0.8	1.0	1.9

Note: Assumes that the marginal value of additional water in irrigation and that the marginal value of additional low flows to ecosystems in the delta are both US$0.05 per cubic meter. Calculations assume a 5 percent discount rate and 50-year time horizon. The values of low flows for irrigation and ecosystem services in the delta in the status quo are unknown and are listed as 'N/A.'

report suggests that flood damages are unlikely to be significantly reduced through the development of new, large-scale upstream infrastructures. Cost-effective flood management will require a sharpened focus on forecasting and warning systems, and localized 'hard' (i.e., embankment management, safe havens) and 'soft' (i.e., disaster preparedness, insurance) responses.

With regard to water quality, as discussed earlier, the construction of large storage structures in the Nepal Himalaya is unlikely to deliver much in the way of water quality benefits in India. The most serious water quality problems in the Ganges are in western Uttar Pradesh along the Ganga and Yamuna before these tributaries merge. By the time the Nepalese tributaries join the main stem of the river, water quality problems are less pronounced, so low-flow augmentation of the tributaries does not solve the most dire upstream problems.

Agricultural and ecosystems values for augmented low flows are particularly difficult to determine, as discussed in the economic optimization modeling section. On the one hand, evidence suggests that the current marginal economic value of increased surface water for

Table 10

Percent Reductions in Peak Flow in the Ganges Main-Stem and Major Tributaries

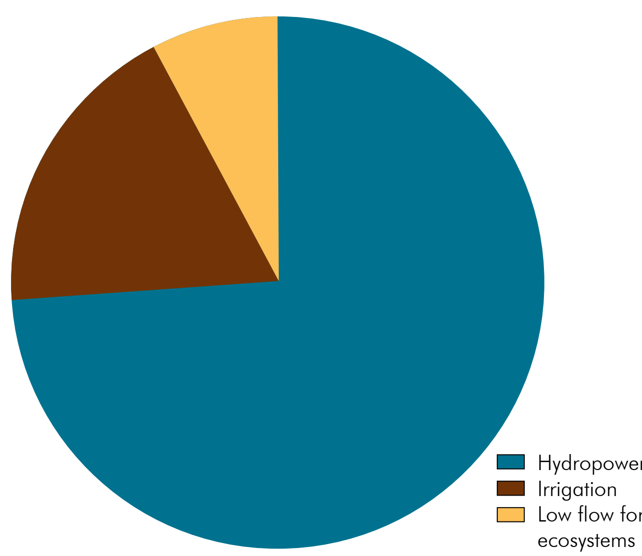
Hydrology	River	Infrastructure Scenario		
		+3 Mega dams	+ 20 Small Dams	+ All Dams
Dry year	Kosi	11	11	22
	Ghagara	18	6	22
	Gandak	1	27	27
	Ganges main stem	6	8	11
Average year	Kosi	7	7	14
	Ghagara	11	6	17
	Gandak	1	22	20
	Ganges main stem	7	8	12
Wet year	Kosi	6	6	9
	Ghagara	11	8	15
	Gandak	1	24	24
	Ganges main stem	4	6	9

irrigation is quite low in India and Nepal.[66] The irrigation water value used in the calculations presented in Table 9 (US$0.05) may overstate current economic returns in agriculture. On the other hand, in the future, agricultural modernization and increased returns to water could change this picture dramatically.

Similarly, it is difficult to place a value on dry-season water for ecosystems services, salinity control, and navigation. Although the essential value of water to communities in the delta is apparent, there has been no systematic measurement of that value. The current evidence is not sufficient to provide a robust estimate of the ecosystems value of water at the scale required for this report. Moreover, the value that society places on ecosystems tends to rise with incomes, and this is a rapidly developing economic region. Given the importance and sensitivity of assigning a value to water in any ecosystem, and in particular to an ecosystem as unique and fragile as the Sundarbans, this report concludes that those values remain to be substantiated. For simplicity, similar hypothetical values were placed on irrigation and ecosystems water. Using these crude estimates, the distribution of incremental economic benefits from development of all of the proposed large dams in the Nepal Himalaya would be roughly 74 percent from hydropower, 19 percent from irrigation and 8 percent from ecosystem services **(Figure 53)**.

Figure 53

Distribution of Economic Benefits from All Proposed Large Dams



[66] Chowdury 2005, Molden et al., 2001, Rogers et al., 1998, and Sharma et al., 2008.

Recognizing the uncertainty of these values, various scenarios were modeled to explore nine combinations of economic values for irrigation in Nepal and India (low-medium-high values) and low-flow augmentation (low-medium-high values) for ecosystems values in the delta **(Table 11)**. Not surprisingly, the resulting water allocations and economic benefits of these two competing objectives are sensitive to assumptions about the value of water for irrigation in India and for low-flow augmentation in Bangladesh.

Case 1 (upper left cell in **Table 11**) illustrates a scenario in which irrigation water has very low value (which the literature suggests is currently the case[67]) and no value is assigned to low-flow augmentation in the lower reaches of the Ganges system. In this case, the model calculates that it is economically optimal to allocate 38 billion cubic meters of the additional low flow to irrigation, with just 6 billion cubic meters to low-flow augmentation in the delta. **Total economic benefits under this scenario are $8.2 billion, 95 percent derived from hydropower**.

Case 3 (upper right cell in **Table 11**) assumes that the value of irrigation water remains small, but that significant value is attached to downstream flows in the delta–a value 10 times that associated with low-productivity agriculture. This could be a reasonable assumption, given the unique ecosystems and associated biodiversity and tourism values of the Ganges delta, the important salinity-control functions of downstream flows, and navigation values. Economic optimization in this scenario pushes 37 billion cubic meters of the additional water to downstream low-flow augmentation in the delta, with none allocated to irrigation. **Total economic benefits under this scenario are $11 billion, 67 percent from hydropower, 33 percent from low-flow augmentation**.

Case 7 (lower left cell in **Table 11**) assumes that the value of irrigation water is several times higher than it is today, and that no value is attached to low-flow augmentation. This would be the case if significant improvements were made in agricultural productivity while no values were recognized for enhanced low flows in the delta. Of the additional low-flow water in this scenario, 28 billion cubic meters are allocated to irrigation while 5 billion cubic meters are allocated to low-flow augmentation relative to the base case. **Total economic benefits under this scenario are $11.7 billion, 67 percent hydropower and 33 percent irrigation**.

Case 9 (lower right cell in **Table 11**) reflects a scenario in which irrigation values are high and low-flow augmentation values are high as well. In this case, the model calculates that it is economically optimal to allocate 38 billion cubic meters of the additional low-flow to irrigation, and 19 billion cubic meters to low-flow augmentation in the delta. **Total**

Table 11

Irrigation and Low-Flow Outcomes for Different Water Assumptions with Full Infrastructure Development

Value of Irrigation Water ($/m³)	Outcome	Value of Low-Flow Augmentation ($/m³) 0.00	0.05	0.10
0.01	Additional surface water irrigation (BCM/yr)	38	0	0
	Additional low flow to Delta (BCM/yr)	6	35	37
0.05	Additional surface water irrigation (BCM/yr)	38	38	25
	Additional low flow to Delta (BCM/yr)	5	16	25
0.10	Additional surface water irrigation (BCM/yr)	38	38	38
	Additional low flow to Delta (BCM/yr)	5	16	19

[67] Chowdhury 2005, Molden et al., 2001, Rogers et al., 1998.

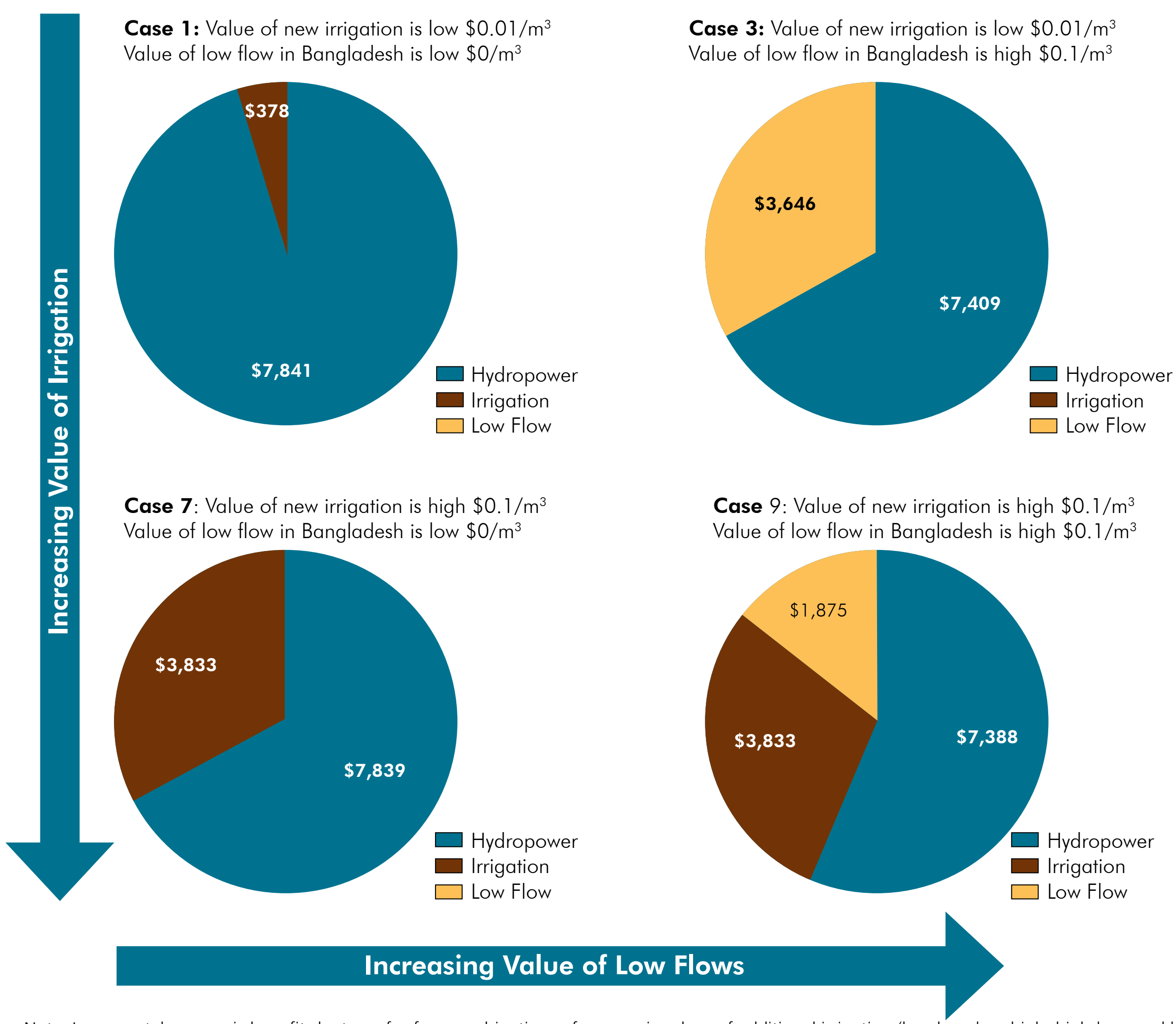
economic benefits under this scenario are $13 billion: 56 percent of economic benefits derive from hydropower, 29 percent from irrigation, and 14 percent from low-flow augmentation.

These scenarios paint a fairly broad picture of the possible economic futures of Ganges development. **Total economic benefits vary from $8 to 13 billion (gross)** depending on the productivity of agriculture and the value assigned to low flows. **The absolute value of hydropower remains fairly steady across all of these scenarios, varying only about 6 percent**.

To illustrate how results can change depending on the values assigned to additional irrigation water and enhanced low flows to the delta, the four cases described above are presented in **Figure 54**. It is clear that gains in agricultural productivity or greater substantiated values in ecosystems services could change the distribution of benefits from large upstream reservoirs. In all cases, however, it should be noted that:

Figure 54

Economic Benefits for Four Assumptions of Irrigation and Low-Flow Values



Note: Incremental economic benefits by type, for four combinations of economic values of additional irrigation (low-low, low-high, high-low, and high-high) in Nepal/India and low flows in Bangladesh.

- the majority of benefits will be generated from hydropower and the absolute levels of these benefits are not substantially diminished when the value of other uses increases, and
- greater agricultural productivity, and restoration of the Gorai, will only be achieved if complementary investments and reforms are undertaken, and those investments and reforms should be of significant value even in the absence of upstream reservoirs.

Sensitivity analyses undertaken in this study provide new information on the tradeoffs between operating water infrastructure with the goals of maximizing hydropower, irrigation, flood control, and/or downstream low-flow augmentation in the Ganges Basin.

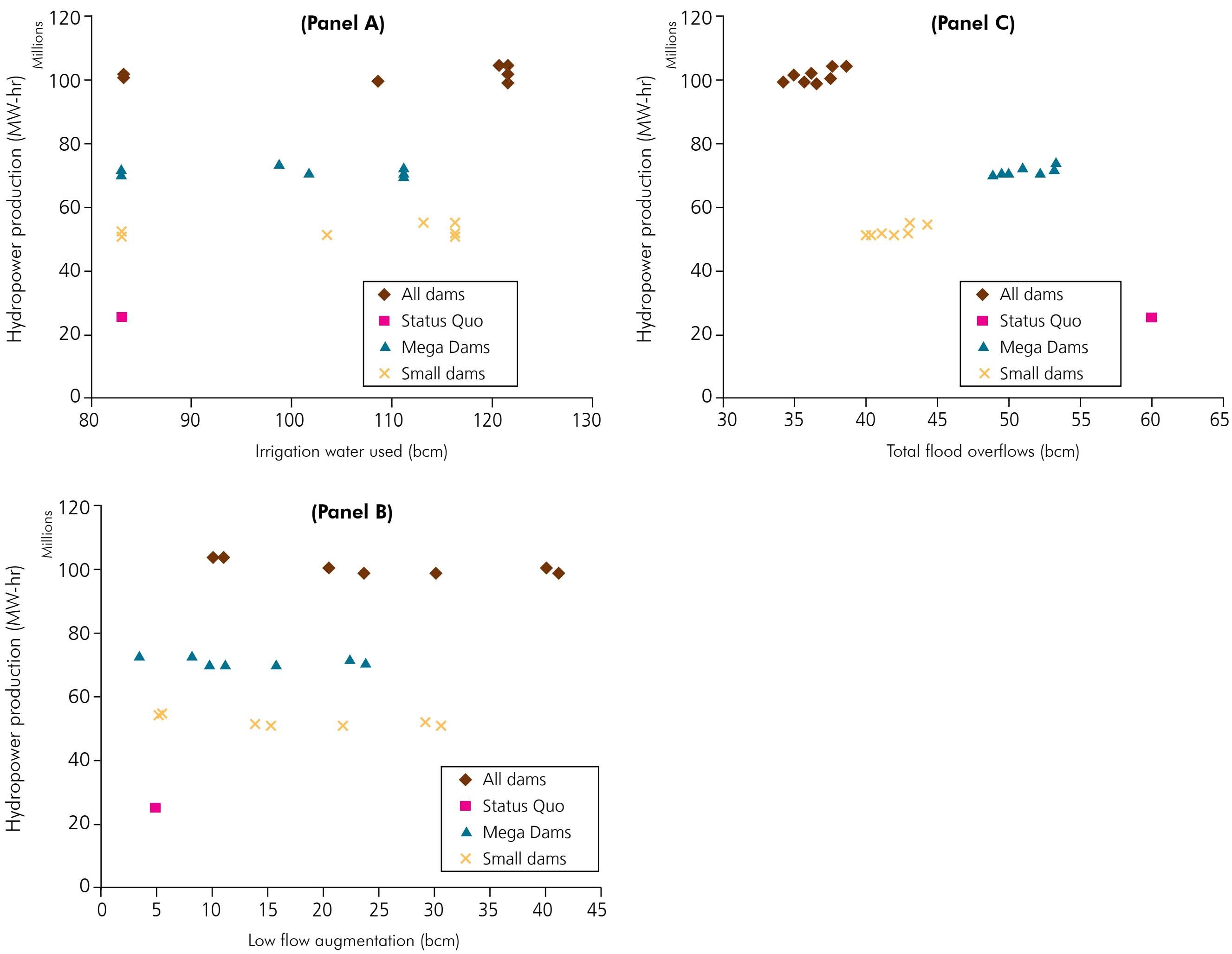
There appears to be little tradeoff between hydropower production, on the one hand, and downstream irrigation and/or low-flow augmentation, on the other, because hydropower producers and all of the downstream users want the monsoon flood peaks to be smoothed and dry season flows increased. As shown in **Figure 55** hydropower benefits decrease very little, by about 5 percent, even when the economic value of water downstream is assumed to be $0.1 per square meter (moving from **Case 1 to Case 9**.) This is because flood waters are stored behind hydropower dams during the flood season and released gradually over the course of the year to generate power, which enhances dry season flows and thus meets the objectives of both water uses. The fact that there is little tradeoff between hydropower production and downstream water uses means that increases in irrigation in the plains or low-flow augmentation in the delta do not come at the expense of significant amounts of hydropower in upstream Nepal. Hydropower production is relatively insensitive to changes in the economic value of water to downstream users.

Figure 55 also illustrates the tradeoffs between hydropower production, on the one hand, and downstream water uses, on the other. Nine combinations of downstream economic values are used across four infrastructure combinations. Panel A depicts tradeoffs between hydropower production and irrigation water. Varying the economic value of water used for irrigation changes the volume of water that the optimization model allocates to irrigation, resulting in shifts along the x-axis under each of the four infrastructure scenarios. Although irrigation water usage varies significantly in Panel A for each of the scenarios, it is notable that power production does not vary greatly (i.e., there is very little shift along the y-axis.) This means that enhanced irrigation water use does not significantly compromise power production: there is little tradeoff between these upstream–downstream uses. **Panel B** illustrates tradeoffs between hydropower and low-flow augmentation for ecosystem services and navigation, and Panel C presents tradeoffs between hydropower and flood control. All three panels exhibit similarly small tradeoffs between hydropower and downstream uses, across all four infrastructure scenarios.

There is, however, a tradeoff between the two downstream uses – irrigation water use in the plains and low-flow augmentation in the delta – because they are both consumptive uses. If the economic value of low flows in the delta is high, the economic optimization model allocates less water for irrigation, and vice versa. This is consistent with the results presented in **Table 11**. Even so, **Figure 56** shows that increasing infrastructure development can allow both surface water irrigation and low-flow augmentation in the delta to increase relative to the status quo. With full development, 40–60 billion cubic meters per year of additional dry-season water would become available that could be shared between these two competing uses. In reality, of course, actual use will be determined not only by the relative economic values of water to different users, but also by political, cultural, and social considerations.

Finally, the economic optimization model was run to test the sensitivity of the results to

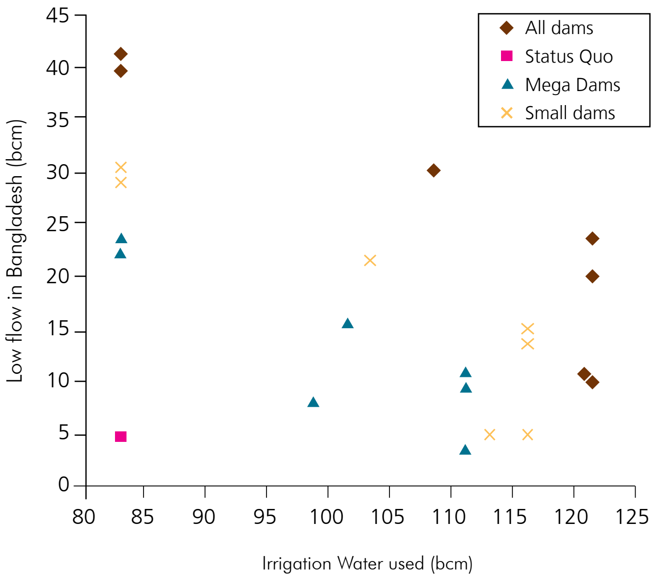
Figure 55
Tradeoffs between Water Uses



Note: Tradeoffs between hydropower production and irrigation water usage (Panel A), low flow augmentation in the Delta (Panel B), and overbank flows during the flood season (Panel C)

low- and high-flow years. When the Ganges optimization model was run with the hydrology for wet and dry years, it was found that the incremental value of hydropower produced by new infrastructure would decrease with flows in the basin as expected. This model run provides some sense of how climate change may affect the variability of the annual results. A 'typical' dry year in the Ganges Basin corresponds to a reduction in additional hydropower of about 16 percent for the three mega-dams, and a reduction of 11 percent for full infrastructure development. The reduction is lower if all dams are assumed to be built because the dry years for individual tributaries do not coincide, so building infrastructure in different rivers reduces the variability in (or spreads the risk to) hydropower production that results from extremes in the most affected tributaries. Conversely, the incremental value of dams to irrigation and low flows

Figure 56
Tradeoff between Irrigation Water Use and Low-Flow Augmentation



in the delta increases somewhat (by about 2 percent) in a dry year because the water storage provides higher incremental dry-season flows. Overall, incremental annual benefits would decrease by 8–10 percent in a typical low-flow year.

In a wet year, hydropower production would not change appreciably compared with an average year (increases by just over 1 percent with full development), because of the limited storage capacity in the dams in Nepal. The value of the dams for providing irrigation and low-flow augmentation in such years also decreases compared with an average year (by 8 and 17 percent for full development and three-dam development options, respectively).

Question 7.
What are the Cost- and Benefit- Sharing Dynamics of Upstream Water Storage Development?

Perceptions: Big benefits upstream and downstream

Perceptions differ by country, but it is generally perceived that downstream countries will benefit greatly from upstream development and therefore should share the costs of that development, perhaps by sharing the initial capital costs. Some stakeholders believe that, in fact, the majority of benefits will accrue downstream.

Findings: Big benefits, mostly in hydropower

If upstream multipurpose dams were built today, with current low agricultural productivity and little flood benefit, this study finds that the overwhelming share of economic benefits would be derived from hydropower. In the future, if agricultural productivity rises dramatically, the distribution of benefits could change. The principal unknown in this equation is the ecosystem and navigation values of enhanced low flows in the delta, which could be significant. The study's findings suggest, however, that the benefit-sharing calculus is simpler than previously assumed because downstream flood control and agricultural benefits are smaller than anticipated. The benefits and costs to be shared at least in the near term will be predominantly associated with hydropower.

The new information provided in this study has implications for benefit and cost sharing in the development and financing of Himalayan dams. **Table 12** considers the following four possibilities:

Table 12
Benefit Assumptions for Himalayan Dams

	Low-flow augmentation augmentation to the delta is worth very little	Low-flow augmentation to the delta is worth a lot
Increased dry-season water to Indian agriculture is worth very little	**Case A**	**Case B**
Increased dry-season water to Indian agriculture is worth a lot	**Case C**	**Case D**

Case A assumes low values for both irrigation water and low flows/environmental flows. Case B assumes that irrigation water is not valuable, but that environmental flows are. Case C assumes that irrigation water is very valuable, significantly more productive than it is today, but that environmental flows have little worth. Case D sees quite high values from both uses.

It is unclear which scenario reflects current circumstances. The literature suggests that surface water supplies to Indian agriculture are worth very little in economic terms, around $0.01 per cubic meter.[68] They may even have negative value if applied to waterlogged areas. With regard to the value of low-flow augmentation in the delta, the literature tells us very little. Given the ecology and biodiversity of the delta and the dependence of delta populations on navigation, however, we must assume there is appreciable value to low-flow augmentation in the downstream reaches of the river.

Although many stakeholders believe the basin is described by Case D, the findings of this study suggest that Cases A and B better describe the Ganges today.

Consider Case A. This is a simple story: the economic benefits from the Himalayan dams are simply hydropower and perhaps some Nepalese irrigation. There are few downstream economic consequences for India or Bangladesh. One implication of this case is that the benefit-sharing calculus between Nepal and India for hydropower development is, in fact, much simpler than previously assumed – Himalayan dams produce hydropower benefits almost exclusively (95 percent). If this is the case, India and Nepal should not delay in negotiating straightforward power development and trade agreements.

Case B is more complicated. If low-flow augmentation to the delta is valuable,[69] those economic benefits can be added to the hydropower benefits because there are low tradeoffs between the two uses. In Case B, Bangladesh, India, and Nepal all gain from the construction of the Himalayan dams. Nepal and India share the benefits of hydropower generation (assuming the excess power produced in Nepal is exported to India), and Bangladesh benefits from the low-flow augmentation (increased environmental flows).[70]

Under this scenario, Bangladesh and India should both be willing to share in the costs of building the Himalayan dams: Bangladesh should invest for the low-flow augmentation and India should invest as part of a power trade agreement with irrigation co-benefits. The magnitude of each country's contribution would depend largely on the current values of power, irrigation, and low-flow augmentation. Although this study has provided very broad indications of the relative magnitudes of these values, the negotiations for benefit and cost sharing of any specific project would require extensive, joint analysis of costs and benefits.

Furthermore, the distribution of costs and benefits under this scenario would be affected by the level of water withdrawals in India. The water systems model assumes that Indian withdrawals would be made to the full capacity of its current infrastructure. Even with this assumption, low flows could be doubled in the driest months if the Himalayan dams were built. In contrast, the economic optimization model, allocates water where its value is highest. This means that if low-flow augmentation in the delta is more valuable than irrigation, the additional low flows would be allowed to pass through India to Bangladesh. The values presented in **Figure 54 Figure 56** which were derived from the economic optimization

[68] Chowdury 2005, Molden et al., 2001, Rogers et al., 1998, and Sharma et al., 2008.
[69] The authors believe there are very important values to low-flow augmentation in the delta. Due to the lack of quantitative research, however, specific values have not been included in this report.
[70] The water systems models assume that Indian off-takes would increase to their full channel capacity, until no more water could be drawn from the system with existing infrastructure. These benefits could be even higher if Indian off-takes did not increase.

model, therefore, assume that India would allow the increased low flows to pass through to Bangladesh. India might do so if:

- as this study suggests, groundwater is, in fact, a better option than increased surface water flows for supplementing dry-season irrigation,
- increased environmental flows were desirable within India, or
- the benefits of regional cooperation were compelling.

Assurances regarding flow abstractions in the plains, and an agreed valuation of low-flow augmentation, would be two key challenges in negotiating a benefit-sharing agreement.

Case C is worth a comment. If the unit values for irrigation water are high, the economic optimization model allocates Nepal 10–12 billion cubic meters for new irrigated agriculture. This withdrawal is substantial, and it would be for new, not existing, irrigated areas in Nepal – although it could involve hydropower tradeoffs. Given the poor availability of spatially specific data on agricultural productivity in the basin, the economic optimization model assumes that the value of water in agriculture to India and Nepal is the same. If irrigation values are high, and differentiated among countries, the economically optimal distribution of enhanced low flows among all three riparians could change.

Case D reflects the current mindset of most stakeholders. It is widely assumed that irrigation water and low-flow augmentation is extremely valuable to Bangladesh and India. Many believe that irrigation water is extremely valuable, particularly in India, and that flood control from upstream dams is extremely valuable for the whole system. The limited empirical evidence reviewed in this assessment, however, suggests that irrigation has very low productivity, such that the benefits from low-flow augmentation to Indian agriculture would currently be quite small (though this could change over time) and that basinwide flood-protection benefits are likely to be negligible.

An immediate benefit-sharing opportunity for the region that is not explored in these scenarios is cooperative investment in regional hydrometeorological data collection and information management, coupled with forecasting and warning systems.

Question 8.
Is Large Infrastructure the Best Strategy for Protecting Communities from Floods?

Perception: Yes

Building infrastructure is the most effective and reliable way to protect communities from flooding.

Findings: Not everywhere, and not exclusively

There is no simple solution to floods. In some areas of the world, a focus on large infrastructure (dams and embankments) has been fairly effective. In the highly variable monsoon-driven Ganges system, with its thousands of tributaries, these solutions are not as effective. To protect communities in the Ganges Basin a shift in focus is needed from flood control to flood management; marked by a greater emphasis on regional forecast and warning systems, embankment asset management, drainage, and, importantly, more localized 'soft' responses including disaster preparedness, land zoning, safe havens, insurance, and training and communications campaigns. Flood protection for basin communities and their livelihoods requires a broad, balanced combination of 'hard' and 'soft,' local and transboundary responses.

Floods are not new to the Ganges Basin, and local populations have been coping with the challenges of periodic inundations for centuries. Accounts from as early as the 12th and 13th centuries[71] record methods of adaptation to the ferocious and unpredictable monsoon flooding in the plains, but

[71] Mishra 2008.

also highlight the benefits of floods.[72] By the late 19th century, floods were generally seen as something to be controlled, and large-scale infrastructure was seen as the best means to achieve this goal.[73] Embankment systems and barrages were built in an attempt to control water flows for irrigation and to contain floods. These were conceived with an expectation that a large water storage infrastructure would someday be built far upstream in the Himalaya, which, along with the embankment systems, would provide full control of floods.[74]

This analysis makes clear that the expectation that upstream storage can fully control floods across the basin is untenable. The emphasis should now shift from the idea of 'controlling' floods to the idea of 'managing' floods through better management and maintenance of the existing embankment systems complemented by nonstructural investments, for example, in forecasting, zoning, insurance, temporary relocations, flood-friendly architecture, and changes in cropping patterns, described later in this section.

Embankments remain the most pervasive flood control technology in the Ganges Basin.[75] Embankment systems gained prominence under British rule in India. It is interesting to note,[76] however, that, despite the public popularity of the idea of flood control, there was significant debate among both British and Indian engineers as early as the turn of the last century as to whether these systems were viable in the monsoonal, silt-laden Ganges Basin. That debate continues in the region today.

Embankments do provide short-term and localized benefit to agricultural land, lives, and property that face chronic flooding.

However, the longer-term impacts of these embankment systems have been mixed, and mounting criticism is challenging the paradigm of such structural investments to control flooding. Some authors point to the fact that embankment systems have altered the hydrological characteristics of the basin[77] because high silt loads, typically deposited in the plains areas during flooding, are carried further downstream, raising river beds, exacerbating drainage and congestion, and, ultimately, increasing the risk of catastrophic flooding from embankment failure. In Bangladesh, it was found that embankments not only increase siltation in the river beds and floodplains but also raise flood water levels, which, in turn, increase the water velocity.[78] As **Figure 57** shows, much of the flooding today in Bangladesh is actually due to waterlogging and drainage congestion, rather than riverine flooding. This type of flooding, because it stays on the land longer, can be more harmful in the long run to agricultural production.[79]

When embankments fail, it can be catastrophic. Embankment breaches or failures—like the devastating Kosi embankment breach of 2008—bring on sudden severe flooding that catches communities off guard. At the same time, embankments lead communities to believe that they are not at risk of flood. This false sense of security manifests in a lack of preparedness, it reduces social awareness of risk and encourages behaviors such as settlements in historic flood plains, thereby actually increasing vulnerability.[80] Embankment management is essential. Regardless of upstream development, asset management systems for embankment monitoring and maintenance are an imperative for protecting communities in the Ganges Basin.

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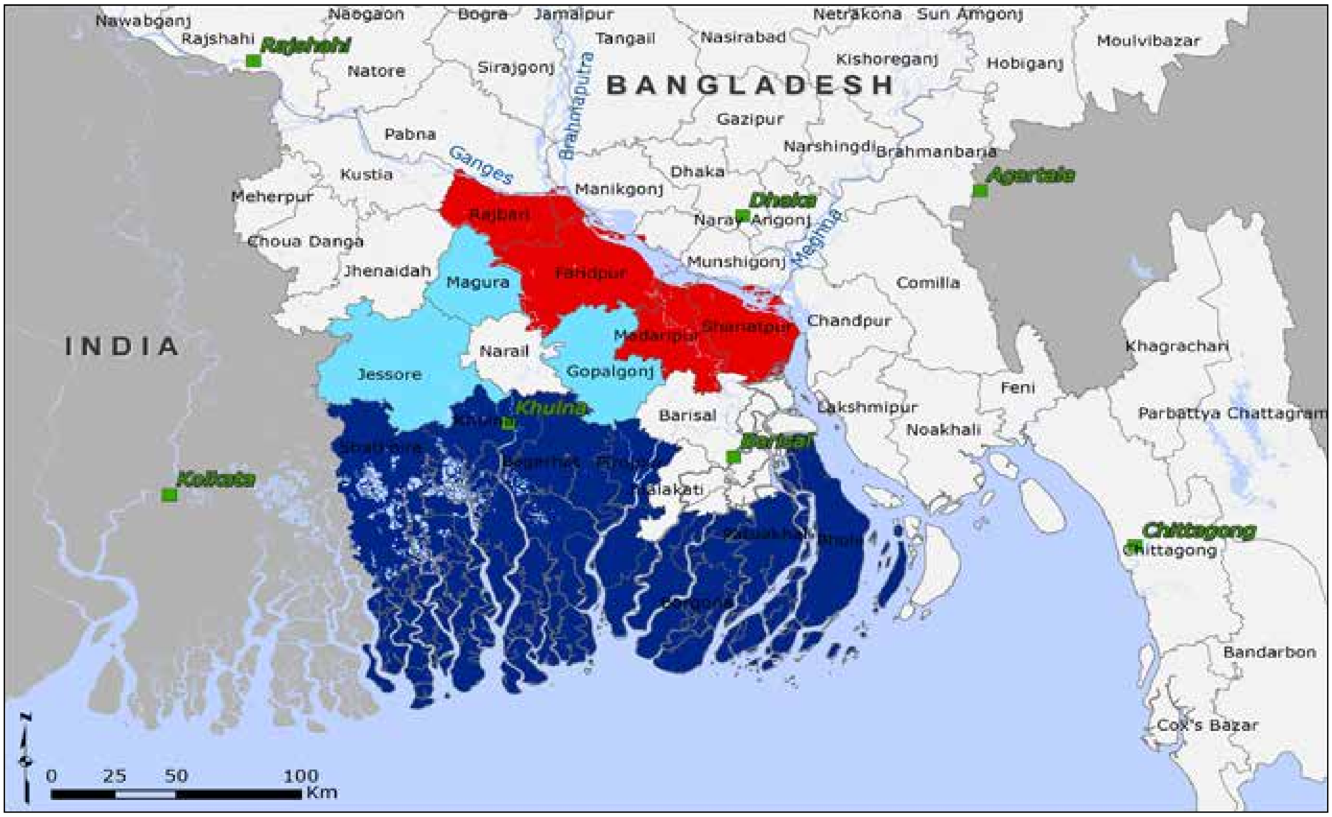
[72] Bandyopadhyay 2009 and Verghese 1990.
[73] Bandyopadhyay 2009.
[74] Mishra 2008.
[75] Embankments, sometimes called levees, are continuous earth bunds on one or both sides of a river constructed to protect surrounding lands from inundation.
[76] See Mishra 2008 for an interesting account of the early debate over embankments along the Ganges.
[77] Moench and Dixit 2007.
[78] Hossain and Zakai 2008.
[79] Planning Commission of India 1981.
[80] Dixit 2009, Moench and Dixit 2007, and Bandyopadhyay 2009.

Figure 57
Flood Typology of Southwestern Bangladesh



Water logging   Riverine flooding   Tidal Flooding

Source: Rashid (2009).

High population (Table 13) growth in the basin has exacerbated the problem of flooding. Over the years, flood plains have been taken over by human settlements, and traditional flood detention areas have been converted to residential areas. The spreading of concrete and paving in these settled areas have left the land with less capacity to absorb rainwater resulting in increased runoff into the rivers, especially in growing urban centers. Large-scale felling of forests has also left land vulnerable to erosion and increased runoff. A 2007 report by the World Health Organization noted that urban flooding is a growing problem in cities in the Ganges Basin, and that big cities find it increasingly difficult to cope with rising flood waters and dense populations.

Flooding disproportionately affects poor and socially vulnerable populations in the basin. The poor and socially marginalized typically live with higher risks of exposure to flooding. These populations also have less access to institutions and services. Poor communication and transportation networks make many communities difficult to access during and after flooding, and many localized floods may not register on the state or national scale so those communities may not be classified as in need

Table 13
Decadal Population Growth Rate Estimates

Country/State	Decadal Population Growth Rate Estimate (2001-2011)
Bangladesh[a]	**14.7**
Nepal[b]	**25.4**
India[c]	**17.6**
Bihar[d]	25.1
Chattisgarh	22.6
Delhi	21.0
Haryana	19.9
Himachal Pradesh	12.8
Jharkhand	22.3
Madhya Pradesh	20.3
Rajasthan	21.4
Uttar Pradesh	20.1
Uttarakhand	19.2
West Bengal	13.9

Note: [a] Estimated 2001-2011 decadal growth rate as per the 2001 Bangladesh Census; [b] Estimated 2001-2011 decadal growth rate as per the 2001 Nepal Census; [c] Average population growth rate for India 2001-2011, preliminary results of the 2011 India Census; [d] State-wide decadal growth rates for India 2001-2011, preliminary results of the 2011 India Census.

of relief. Social prejudice against the poor and lower castes may also impact the way in which relief is distributed. For example, during the 2008 floods in India, reports emerged that relief supplies in Bihar were going to the highest castes first[81] and that lower castes were often the last to be rescued.[82] This lag in or lack of relief to reach the poor means, in turn, that those most vulnerable populations face the greatest difficulty in recovering from shocks and disaster events.

The poor also have more limited income opportunities and fewer assets, which make them more vulnerable to extreme poverty and destitution.[83] Many of the households surveyed in Bihar take loans from local moneylenders to rebuild their homes and to purchase inputs for agriculture or livestock.[84] In the post-flood period, many respondents said that rates increased from 5 percent per month to 10 percent per month for a loan, creating difficulties in repayment and undermining their recovery.

Women face particular challenges from diminished water quality and agricultural productivity. Research from the Sundarbans area of Bangladesh has shown that increasing contamination of drinking wells and lower agricultural production has placed disproportionate pressure on women. Because women typically collect water for drinking and domestic uses, less water availability means they travel further distances to complete this task. Interviews with women have shown that they have adjusted by drinking less water during the day to conserve the number of trips needed to fetch water.[85]

"During floods, those who have cattle take them to higher places and feed them with dry fodder. Also, many people sell them at lower prices. The person who is buying [them] bargains and takes animals at much lower prices. Many businessmen come to buy these cattle during floods… We can't pawn animals but yes we pawn our jewelry."

– Female respondent, Khagaria District, Bihar, India

"[In the floods of 2007]… we lost everything, our livestock, livelihood, and our houses were damaged. I don't think we have recovered yet… at this point I think we won't recover."

– Female respondent, Muzzafarpur District, Bihar, India, July 2010

[81] Ramesh 2007.
[82] Rabinowitz 2008.
[83] Maxwell Stamp 2010, chapter 4, note 48.
[84] Focus Group Discussion, Madhubani District, Bihar, India
[85] Ahmad forthcoming.

Also, lower agricultural production caused by saline intrusion has resulted in greater food insecurity for women because the intra-household allocation of food often disadvantages women and young girls.[86]

It is clear that to protect basin communities, and in particular the poor and socially vulnerable, current strategies are inadequate. Much of the current literature shows that while embankments continue to be the preferred flood-control intervention in the Ganges Basin, they have failed to solve the problem of excessive flooding during the rainy season.[87] Moreover, the illusion of security provided by embankments often means that softer measures, such as early warning systems, preparedness and disaster response have been overlooked; there is little systematic response to disastrous events.

The findings of this report confirm the limitations of large infrastructure strategies for flood control in the basin, and point to the need for a shift in focus from flood control to flood management. Rather than trying to control floods, complementary nonstructural flood management interventions are needed to manage them. Flood management has been increasingly advocated in recent years by a range of basin opinion makers. Nonstructural, or 'soft' interventions, are not new to the Ganges Basin. Indigenous settlement patterns and architecture in the Indian floodplains show elevated housing built on bamboo posts, excavated ponds serve water use needs but also act as flood buffers, and strategies of high mobility during flood seasons through the use of boats and seasonal movements to higher grounds.[88] Many of these measures are still used today by people living in flood-prone areas of the basin. **Box 4** shows that a strategy of nonstructural management of floods can be effective.

Although well-managed embankments cannot control flooding, they can form part of a larger flood management solution in the Ganges Basin. Decades of investments in embankment systems have created localized and short-term benefits for many of the basin's populations who rely on these buffers to protect their land, assets, and livelihoods. In addition, elevated embankments are also often the first point of evacuation for flood-affected populations, who rely on them for refuge and to await relief. Over the longer term, embankments can have significant social and environmental consequences, so their management and maintenance require a fresh look. Still, maximizing the current embankment systems' benefits by improving maintenance, drainage, and silt removal is essential for protecting communities and key assets.

Information, forecast and warning systems are clearly a priority. As experience in Bangladesh has shown, community-based preparedness and early-warning systems can contribute significantly to reduced loss of life and property caused by cyclones. A reliable, real-time hydrometeorological monitoring system (ideally on a regional scale to track the movement of the monsoon) will be fundamental to managing floods in the region. Technical innovations in data gathering (satellite and land-based), information management, modeling and forecasting protocols, and communications technologies have dramatically increased the potential of these systems to quickly and economically provide life-saving warnings to communities. Additional benefits of these investments could be timely agrometeorological information to help farmers time their planting, fertilization, and harvesting, and the collection and management of information for monitoring of and adaptation to climate change.

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[86] ibid.
[87] Ahmad Ahmad 1992 and Dixit 2009.
[88] Bandyopadhyay 2009.

Box 4

Are Embankments a Good Flood-Control Strategy? A Case Study of the Kosi River

On August 18, 2008, the Kosi River breached its embankment in Nepal close to the Bihar border. The Kosi's westward loop was cut off, flooding a vast, roughly triangular area with the apex of the triangle at the breach site and the base of the triangle 150 kilometers to the south. According to official sources, 493 people were killed and some 3,500 reported missing after the disaster. In all, 3.3 million people in Bihar were affected and, at the peak of the flood, 440,000 were living in camps.

In February and March 2009, a survey was conducted of 10 flood-affected villages in Bihar. Eight were flooded by the Kosi after it breached the embankment ('unexpectedly flooded villages'). The other two, located near the Ganga and the Kosi, are flooded annually during the monsoon by their respective rivers, thus they are adapted to flooding. In fact, both of these villages have most of their fields inside an embankment.

The following year, in April and May 2010, the researchers resurveyed the 10 villages. They also surveyed eight more villages for comparison. Some of these additional villages were regularly flooded; others were not regularly flooded by river overflow, nor were they unexpectedly flooded due to the embankment breach ('control villages').

The researchers compared these three types of villages – unexpectedly flooded, regularly flooded, and not flooded – over the period July 2008 to March 2010. Their objective was to see whether a strategy of allowing floods but building dispersed infrastructure to cope with them would be better than the current government strategy of flood protection based on embankments.

The study found that, in fact, the regularly-flooded villages were, on average, no worse off than the control villages. The most striking finding was that the gross value of crop output in the regularly flooded villages was the same or higher than that in the control villages, despite the fact that three out of four of the regularly-flooded villages in the sample are located inside embankments, and, therefore, are highly exposed to seasonal and concentrated river flooding. The second major finding was that mean wages of agricultural and casual workers were no lower in the regularly-flooded villages than in the controls. Third, these regularly-flooded villages do no worse on measures of schooling, health, wealth, and household amenities.

There was one big difference between the regularly-flooded villages and the controls: in the regularly-flooded villages, agricultural output varied much more sharply over the year, which caused dips in the proportion of households getting sufficient food during the monsoon.

These results suggest that a strategy of gradually moving away from reliance on embankments and instead building infrastructure to live with floods would (1) not result in a net loss of agricultural or other output or health indicators (2) save money currently going into embankment maintenance, and (3) prevent the apparently inevitable disasters that occur every few years when there is a major embankment breach. The infrastructure to replace embankments, apart from obvious measures like raising buildings on stilts and digging new channels for river flow, should include the social infrastructure of employment generation or other social and food security during the monsoon for areas that will face increased flooding.

Source: Adapted from E. Somanathan 2011. Based on surveys undertaken by E. and Rohini Somanathan.

Other 'soft' interventions could include large-scale flood-plain management, disaster preparedness, land-use planning, modification of cropping patterns, flood zoning, raising of villages and/or safe havens, insurance, microfinance, and education and communications campaigns.[89] **Flood protection for basin communities and their livelihoods requires a broad, balanced combination of 'hard' and 'soft,' local and transboundary responses**.

Question 9.
Is it Possible to Control Sediment in the Ganges?

Perception: Yes

Watershed management and upstream storage can control sediment loads.

Findings: Not Really

The high altitude and steep terrain of the sediment source regions, as well as the nature of the sediment and the ongoing tectonic processes, make it impossible to undertake the scale of watershed management interventions that would be necessary to have any measurable impact on basinwide sediment yields.

The volume of sediment is so large that capturing it behind large dams would be extremely costly; the reservoirs of these large, expensive structures would fill quickly and thereafter produce very few benefits.

As shown earlier **(Table 1)** the Ganges is one of the most sediment-laden rivers in the world, carrying more suspended sediment than the next three most sediment-laden rivers combined. The Ganges-Brahmaputra system carries about 2.9 million tonnes of silt daily.

The high level of sediment transport in the Ganges system is of great concern because it affects the morphology of the river, the floodplains, and the delta. About 95 percent of the sediment load is delivered during the monsoon, so sediment loads are extremely sensitive to unpredictable and highly variable flood flows. These variations influence the erosion and deposition dynamics of the river, for example at existing bridge areas, river training works, and the intake points for irrigation schemes. They also affect navigation and drainage by changing the level of the river bed, and decrease flows to distributaries as sedimentation clogs irrigation offtakes **(Figure 58.)**

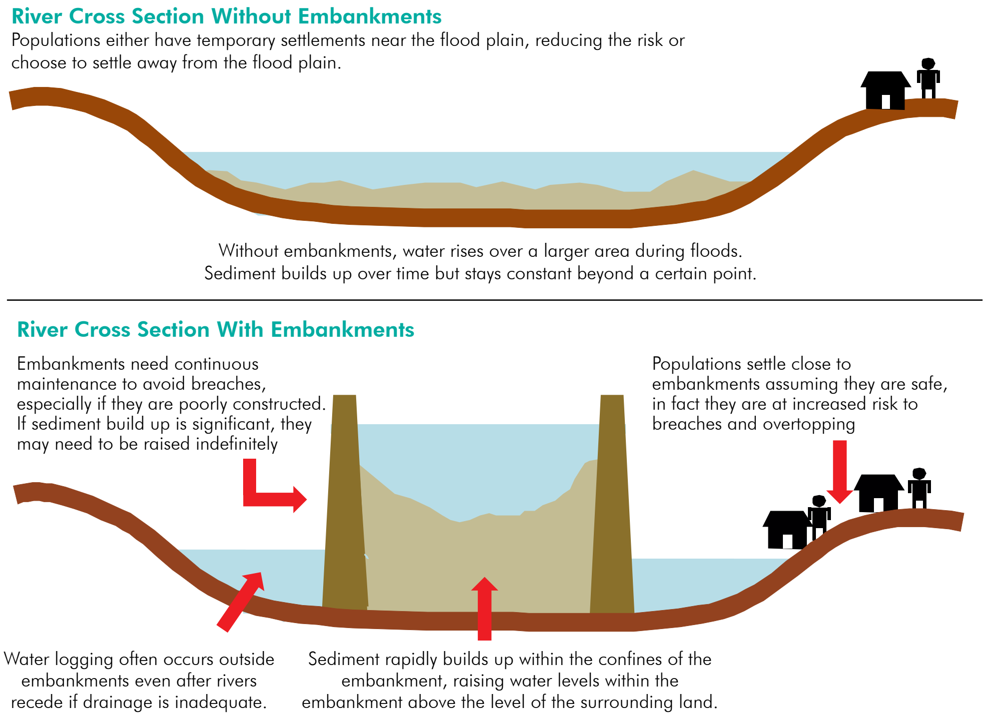
Figure 58
Sedimentation in an Irrigation Canal in Uttar Pradesh

Source: Nagaraja Harshadeep Rao (2010).

A particular challenge posed by sediment in the Ganges is the dynamics of high sediment loads in embanked stretches of the river. The Kosi, which is largely embanked and estimated to carry more than 100 million tonnes of sediment every year, is a good example. A substantial quantity of the highly variable sediment gets deposited within the Kosi's embankments, raising the river bed above the level of the surrounding land in some stretches, causing the river to move to possibly more dangerous courses within the embankments, and enabling even low flows of water to come close to embankment

[89] WHO 2007, Moench and Dixit 2007, and National Committee on the Development of Backward Areas 1981.

Figure 59
Schematic of Embankments in Sediment-Laden Rivers



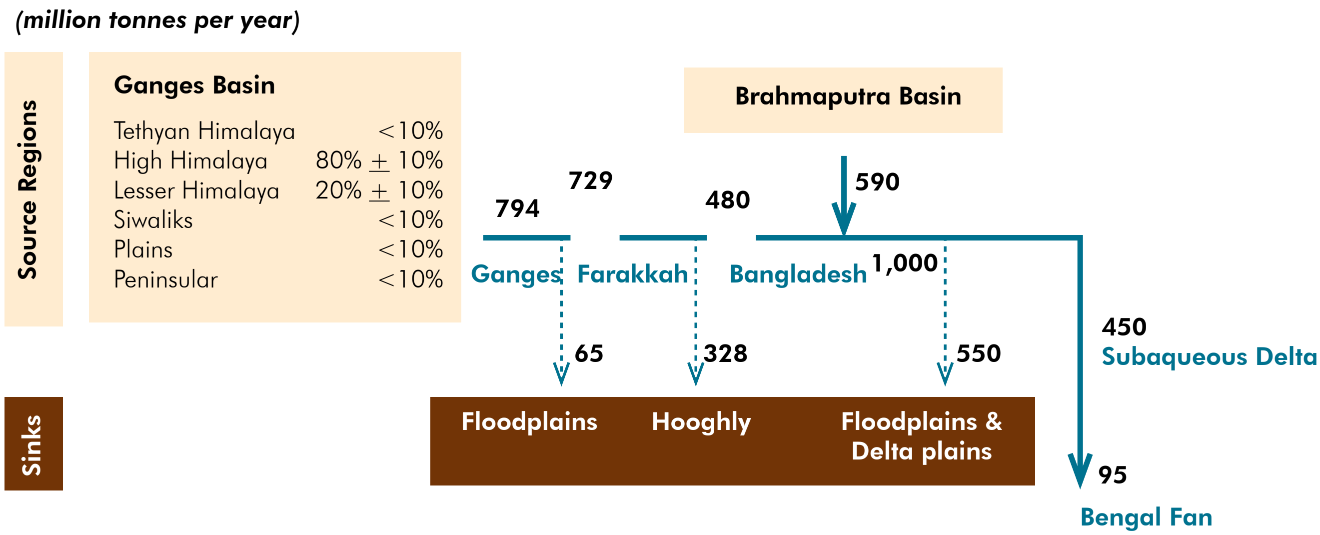
capacity **(Figure 59)**. The Yellow River in China, which, along with the Amazon, has silt loads comparable to the Ganges, is a striking example of this phenomenon. The Yellow River's embankments have trapped so much silt that at some locations the river bed is six meters higher than the surrounding landscape. Rivers, of course, are supposed to be the lowest points in the landscape to facilitate drainage of both river and rain water. In the case of the Kosi, sediment build-up has rendered other embankment defenses, such as drainage gates, inoperable because they have become buried under the sediment.

Both the volume and the source of sediment in the Ganges make it extremely difficult to manage. There are two general strategies for managing sediment in a river system: (1) watershed management to stabilize soils and diminish the amount of sediment entering the system, and (2) infrastructure designed to capture and regulate sediment once it is in the system. **The volume of sediment in the Ganges is so extreme that capturing sediment in large infrastructure would not be economic; these large expensive structures would simply fill up too quickly**. Any infrastructure developed in the Ganges system will need sophisticated systems for flushing sediment downstream.[90]

To assess the potential for watershed management to control sediment in the Ganges, it is necessary to identify the geographic sources of the sediment. **Figure 60** shows that the vast majority of sediment in the Ganges Basin comes from the High Himalaya (3,000–8,848 meters), and, to some extent, from the Lesser Himalaya or Mahabharat Range

[90] Significant advances have been made in sediment flushing techniques, China's Three Gorges Dam is a notable in this regard.

Figure 60
Sediment Flow in the Ganges-Brahmaputra System



Source: Prepared by IWM based on data from Wasson 2003.

(2,000–3,000 meters). **The altitude and terrain of the sediment source regions, as well as the nature of the sediment and the ongoing tectonic processes, make it impossible to undertake the scale of watershed management interventions that would be necessary to have any measurable impact on basin sediment yields**. Nepal, in particular, has an impressive history of community forestry management, with strong results in terms of local erosion management and livelihood benefits. These activities, however, are predominantly undertaken in the Siwaliks or Churia Hills at elevations of just 600–1,200 meters above sea level, far below the main sediment source regions.

Question 10. What will Climate Change Mean for the Basin?

Perceptions: Enormous change

Many fear that the Himalayan glaciers will melt and change the Ganges River from a perennial to a seasonally flowing river, and that changing temperatures and precipitation patterns will create crippling water stress as well as more severe and more frequent droughts and floods.

Findings: Uncertainties are great, but immediate actions can be taken

Climate change uncertainties in South Asia and the Ganges Basin, in particular, are extreme, but the range of mean basin runoff predictions is roughly comparable to the recent historical record and the basin's highly variable climate today. Moreover, even the most extreme scenarios do not change the basic findings and recommendations of this report. A focus on managing current hydrological variability is, therefore, a good place to start in addressing the future climate change challenges of the Ganges.

Climate Change in the Ganges Basin

Everywhere, climate change presents uncertainties. But in South Asia these uncertainties are compounded by a profound lack of data and the inability thus far to construct a credible methodology for modeling predictions of how monsoon patterns might change, in particular with regard to the relationship between climate and hydrology. Added to the complexity of the massive monsoon system is the diversity of microclimates in a region where altitudes can range almost 8,800 meters across a distance of 200 kilometers.

The Fourth Intergovernmental Panel on Climate Change (IPCC) report[91] left a 'white spot' over South Asia and the greater Himalayan region suggesting that data were insufficient to support credible analysis It is one of several key regions having greatly divergent predictions of future changes in precipitation. A new generation of global circulation models is being developed and efforts are underway to downscale existing models to a regional basis in South Asia. But none of this information is yet available, leaving tremendous uncertainty in any discussion of South Asian, and Ganges-specific, climate futures.

This study estimated temperature, rainfall, and runoff for the Ganges Basin using all of the 16 United Nations Framework Convention on Climate Change (UNFCCC)-recognized Global Circulation Models (GCMs). Although there appears to be a clear trend toward increasing temperatures, predictions regarding rainfall and runoff vary widely and point to the possibilities of either increasing or decreasing water availability. The range of model results underscores their uncertainty, and their predictions can mask extremes, but the results do suggest that the scale and focus of today's climate challenges – unpredictable and intense rainfall, alternating extremes of flood and drought – will continue to be the key climate challenges in the coming decades. A focus on managing current hydrological variability (whether or not it is attributable to climate change) is, therefore, a good place to start in addressing the future climate change challenges of the Ganges.

Temperature in the basin will rise. The extent of the temperature rise will depend on the level of coordinated global actions to mitigate carbon releases into the atmosphere. All climate models are in accord that the Ganges Basin will experience significantly increased warming. Mean annual temperature at the country level is projected to increase 1.2 – 1.5 °C (A2 scenario)[92] by mid-century and 2.8 – 3.9 °C (A1B scenario)[93] to 3.5 – 4.8 °C (A2 scenario) by 2100. As shown in **Figure 61**, the GCMs agree that temperatures will increase, though they disagree on the level and spatial distribution of change.

Evaporation losses in the Ganges system will increase, as will system water demands. Increased temperatures expected under climate change scenarios will result in increased evapotranspiration losses from catchments and increased evaporation from reservoirs and streams. Crop water requirements will increase substantially as temperatures increase. Other changes (e.g. increased cooling requirements) will also put pressure on water systems.

Glacier melt rates will increase. A study done as input to this report[94] indicated that glacier melt contributes only about 4 percent of the Ganges annual flow (see **Figure 62**.) Melting occurs mostly during the high-flow season in the Ganges. In contrast to Europe and North America, where glacier melt contributes to low summer flows, the Himalayan glaciers melt during the monsoon season when temperatures are highest but rainfall is also heaviest. Thus, while changes in glacier melt will be a fundamental challenge for some melt-dependent mountain communities, it is not a major driver of basinwide hydrology.

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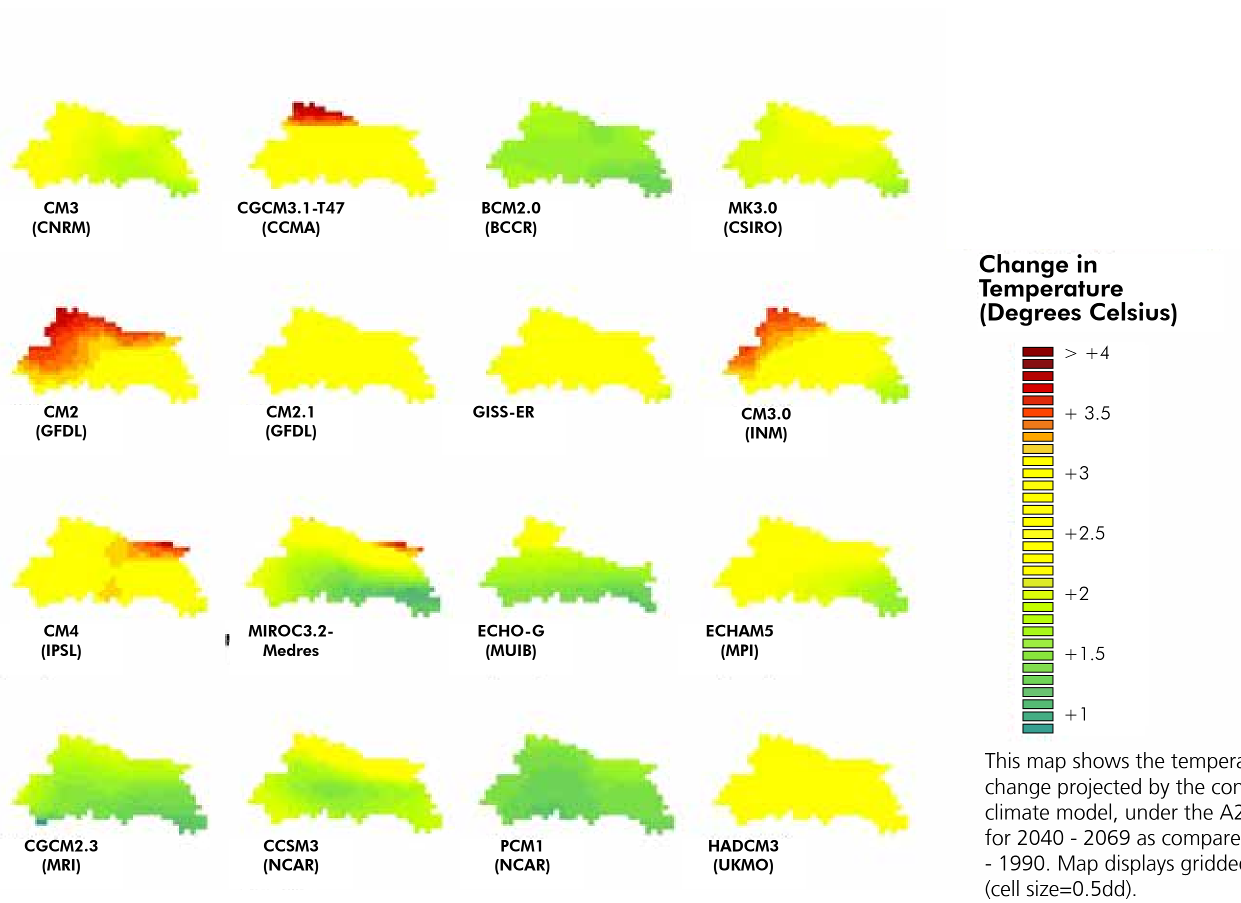
[91] IPPC 2007.
[92] 'The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.' (IPCC Special Report Emissions Scenarios. IPCC, 2000)
[93] The A1 storyline is a case of rapid and successful economic development, in which regional average income per capita converge - current distinctions between 'poor' and 'rich' countries eventually dissolve. The A1B scenario assumes a balance across energy sources. (IPCC Special Report Emissions Scenarios. IPCC, 2000)
[94] Alford and Armstrong 2010.

Figure 61

Temperature Predictions for the Ganges Basin for 16 GCMs

Ganges - Differences between GCMs, in terms of Change in Temperature, by the 2050s



This map shows the temperature change projected by the considered climate model, under the A2 scenario for 2040 - 2069 as compared to 1961 - 1990. Map displays gridded data (cell size=0.5dd).

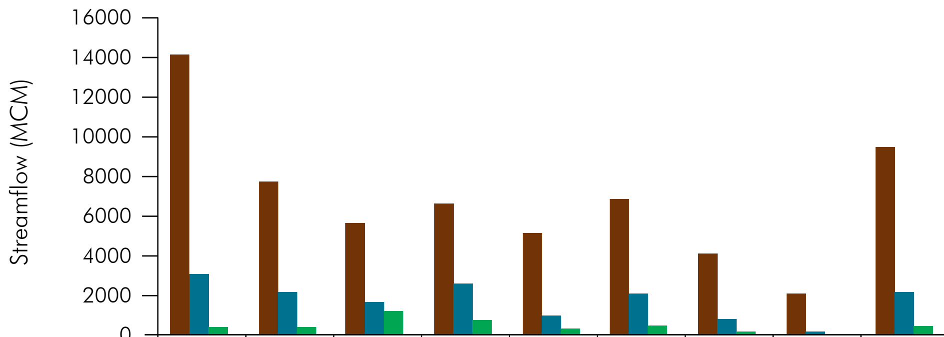
Source: WCRP's CMIP3 (Meehl et al. 2007), downscaled by Maurer et al. (2008).

Disclaimer: The boundaries, colors, denominations, and other information shown in any map do not imply any judgment on the part of the World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

Melt is likely to increase in the future. For example, the zero-degree isotherm (the steady-state equilibrium line altitude, where total annual accumulation equals total annual ablation and the glacier net balance is zero) could move in the summer from its current height of about 5,400 meters to about 6,100 meters by the end of the century. This movement would increase melting in many glaciers, but it would still leave almost half Nepal's Himalayan glaciers above the new isotherm.

Although changes in glacial area (e.g. the well-publicized retreats of some glacier 'tongues') are apparent in aerial photographs and high-resolution satellite images **(Figure 63)**, they can be misleading. Although a glacier might retreat at its terminus, it could still be growing in mass. It is the mass and volume of the glacier that is relevant for water storage and supply, but the changes in glacier mass or volume are much harder to measure that the reduction in the tongues. Given the complexity of glacial dynamics, the response of glaciers to

Figure 62
Share of Glacier Melt in Nepal's Himalayan Rivers



	1	2	3	4	5	6	7	8	9
Basin	14149	7765	5624	6672	5192	6929	4153	2091	9510
4-6 km	3119	2197	1682	2669	1007	2130	828	247	2194
Glacier Melt	418	421	1248	878	482	496	160	52	484

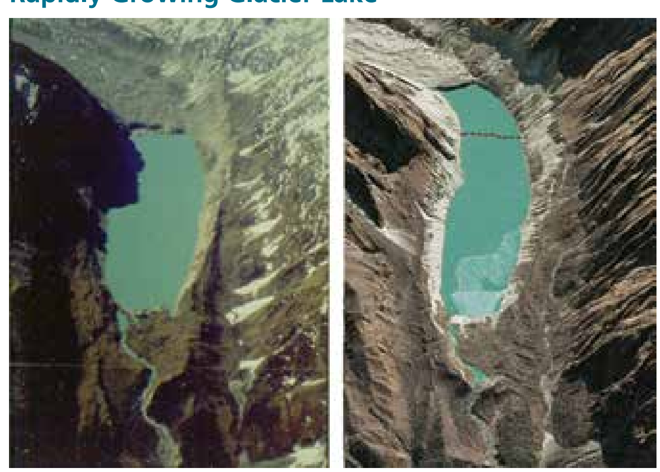
Source: Alford, et al., 2010.
Note: Relative streamflow, in million cubic meters per year, of: (green) glacier melt, (red) 4000-6000 meter altitudinal belt, and (blue) basin total, for glacierized gauged basins in the Nepal Himalaya. Basins are: 1. Bheri, 2. Kali Gandaki, 3. Budhi Gandaki, 4. Marsyangdi, 5. Trisuli, 6. Dudh Kosi, 7. Tama Kosi, 8. Likkhu, 9. Tamor.

variations in temperature and precipitation are not well known. Further complicating these analyses are recent concerns about the acceleration role of aerosols and the Asia Brown Cloud (a persistent layer of air pollution over the South Asia region). Field-based glacier measurements are sparse in the High Himalaya. However, it seems clear that glacial melt under climate change will not be important in the Ganges from a regional hydrologic perspective.

The Ganges system as a whole is unlikely to be significantly affected by glacier melt, but melting glaciers will have serious local impacts. Communities living in some glaciated sub-basins, for example, could face dramatic changes in water availability. In the Nepal Himalaya, the annual contribution of glacier ice melt to total river volumes varies among the nine catchment basins from 2 to 30 percent.

Similarly, glacier melt increases the risk of glacial lake outburst floods (GLOFs.) Natural dams (moraines) form when glaciers retreat/melt, due to the deposition of rock and debris carried by the glacier. As these lakes grow, water pressure builds behind the natural dams, which can burst, threatening communities and infrastructure downstream. There are currently some twenty glacial lakes in Nepal that are considered GLOF risks.[95]

Figure 63
Rapidly Growing Glacier Lake

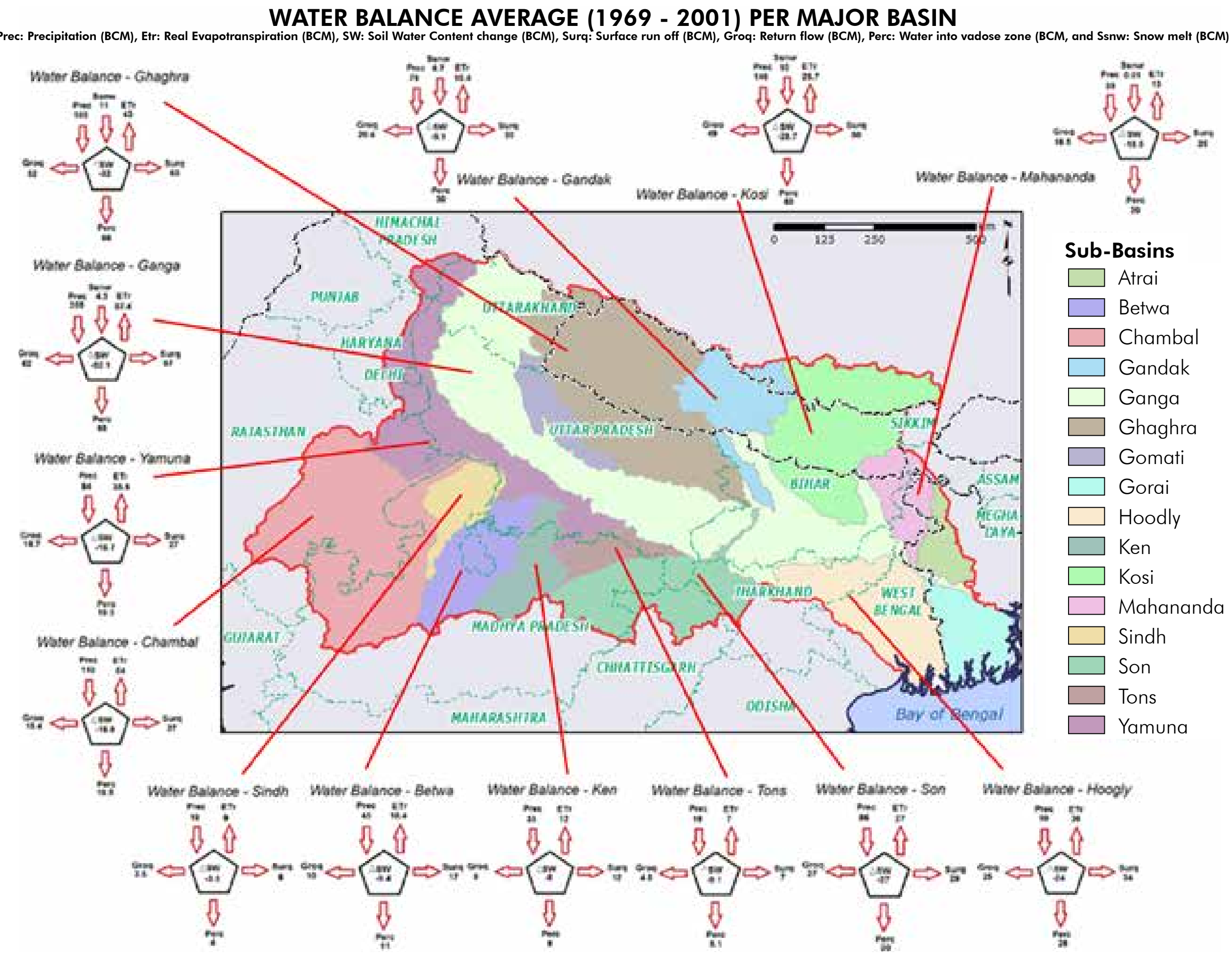


Source: ICIMOD (2011). ICIMOD photo.

[95] ICIMOD 2010.

Figure 64

Water Balance and Snowmelt Contribution in Himalayan Basins



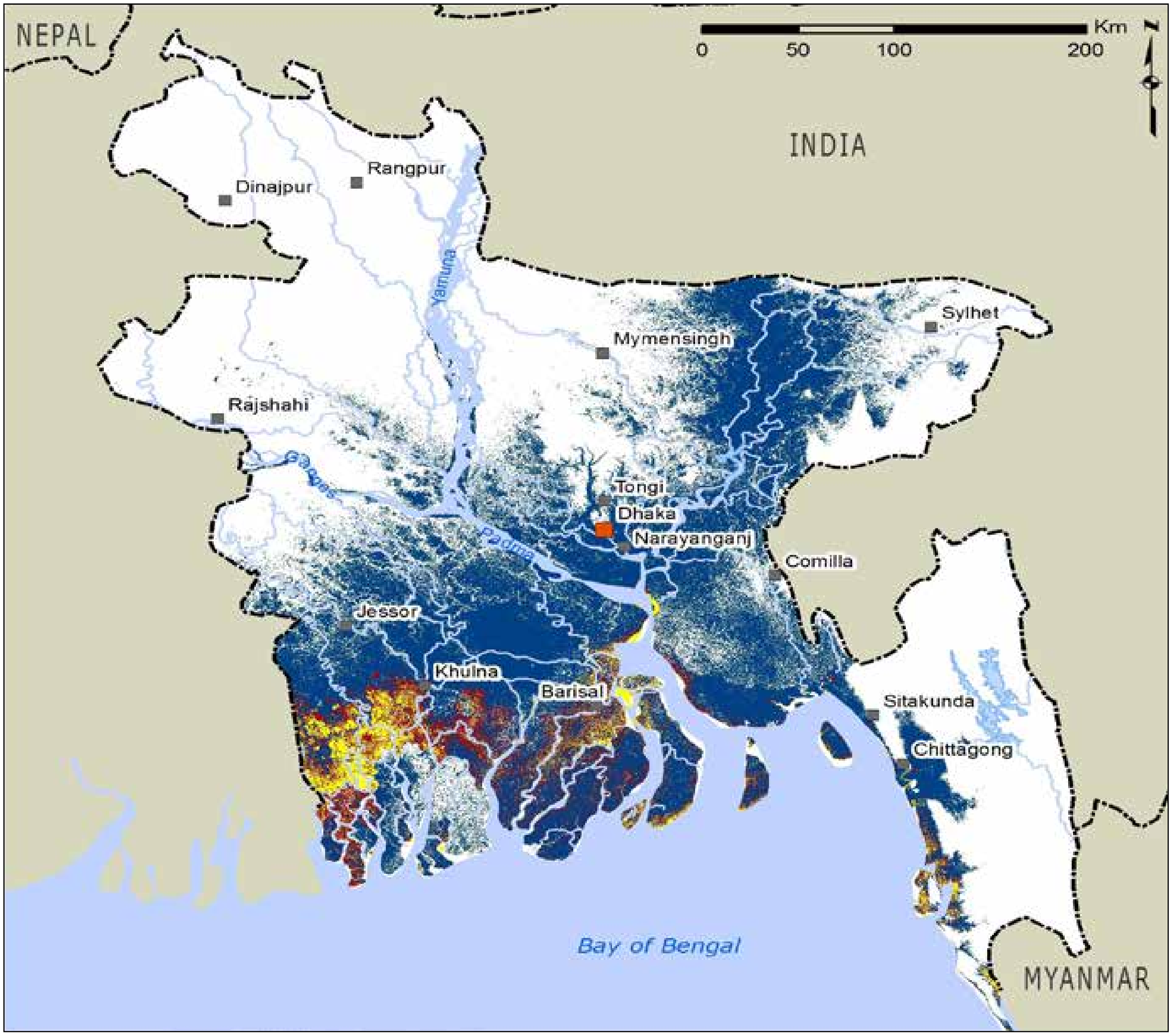
Source: Derived from the Ganges SBA SWAT model, using IPCC climate scenarios (from INRM).

Snow accumulation and melting regimes could change. A critical change in the basin hydrology could result from changes in snow. Given that temperatures during the monsoons are expected to be warmer and the zero-degree isotherm is expected to rise to a higher altitude, some of the precipitation that today falls as snow will become rain, resulting in lower snow accumulation and higher runoff. Consequently, during the spring thaw, there will be less snow to melt, resulting in lower water flow in the pre-monsoon low-flow season. This could have a significant impact in some catchments where snowmelt is a major input. **Figure 64** indicates that snowmelt currently contributes about 30 billion cubic meters annually to the 500 billion cubic meters of flows.

Sea level will rise. The delta regions of the Ganges Basin are very flat and fertile, and very vulnerable to sea-level rise. Significant inundation and salinity intrusion are predicted. As illustrated in **Figure 65**, a predicted one-meter rise in sea level would inundate 2,062 square kilometers (1.5 percent of the country and affect 1.52 million people (1.12 percent of the population.) A significant increase in storm surges is also predicted to accompany the one-meter rise in sea level.

Figure 65

Predicted Sea-Level Rise and Storm Surges in Bangladesh



Future storm surge zone | Current storm surge zone | Other coastal zone < 10m

International boundaries | Capital city | Cities

Source: Based on analysis carried out by the World Bank (2010), major lakes and rivers (RWDBII, CIA 2006), populated places (GRUMP, CIESIN, Columbia University, IFPRI, the World Bank, and CIAT, 2004).

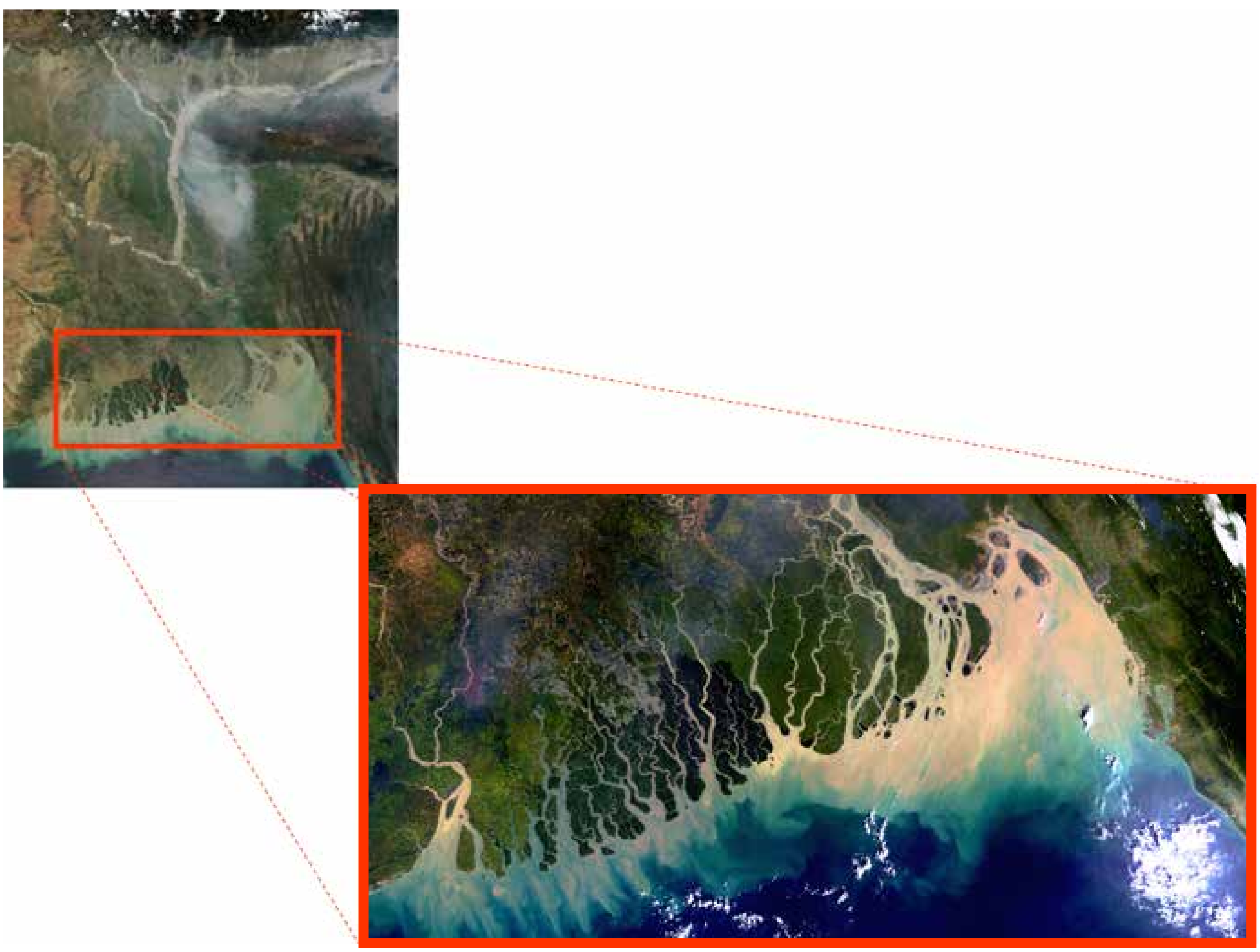
Data sources: sea storm surge (World Bank, 2010) major lakes and rivers (RWDBII, CIA 2006), populated places (GRUMP, CIESIN, Columbia University, IFPRI, the World Bank, and CIAT, 2004).

It is interesting to note, however, that even with sea-level rise, it is unclear whether the delta will suffer a net loss in land area. Sediment loads are so high in the Ganges-Brahmaputra-Meghna delta that in recent years land has been steadily accreting (forming). The recent rough balance between erosion and accretion is presented in **Figure 66**.

Enduring Uncertainties Surrounding Climate Change in the Ganges

Precipitation projections are particularly unclear. Figure 67 presents basin precipitation predictions by the different Global Climate Models, all for the same (A2) climate scenario. Results diverge enormously, underscoring how difficult it is to draw conclusions about precipitation change in the basin.

Figure 66
Erosion and Accretion along the Bangladesh Coast



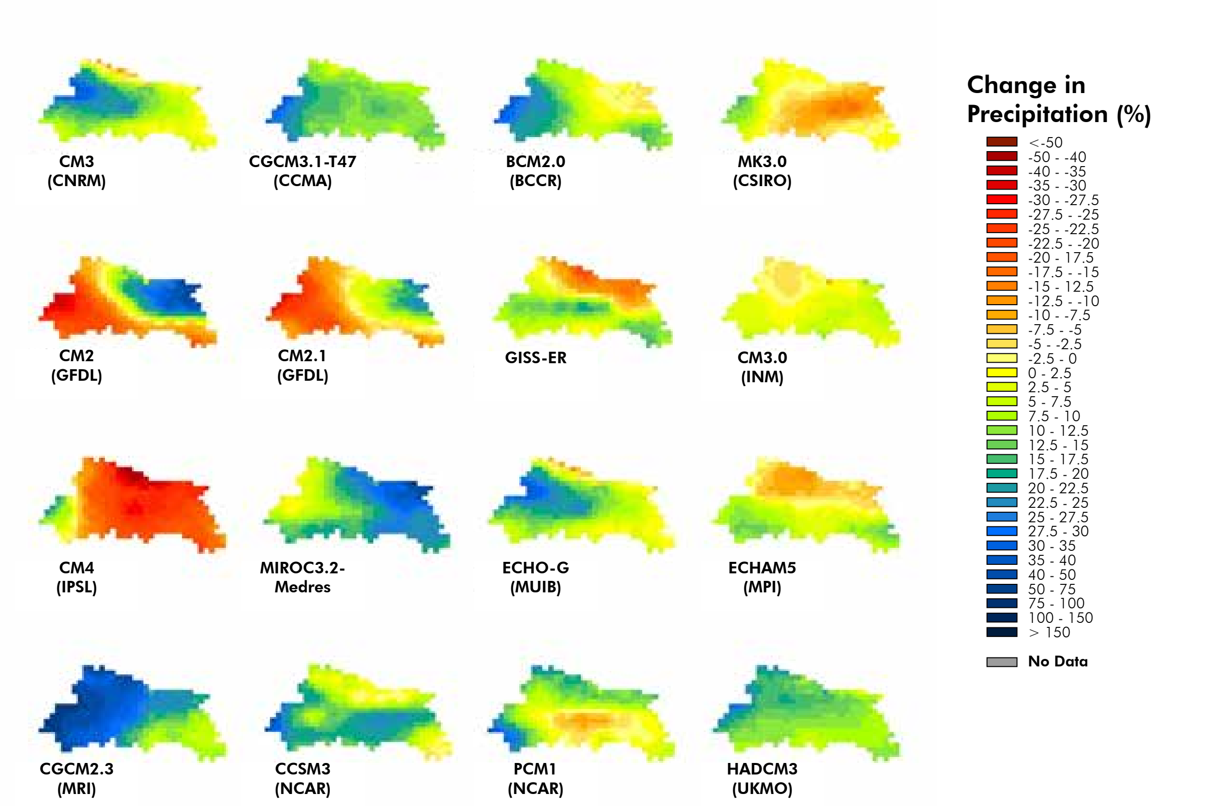
Source: European Space Agency (2010).

There is no consensus among climate models even as to the sign of the projected changes in rainfall for the Ganges Basin. Some of the scenarios indicate very high rainfall in the Himalaya (i.e., 80 percent increase in precipitation) whereas others indicate just the opposite (i.e., 80 percent decrease in precipitation). Such divergent, yet 'equally likely,' GCM scenarios make it difficult to justify any specific models as representative.

Runoff could change, but how? Changes in the spatial and temporal distribution of precipitation and temperature interact in complex ways to determine both 'green' water (the water used/lost in catchments before it reaches rivers) and 'blue' water (the runoff that reaches rivers). Green water tends to impact rainfed agriculture and rangeland livestock, whereas blue water affects the reliability of surface water systems for irrigation, hydropower,

Figure 67
Precipitation Projections for the Ganges Basin from 16 GCMs

Ganges - Differences between GCMs, in terms of Change in Precipitation, by the 2050s



This map shows the precipitation change projected by the considered climate model, under the A2 scenario for 2040 - 2069 as compared to 1961 - 1990. Map displays gridded data (cell size=0.5dd).

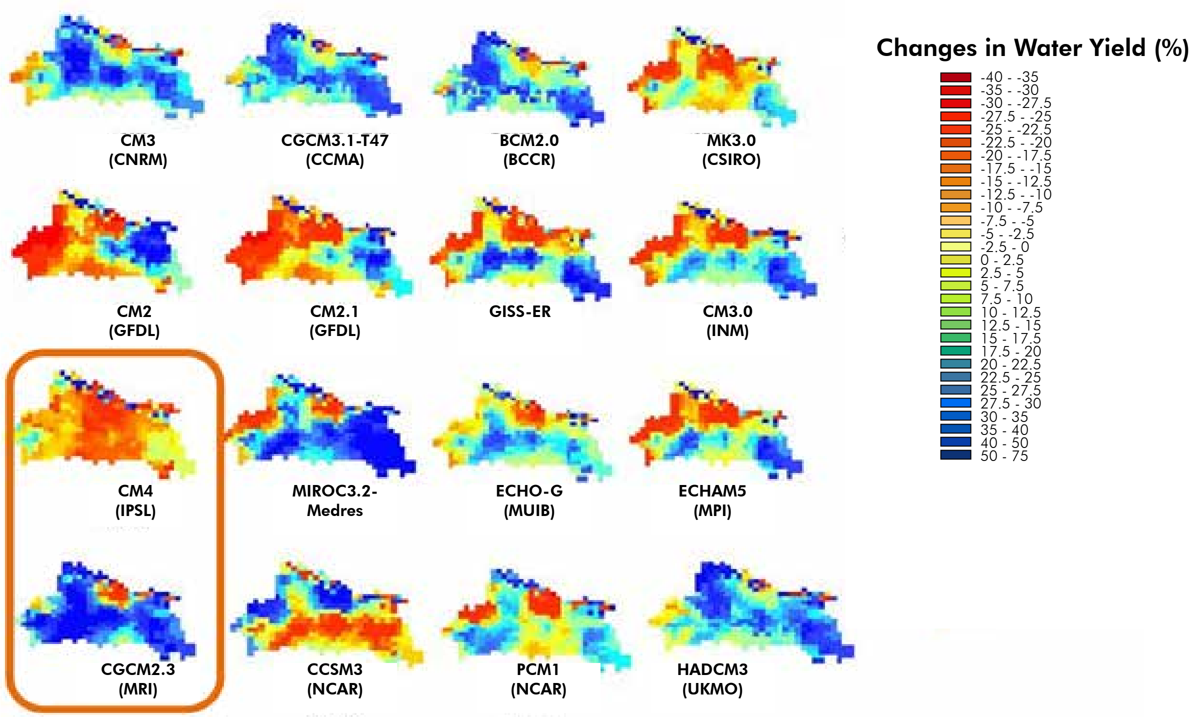
Source: WCRP's CMIP3 (Meehl et al. 2007), downscaled by Maurer et al. (2008).

Disclaimer: The boundaries, colors, denominations, and other information shown in any map do not imply any judgment on the part of the World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.
Note: Divergent results are highlighted (boxed) for illustrative purposes.

bulk water supply, and environmental flows. Runoff could change substantially (or not) in the basin – but the magnitude, or even direction, of the change is not easy to assess given the wide variations in precipitation changes. There is little agreement on the range of runoff predictions generated by the 16 GCMs under an A2 scenario **(Figure 68)**.

The changes in mean flows projected by the suite of GCMs represent average changes that are not outside the natural variability in the system. But it must be emphasized that these are changes in mean flows, and that the inter-annual variability around the range of projected mean changes could potentially create major new challenges for populations in the basin. When the temperature and precipitation outputs of the IPCC Global Circulation Models were fed into the SWAT model used in this study, we obtained a wide range of runoff scenarios on both sides of the current baseline, as shown in **Figure 69**: Predicted and Historical Monthly Runoff in the Ganges Basin. This broad variability points to the need for robust, flexible water management systems that can predict and respond to both wet and dry

Figure 68
Runoff Predictions for the Ganges Basin from 16 GCMs



This map shows the precipitation change in water yield (wy) by the considered wy of the GCMs model, under the A2 scenario for 2040 - 2069 as compared to the baseline 1961 - 2001. Map displays gridded data (cell size=0.5dd).

Sources: WCRP'S CMIP3 (Meehl et al., 2007), downscaled by the World Bank (2011)

Disclaimer: The boundaries, colors, denominations, and other information shown in any map do not imply any judgment on the part of the World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

Note: Divergent results are highlighted (boxed) for illustrative purposes.

extremes. As the climate models for this part of the world improve, there may be more convergence of results, but currently, the historical variability, the temperature signal, and the range of precipitation and runoff scenarios are all that is available to work with in improving climate risk management.

All this uncertainty leaves water planners in a difficult position as they must carefully weigh what information in the climate change domain they can reliably use, and what they cannot. In reality, water managers in the Ganges Basin are struggling to manage today's climate variability. It is difficult to adapt to the degree of hydrologic variability that already exists, let alone the additional variability that climate change could bring. **Focusing on the urgent requirement of managing today's variability, however, will strengthen the region's ability to cope with climate change in the future**.

Robust Recommendations in a Changing Climate

Policy decisions must be (and are being) made in the context of unresolved uncertainty. It is essential, therefore, to acknowledge these uncertainties and design recommendations that are generally robust to climate.

Do we know enough to act? Yes.

In the Ganges Basin the most critical uncertainty is hydrology, more specifically, predictions regarding the timing and volume of rainfall and runoff. Because these predictions are so varied across a range of credible models, it is impossible to define a 'most likely' future for which policies could be targeted. Moreover, even if water availability could be predicted, water demand is changing rapidly in the region due to both climate (i.e., increasing evapotranspiration) and non-climate drivers (i.e., broad population and economic growth, increasing nonagricultural water demands, increasing ecosystems values.) This means that a 'predict-then-act' framework for managing climate uncertainty, which is often considered the first best approach for incorporating climate change into adaptation and development planning, cannot and should not be followed.

Where credible predictions cannot be made, as this report finds to be the case in the Ganges Basin, the best option is to assess the sensitivities of policy choices and recommendations to the uncertain range of climate futures. That is the approach we adopt here.

The findings and recommendations of this report are therefore examined against extreme scenarios to determine whether there are potential 'tipping points' at which the recommendations might prove counterproductive maladaptations. Where great uncertainty exists, emphasis should be placed on flexible approaches that can accommodate adaptive management as more information becomes available, approaches that both perform well over a wide range of potential conditions, and those that deliver immediate benefits regardless of climate change.[96]

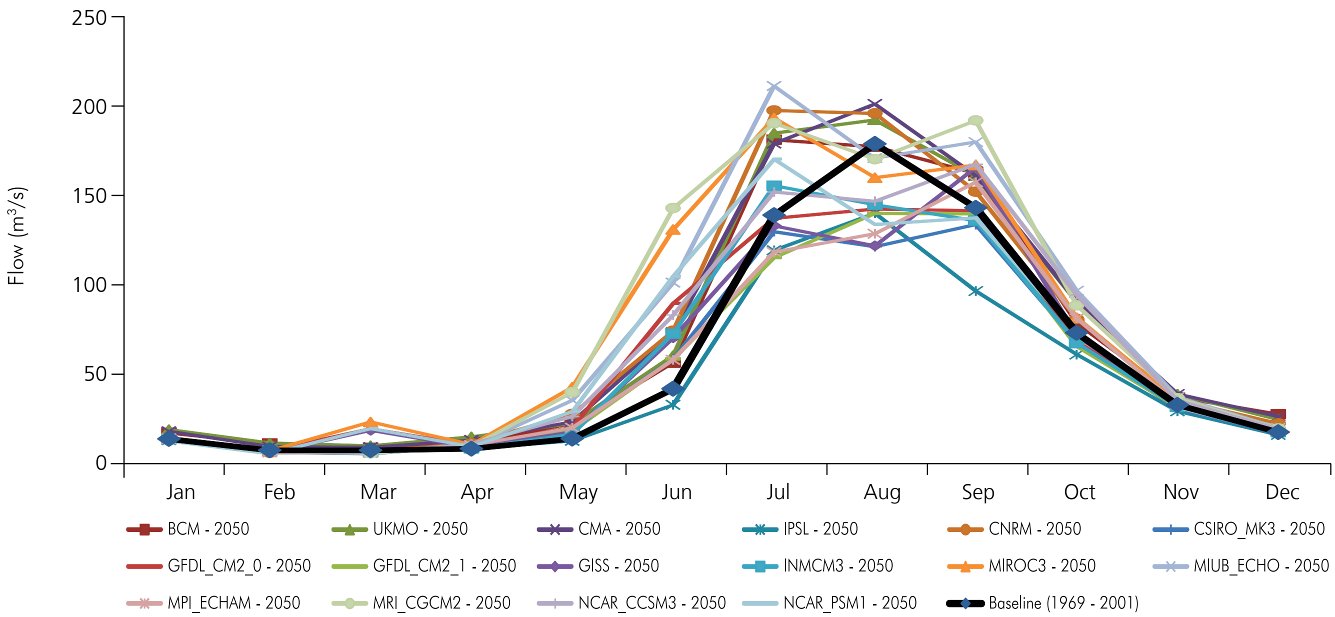
The recommendations of this study appear robust in all of these regards. Even the most extreme climate change scenarios are not anticipated to change the basic findings of this report.

A focus on large-scale infrastructure for flood control, and on surface water for irrigation, could prove susceptible to climate change. It is conceivable that there might be extreme hydrological changes that could diminish the usefulness of reservoirs for flood control, for example if they were consistently overtopped or unfilled. With regard to irrigation, extreme combinations of rainfall and

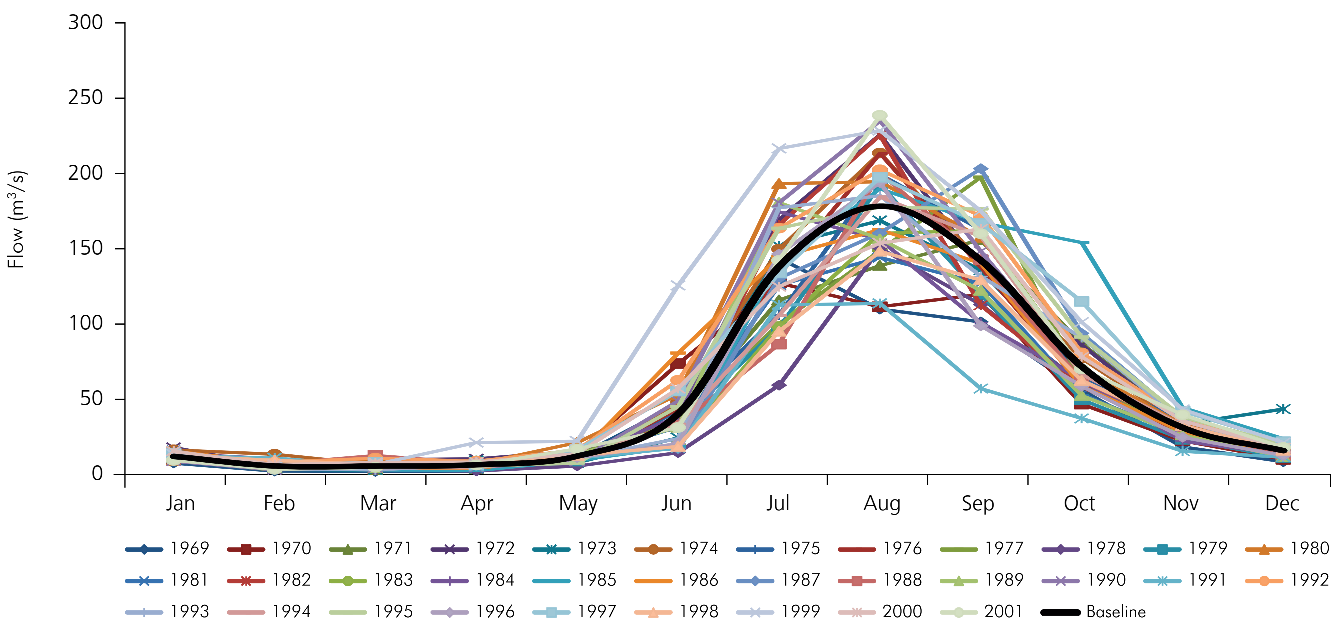
[96] Dessai and Wilby 2010–2011.

Figure 69
Predicted (a) and Historical (b) Flow Rates at Farakka on the Ganges

Predicted (a)



Historical (b)



Source: INRM (2011).
Note: Predictions of monthly mean runoff (flows) in 2050 are presented for the 16 UNFCCC GCMs, alongside the historical monthly average flows for the years 1969-2001. Measured at Farakka Barrage near the India-Bangladesh border.

temperatures (which drive evaporation and crop water needs) might undermine the function of surface-water irrigation schemes.

In contrast, the recommendations of this study are likely to become more valuable under greater climate extremes. With regard to flood management, for example, this study finds that storage capacities in the system are simply inadequate to make large-scale infrastructure-focused flood management a viable strategy on a basinwide scale. Changing hydrology cannot improve the small ratio of available storage to annual flow rates that limit water managers' capacity to hold back flood peaks. In fact, the evidence suggests that annual rainfall could increase, making storage capacities even less adequate for regulating flows.

The report suggests that a shift in focus toward enhanced forecast and warning systems in concert with a suite of tailored, localized responses is, therefore, urgently needed. Greater climate extremes, variability and uncertainty only strengthen the logic of this recommendation. Similarly, the need and potential for enhanced conjunctive use of surface and groundwater only becomes more compelling as temperatures and hence evaporation rates increase, and the timing of surface flows become even less predictable.

This report's recommendations also remain robust when considered in terms of their immediate benefits and flexibility looking forward. In the basin today, millions of people routinely suffer from flood, drought, and crop failure due to unpredictable rains. The Ganges is one of the most disaster-prone regions of the world, in addition to being one of the most vulnerable to changes in climate. A focus on strengthening capacities to manage current climate variability will deliver immediate benefits to people–especially the poor and vulnerable–throughout the Ganges Basin while strengthening the knowledge and institutions needed to manage future changes.

At the heart of this report's recommendations is a focus on information and institutions, in particular in regards to flood management and conjunctive use of water resources. Moreover an early investment in climate information will support future climate change research and model development. These types of interventions are far more flexible and adaptive than large-scale, long-lived infrastructure. The risk of maladaptation is therefore quite low.

Priorities for Future Climate Research

A great deal of research on climate change is underway and no doubt the people of the basin will benefit from this work. Of urgent importance to the basin, however, are some specific challenges:

- Climate to hydrology modeling of the South Asian Monsoon
- The significance of rainfall intensity in the basin
- Enhancement and sharing of the basic hydrometeorological data
- Greater understanding of glacier dynamics

5.

Findings, Implications, and Opportunities

Findings

This report highlights the complexity of the Ganges Basin and clearly indicates the need to revisit commonly held perceptions about the basin's resources and future development path. Storage in the Himalaya, long seen as the preferred strategy for managing the region's devastating floods, appears untenable as an exclusive basinwide solution.

Hydropower potential, on the other hand, remains as promising as ever – with the benefit-sharing calculus appearing much simpler because downstream benefits and tradeoffs among different water uses are smaller than previously assumed. Low flows can be meaningfully augmented by the development of upstream storage, but the immediate economic benefits are surprisingly unclear. Moreover, groundwater utilization could offer the same storage benefits much more rapidly and at lower cost (but not the hydropower generation associated with Himalayan storage).

Although climate change remains an area of great uncertainty, the basic findings of this report are robust to the range of anticipated futures. A strategy to cope with existing climate variability by investing in strengthened information and institutions at the regional level, along with a range of tailored interventions at the national and local levels, would be a no-regrets path that should enhance productivity and resilience in the Ganges Basin today and the capacity to manage climate change in the future.

Regional cooperation in information management

The Basin holds clear and immediate opportunities for regional cooperation in information management to enhance the productivity and sustainability of the river and, at the same time, safeguard lives and livelihoods. Systematic collection and exchange of appropriate, modern water, weather and climate data; cooperative efforts in advanced modeling, forecasting and communications, and warning systems; and a shared information base for basin planning will help the countries seize the basin's opportunities and manage its risks. The pieces are all in place. There is tremendous expertise in the region. Bangladesh boasts world-class water modeling institutions and cutting-edge flood warning systems. India's long experience in water engineering is now coupled with burgeoning satellite and information technologies sectors, essential for modern hydrometeorology. Nepal, with its wealth of water resources, sets an excellent global example for information sharing by making real-time hydrological data available online. Moreover, all three countries are involved in or planning significant investments in hydromet monitoring systems, systems that could be made interoperable for basinwide information management. Cooperation could take many forms, from a network of national institutions with an agreed information sharing protocol, to a dedicated multilateral institution that would gather, analyze and then disseminate crucial hydromet and climate data. A strengthened real-time regional hydromet information system (eventually in the public domain with open data infrastructure to facilitate its use) would provide the scientific information needed by planners to sustainably manage and develop the basin; by farmers to enhance productivity and food security; by disaster risk-management professionals to safeguard lives and assets; and by climate researchers to understand, predict and adapt to the changing – but also immediately challenging – climate in the Ganges Basin.

Hydropower development and trade

Immediate opportunities are also apparent for hydropower development and trade. There is significant untapped potential in the basin and a steadily growing demand for clean energy. Moreover the benefit-sharing calculus appears simpler than commonly believed for several reasons. First, the tradeoffs among different water uses are modest. Infrastructure would be designed and operated much the same way whether the goal was to maximize hydropower, or to maximize flood and irrigation benefits downstream. Negotiations over the design and operation of multipurpose infrastructure with transboundary impacts should, therefore, be tractable. Second, the current economic value of downstream irrigation benefits is surprisingly small in comparison to hydropower benefits, due to low agricultural productivity. At least in the near term, the direct economic benefits of these upstream reservoirs would derive overwhelmingly from hydropower. Co-benefits for agriculture should be amenable to transparent negotiations. Third, flood benefits (if any) are confined to tributaries. Upstream storage will have negligible basinwide flood impact. Benefit sharing with regard to flood protection could therefore be appropriately negotiated at the tributary scale (i.e., between two countries), rather than basinwide. Benefit sharing with regard to the enhancement of low flows for irrigation and ecosystems, conversely, remains an appropriate issue for basinwide discussions. Finally, the models developed in this report provide a new set of third-party tools that could be used to help quantify impacts and support information-based negotiations on hydropower development.

Enhancing low-flow season water availability

The basin also holds promising possibilities for enhancing low-season water availability. Low flows can be significantly augmented (potentially doubled in the dry months) as a co-benefit of developing multipurpose storage reservoirs upstream. But the development of upstream storage reservoirs is a costly undertaking, and this report suggests that storage investments would not be economically justifiable solely – or even significantly – on the grounds of their immediate contribution to enhancing agricultural productivity in the basin. In fact, there are large areas of seasonally waterlogged land whose productivity could potentially be diminished if more water were applied during the dry season, a time that usually allows for recovery. Upstream storage alone will not modernize agriculture in the Basin. A range of interventions are needed (and are underway in some areas) to enhance agricultural productivity and support the livelihoods of poor farmers, interventions anticipated to be effective regardless of the development of upstream storage.

Enhanced low-season flows may hold important potential to sustain ecosystem services, particularly in the fragile Sundarbans (mangrove forests) of the Ganges delta. Yet the ecosystem values of increased low-flows downstream—while possibly quite high—remain unsubstantiated. Even if upstream reservoirs were built and low-flows were raised, key areas like the Gorai in southwestern Bangladesh would not be restored without additional investments and institutional arrangements to dredge key intakes (investments like these might be adequate to restore the Gorai in the absence of upstream reservoirs.) A final important unknown is the value of augmented low flows in combating saline intrusion in the delta, and the importance of the Ganges freshwater plume for the dynamics of currents and storm patterns in the Bay of Bengal. More study of the morphology and ecosystems values in the Ganges delta is urgently needed.

A promising alternative to upstream water storage reservoirs is the potential to augment low-season flows by increasing groundwater use in conjunction with well-managed surface water schemes. In eastern Uttar Pradesh and Bihar, groundwater could produce effective storage (and hence augment dry-season water supplies) on a scale comparable to the Himalayan dams, but much more rapidly, at lower cost, and at the national or local scale. If upstream multipurpose dams are found to be economically, socially, and environmentally justified by the bundle of benefits they can produce (predominantly hydropower), additional dry-season water could prove to be an important co-benefit, perhaps as a complement to more immediate interventions in conjunctive use.

Flood management

Still the basin faces persistent challenges, particularly in managing floods. Large dams built to hold back flood waters high in the Himalaya have long been seen as the preferred strategy for managing the region's devastating floods. But as an exclusive strategy, it is untenable. The physical storage volume available in the mountains is simply too small to have a meaningful impact on basinwide floods. Flood management is needed, flood control is not possible. Effective flood management will call for regional information and warning systems, coupled with a range of hard and soft, national and local investments.

Finally, significant climate change uncertainties remain in the basin. Current data and models give little compelling evidence of what the future holds. It appears that mean hydrological variability in the future will be similar to the pronounced variability seen in the basin today, but extremes may well be greater and could potentially create major new challenges for populations in the basin.

Climate change

Greater climate extremes, however, would only strengthen the justification for the basic recommendations of this report. Investing in cooperative information management, modeling and forecasting systems at the regional level, along with a range of tailored interventions at the national and local levels, would enhance productivity and resilience in the Ganges Basin today, as well as the capacity to manage climate change in the future.

Implications and Immediate Opportunities

If many of the commonly held perceptions of the basin are incorrect, what are the real opportunities for sound, cooperative action?

Cooperative Basinwide Information Management

Implications: *Fragmented and inaccessible information can sustain broad misperceptions*

- The scale and complexity of the Ganges system, and the extremes of its landscape, require systematic study using modern data and modeling techniques.
- The development of this first basinwide model suggests that on several critical issues, broadly held perceptions are at odds with the evidence.

Opportunities: *A cooperative regional information system is needed*

- Systematic collection and exchange of appropriate, modern water, weather, and climate data; cooperative efforts in advanced modeling, forecasting, communications and warning systems; and a shared public-domain hydromet information management system are immediate opportunities.
- A strengthened basinwide knowledge base would provide the scientific information needed by planners to sustain and develop the basin; by farmers to enhance productivity and food security; by disaster professionals to safeguard lives and assets; and by climate researchers to understand, predict and adapt to the changing climate as well as the current challenging weather systems in the Ganges Basin.
- An inclusive river committee or commission could develop a shared knowledge base and operational model of the basin, establish norms and protocols for transparency and information sharing, and identify and pursue opportunities for cooperative development projects.

Hydropower Development and Trade

Implications: *Hydropower potential is significant, and should be simpler to negotiate than previously thought*

- Because downstream benefits and tradeoffs among water uses are currently smaller than assumed (due to low agricultural productivity and waterlogging) the benefit-sharing calculus should be simpler than previously thought.
- Over time, if agricultural productivity increases and ecosystem uses are better understood, the bundle of benefits that could be derived from multipurpose dam development could grow substantially.
- The challenges of managing social and ecological impacts, sediment loads, and seismic risks remain.

Opportunities: *Power development and trade are possible*

- Significant potential exists to deliver clean peak-load power and improve trade imbalances.
- Potential also exists for upstream storage-backed hydropower that could be fairly traded among the basin countries to the benefit of all.

Improve Water Delivery Through Groundwater Development

Implications: *Look for water storage underground, not just upstream*

- Groundwater storage in Uttar Pradesh alone could provide as much storage as upstream dams in Nepal.
- Groundwater storage is the quickest and probably the lowest-cost way to create system storage and improve water delivery efficiency.

Opportunities: *Make sustainable, strategic, conjunctive use of significant additional groundwater resources*

- Significant untapped groundwater resources exist in the central and lower reaches of the basin.
- Immediate opportunities exist to increase strategic use of groundwater, within an appropriate policy and energy-pricing environment in conjunction with a well-managed surface water system.
- In the Gaghra Gompti Basin (Uttar Pradesh), for example, 2.5 million new tubewells could be sustained.
- A conjunctive-use strategy could also help manage waterlogging in the basin, and enhance the reliability of water supplies to tail-end users in surface irrigation schemes and/or eastern downstream irrigators.

Flood Management

Implications: *Infrastructure alone is not the answer*

- Upstream storage infrastructure cannot protect the basin from flooding.
- Strategies must shift to flood management because flood control is not possible.
- Flood management calls for a range of 'hard' and 'soft' investments that might include:
  - Data Data collection, information management, and knowledge sharing
  - Warning and forecast systems, inundation and risk mapping
  - Asset management systems for embankment monitoring and maintenance
  - Disaster preparedness including safe havens and escape routes, designated inundation areas, insurance schemes, and land zoning
  - Re-engineering of drainage, housing, water supply and sanitation, etc.
  - Awareness and community mobilization campaigns.
- Institutions and networks will be needed to implement and sustain these efforts.

Opportunities: *Develop regional information; forecast and warning systems; and national/local flood management including:*

- A basinwide hydromet information system designed to collect and manage the information needed for protection (disasters) and productivity (agrometeorological) today, and climate change tomorrow.

- A basinwide forecasting capacity and disaster warning system that includes regional forecasts and a system to communicate warnings to national institutions for action.
- Regional platforms for information sharing, research, collaboration, and shared learning on flood management and climate adaptation in the Ganges Basin.
- National and local flood management measures, as above.

Key Issues for Future Research

This report begs many questions. Based on the evidence the study produced, and, importantly, on the evidence that could not be found or produced in this limited effort, several priority areas for additional information emerge.

Ecosystems values of water in the Ganges delta

Water is the lifeblood of ecosystems, nowhere more so than in delta ecosystems like the Sundarbans. Although the essential value of water to communities in the delta is apparent, there has been no systematic measurement of that value. The current evidence is not sufficient to provide a robust estimate of the ecosystems value of water at the scale required for this report. Moreover, the value that society places on ecosystems tends to rise with incomes, and this is a rapidly developing economic region. Given the importance and sensitivity of assigning a value to water in any ecosystem, particularly to an ecosystem as unique and fragile as the Sundarbans, the conclusion of this report is that those values remain to be substantiated. This is a very important gap in the literature.

Agricultural productivity in the Ganges plains

Agricultural productivity is an enduring challenge in the region, complicated by the dynamics of energy availability and pricing, market access and infrastructure, labor and land tenure issues, among other issues. Climate change will likely bring a new dimension to the challenges already facing agriculture. The issue of agricultural productivity is receiving attention from both committed researchers and policy makers, notably India's National Planning Commission. Efforts to enhance productivity, whether through focus on the augmentation of surface and groundwater supplies or the host of other challenges faced by farmers in the Ganges, are priorities both for farmers' livelihoods and for food security in this rapidly growing region.

Climate change in the basin and the region

Climate change is an area of priority research globally, but it is particularly pressing in the Ganges. Vulnerability of the basin, by virtually any measure, is extreme. At the same time, uncertainties are pronounced. Modeling efforts have been unsuccessful in predicting changes in the South Asian monsoon, and the range of microclimates in this basin – which runs from the summit of Mount Everest to the sea – further frustrates these efforts. The vast, dense, dynamic population of the basin, and its extreme vulnerability to climate change, give good reason for a sustained regional research effort. A cooperative regional effort in climate research could be particularly valuable.

Looking Forward

This report is intended to encourage research and debate on the fundamental strategic questions of the Ganges Basin. In doing so, it has challenged a number of commonly held perceptions and concluded that many are ill-founded. It is hoped that this new knowledge will help policy makers and water resources professionals explore new visions for the basin, and that the basin countries will move forward in a cooperative manner to sustainably manage this extraordinary resource.

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Notes

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Established in 2009, the South Asia Water Initiative (SAWI) aims to *increase regional cooperation in the management of the major Himalayan river systems in South Asia to deliver sustainable, fair and inclusive development and climate resilience.* It is designed to support countries improve and deepen transboundary dialogue, enhance the basin and water resources knowledge base, strengthen water institutions, and support investments that lead to reducing extreme poverty and promoting shared economic development. SAWI is a multi-donor trust fund managed by the World Bank on behalf of the governments of United Kingdom, Australia and Norway and supports activities related to the management of the Greater Himalayas transboundary water systems in Afghanistan, Bangladesh, Bhutan, China, India, Nepal and Pakistan. SAWI's program is built around the theme of knowledge, dialogue, cooperation; the region's three shared river basins – the Brahmaputra, Ganges and Indus rivers; and the Sundarbans landscape.

SAWI South Asia Water Initiative

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