WATER GLOBAL PRACTICE

High and Dry

Climate Change, Water, and the Economy

WORLD BANK GROUP

Water Global Practice

High and Dry

Climate Change, Water, and the Economy

WORLD BANK GROUP

1818 H Street NW, Washington, DC 20433
Telephone: 202-473-1000; Internet: www.worldbank.org

1 2 3 4 19 18 17 16

Cover photo: View of lakes, hillsides, and mountaintops. © Curt Carnemark/World Bank. Permission required for reuse.
Cover design: Bill Pragluski, Critical Stages, LLC.

Contents

Boxes

Figures

Maps

Acknowledgments

This report was prepared by a World Bank team led by Richard Damania and comprising Morgan Bazilian, Stephane Dahan, Stephane Hallegatte, Irina Klytchnikova, Scott Moore, Lia Nitake, Diego Rodriguez, Jason Russ, and William Young. The report has benefited greatly from the strategic guidance and general direction of the management of the Water Practice, Marianne Fay (Chief Economist, World Bank), and the advice of Laura Tuck (Vice President, Sustainable Development Practice Group, World Bank).

The report draws on background papers and notes prepared by the following: Global Change Assessment Model modeling and analysis was provided by a team comprising Leon Clarke (Joint Global Change Research Institute, Pacific Northwest National Laboratory, and University of Maryland), Kelly Gustafson (Department of Geographical Sciences, University of Maryland), Mohamad Hejazi (Joint Global Change Research Institute, Pacific Northwest National Laboratory, and University of Maryland), Sonny Kim (Joint Global Change Research Institute, Pacific Northwest National Laboratory, and University of Maryland), Fernando Miralles-Wilhelm (Earth System Science Interdisciplinary Center, University of Maryland) and Raul Muñoz-Castillo (Department of Geographical Sciences, University of Maryland); Computable General Equilibrium modeling and analysis was undertaken by Roberto Roson (Ca'Foscari University/Bocconi University). A survey on the economics of water and climate change was undertaken by Anil Markandya (Basque Centre for Climate Change). A survey of urban water management and climate change was provided by Bernard Barraqué (Centre International de Recherche sur l'Environnement et le Développement) and Bruno Tassin (Ecole Nationale des Ponts et Chaussées). Research on urban water management and climate change was undertaken by Meleesa Naughton (World Bank). Christina Leb and Marcus Wijnen from the World Bank provided expert advice and inputs.

The support and guidance of Junaid Ahmad (Chief of Staff and former Senior Director of the Water Global Practice) is gratefully acknowledged. Incisive and helpful advice and comments were received from Marianne Fay (Chief Economist, World Bank), Carter Brandon (Lead Economist, World Bank), Malcolm Cosgrove-Davies (Lead Energy Specialist, World Bank), Nathan Lee Engle (Climate Change Specialist, World Bank), Rafik Fatehali Hirji (Senior Water Resource Specialist, World Bank), Sanjay Pahuja (Lead Water Resources Specialist), Glenn Pearce-Oroz (Principle Regional Team Leader, World Bank), Claudia Sadoff (Lead Water Economist, World Bank), Vijay Jagannathan (World Resources Institute), Betsy Otto (World Resources Institute), Marc Sadler (Adviser, World Bank), Dominic Waughray (World Economic Forum), and Louise Whiting (WaterAid).

This work was made possible by the financial contribution of the Water Partnership Program (WPP), http://water.worldbank.org/wpp.

Executive Summary

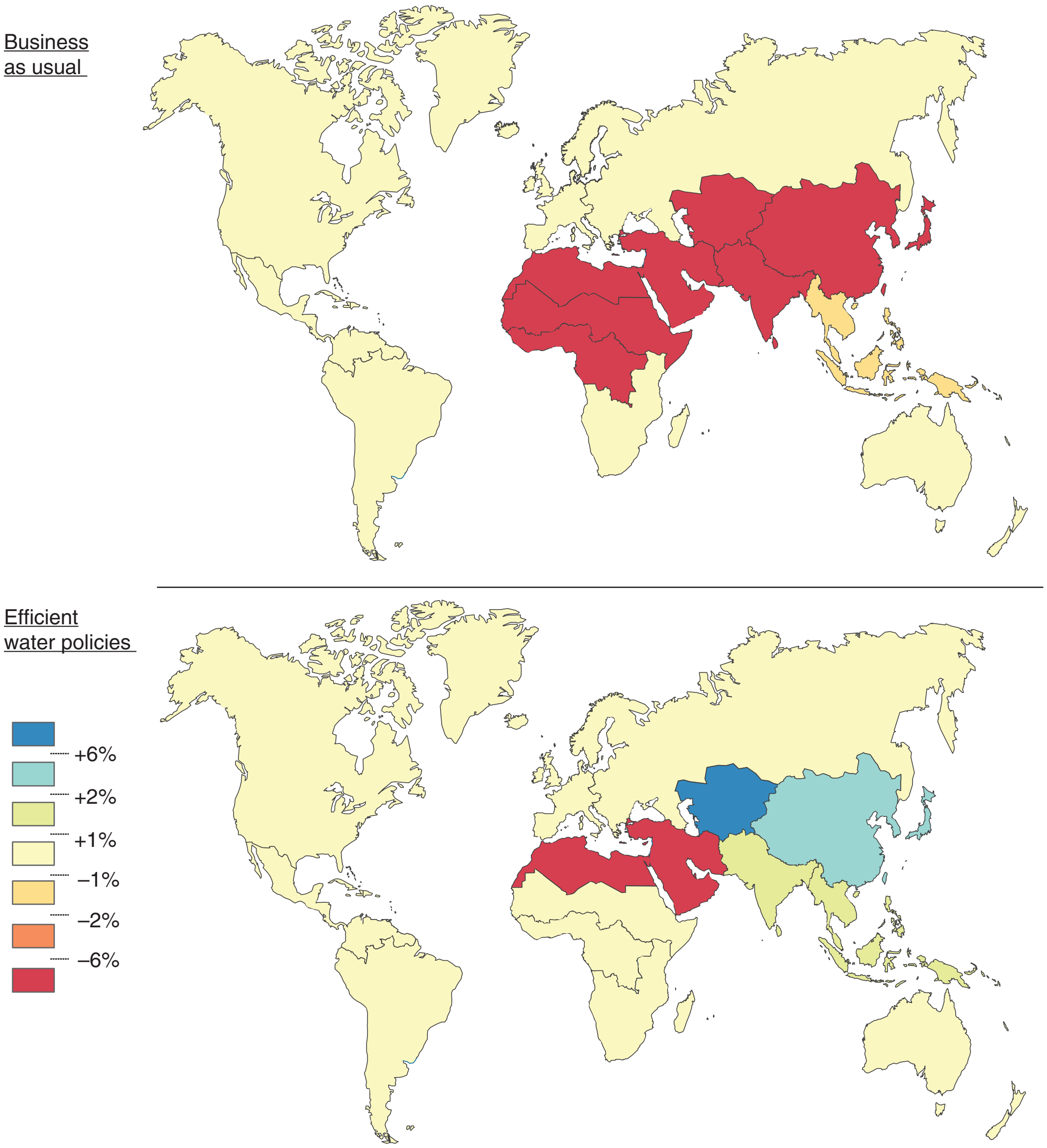
The impacts of climate change will be channeled primarily through the water cycle, with consequences that could be large and uneven across the globe. Water-related climate risks cascade through food, energy, urban, and environmental systems. Growing populations, rising incomes, and expanding cities will converge upon a world where the demand for water rises exponentially, while supply becomes more erratic and uncertain. If current water management policies persist, and climate models prove correct, water scarcity will proliferate to regions where it currently does not exist, and will greatly worsen in regions where water is already scarce. Simultaneously, rainfall is projected to become more variable and less predictable, while warmer seas will fuel more violent floods and storm surges. Climate change will increase water-related shocks on top of already demanding trends in water use. Reduced freshwater availability and competition from other uses—such as energy and agriculture—could reduce water availability in cities by as much as two thirds by 2050, compared to 2015 levels.

Economic growth is a surprisingly thirsty business. Water is a vital factor of production, so diminishing water supplies can translate into slower growth that cloud economic prospects. Some regions could see their growth rates decline by as much as 6 percent of GDP by 2050 as a result of water-related losses in agriculture, health, income, and property—sending them into sustained negative growth. Economic modeling described in this report suggests that bad water-management policies can exacerbate the adverse growth impacts of climate change, while good policies can go a long way towards neutralizing them (map ES.1). Some regions stand to see growth accelerate as much as 6 percent with better water resource management. The impacts of water mismanagement are felt disproportionately by the poor, who are more likely to rely on rain-fed agriculture to feed their families, live on the most marginal lands which are more prone to floods, and are most at risk from contaminated water and inadequate sanitation. Ensuring a sufficient and constant supply of water under increasing scarcity will be essential to achieving global poverty alleviation goals.

Changes in water availability and variability can induce migration and ignite civil conflict. Food price spikes caused by droughts can inflame latent conflicts and drive migration. Where economic growth is impacted by rainfall, episodes of droughts and floods have generated waves of migration and statistical spikes in violence within countries. In a globalized and connected world, such problems are impossible to quarantine. And where large inequities prevail, people move from zones of poverty to regions of prosperity which can lead to increased social tensions.

This is why water management will be crucial in determining whether the world achieves the Sustainable Development Goals (SDGs) and aspirations for reducing poverty and enhancing shared prosperity. Water is the common currency which links nearly every SDG, and it will be a critical

MAP ES.1 **The Estimated Effects of Water Scarcity on GDP in Year 2050, under Two Policy Regimes**



Source: World Bank calculations.
Note: The top map shows the estimated change in 2050 GDP due to water scarcity, under a business-as-usual policy regime. The bottom map shows the same estimate, under a policy regime that incentivizes more efficient allocation and use of water.

determinant of success. Abundant water supplies are vital for the production of food and will be essential to attaining SDG 2 on food security; clean and safe drinking water and sanitation systems are necessary for health as called for in SDGs 3 and 6; and water is needed for powering industries and creating the new jobs identified in SDGs 7 and 8. None of this is achievable without adequate and safe water to nourish the planet's life-sustaining ecosystem services identified in SDGs 13, 14 and 15.

Water is to adaptation what energy is to mitigation, and the challenges the world will face in adapting to water issues are enormous. It calls for recognizing the interlinkages between water for food, energy, cities, and the environment through an "*expanded water nexus*," which acknowledges that the fortunes of these sectors are tied through a common dependence on water. The costs of policy inaction are high, and prudent stewardship of water resources will pay large dividends. Although significant challenges exist, the right actions need not be costly. Thoughtful policies and well-placed investments can yield large benefits in improved welfare and increased economic growth.

There are three overarching policy priorities that can help lead countries down the road to a water secure and climate resilient economy. None of these will be a panacea, however, just as there is no one-size-fits-all solution. In practice, hybrid solutions will be needed, determined by country and regional risks and circumstances.

- **Optimizing the use of water through better planning and incentives**. Building climate-resilient economies that can develop and grow in a warming world will require better ways of *allocating scarce water resources across sectors* to higher-value uses. This could be achieved through planning and regulation, or using market signals through instruments such as prices and permits. In both cases there would need to be adequate safeguards to assure access to poor households and farmers as well as the environment. None of this will be easy. It will call for establishing credible institutions, policies and legal systems that can facilitate transfers of water in ways that benefit all parties to the transaction. Economic instruments such as water permits and prices can be valuable for promoting improved environmental stewardship of water resources, but they are also the most misunderstood due to anxieties of elite capture, denial of services to the poor, and the complex social and cultural values of water. Much depends upon how such policies are implemented and enforced. In countries where water is deemed to be free, the poor are unserved or under-served and are compelled to pay a much higher price than the rich for each drop of water. As a consequence, free water is typically costly for the poor as well as harmful to the environment.

  Water *efficiency must also increase within sectors*. This calls for the creation and adoption of new water saving technologies, incentives, education, and awareness. Approaches are already available, such as Climate Smart Agriculture (CSA) or Sustainable Agricultural Intensification (SAI), that allow farms to maintain or even increase yields, while reducing their energy and water footprint. Similar approaches exist for significant water savings in the energy sector through improved efficiency. However, the adoption of these solutions is slow, hesitant, and below desired levels. The constraints most often lie in misaligned incentives. For instance, a large proportion of the benefits of approaches such as CSA are public, while technology adoption costs are private. This requires sharper incentives for technology uptake that might require a change in the subsidy regime, public investments in infrastructure or extension services, selective forms of crop insurance, and increasing access to credit. There are opportunities to alter behavior and change thirsty consumption patterns through education, contextual cues, and using social norms to signal consent or disapproval. The tools based on these behavioral nudges do not displace existing policy approaches that target incentives; rather, they complement and enhance them. Some of these approaches may cost little to implement because they depend on nuances in messaging and policy design, while others may entail longer periods of engagement, especially when changes in attitudes and values are involved.

- **Where appropriate, expand water supply and availability.** This includes investments in storage infrastructure such as dams that makes water available when it is needed; water recycling and reuse; and where viable, desalination. While expanding the water supply will be vital in some countries, particularly the driest regions, these tools must be used with caution. Other tools like groundwater recharge and wetlands preservation may offer lower risk, lower costs, and higher returns than other policy approaches. Historically, when supply is increased without corresponding safeguards to manage use, demand rises to meet the new level of supply, resulting in a higher level of water dependence in often arid areas. To be effective, these interventions must be accompanied by policies to promote water efficiency and improve water allocation across sectors.
- **Reducing the impact of extremes, variability, and uncertainty.** A final set of interventions require "*water proofing*" economies to limit the impact of extreme weather events and rainfall variability. Increasing storage capacities and water reuse systems will go a long way towards building resilience. Better urban planning, risk management, and citizen engagement will likewise reduce the exposure of cities to flood risk. In rural areas, expanding crop insurance programs can protect farmers against rainfall shocks. Large capital investments such as seawalls, levees, and dams, meanwhile, can protect coastal cities from storm surges and floods. As the precise impacts of climate change are uncertain and large investments are costly and irreversible, their siting and design must be carefully chosen to minimize regret.

Smart water policy is fundamental to smart climate policy and smart development policy. While adopting policy reforms and investments will be demanding, the costs of inaction are far higher. The future will be thirsty and uncertain, but with the right reforms, governments can help ensure that people and ecosystems are not left vulnerable to the consequences of a world subject to more severe water-related shocks and adverse rainfall trends.

Chapter 1

Shocks and Trends: Uncertain Water Supplies Meet Unquenchable Thirsts

Water is on the frontlines of climate change. It channels the main impacts of climate change to all aspects of the economy, society, and environment—through precipitation, storm surges, floods, droughts, rising seas, and groundwater recharges. Harnessing the productive potential of water and limiting its destructive impacts are important even in the most advanced economies. Doing so requires coming to grips both with shocks—water-related extreme weather events like severe droughts and floods—as well as trends that will change rainfall patterns and increase the demand for water.

About 1.6 billion people—almost a quarter of humanity—live in countries with physical water scarcity, and in just two decades this number may double. Some regions of the world already suffer from significant water scarcity and excessive variability. Climate change will only magnify the challenges of managing such a complex natural resource. Indeed, in a recent survey of almost 900 leading decision-makers from business, academia, and the public sector, the World Economic Forum identified water crises and failures to adapt to climate change as two of the greatest global risks to economic growth and social stability.[1]

The world will face significant challenges adapting to a future where demand for water is ever increasing, but supply remains fixed and more variable. Addressing these problems will be critical in achieving the new and ambitious Sustainable Development Goals (SDGs) adopted by the United Nations in 2015. SDG Goal 6 relates to water, and includes targets for improving access to sanitation, reducing water pollution, improving water use efficiency, and making water use more sustainable. Water with its cascading impacts across the economy will impact the achievement of other SDGs too; such as those relating to food security, cleaner energy; sustainable cities; climate action and the protection of ecosystems. The vision articulated in the SDGs is high on ambition and will call for a fundamental shift in the way water is managed, far beyond business-as-usual remedies. It will require greater coordination between sectors that are impacted by a nexus that emerges through the use of water as the common factor of production.

The purpose of this report is to document the drivers of the changing patterns in supply and demand for water in a climate change impacted world, and to offer solutions which ensure that water does not become a constraint on prosperity. In order to do this, the report takes a holistic view of water needs, recognizing that expanding water uses in one sector often involves trade-offs with other sectors. These inter-relationships are represented by what is referred to as "the expanded water nexus" which includes the major water consumers of the planet: food production, urban areas, energy production, and the environment. The rest of this chapter will examine the physical impacts that climate change will have on the planet's water supply, and introduce the expanded water nexus. Chapter 2 then investigates the macroeconomic impacts that this changing water supply will have, as well as implications for poverty reduction. Chapter 3 dives deep into each of the four sectors of the nexus, describing the constraints that they will face, and offering solutions. The report ends with policy conclusions.

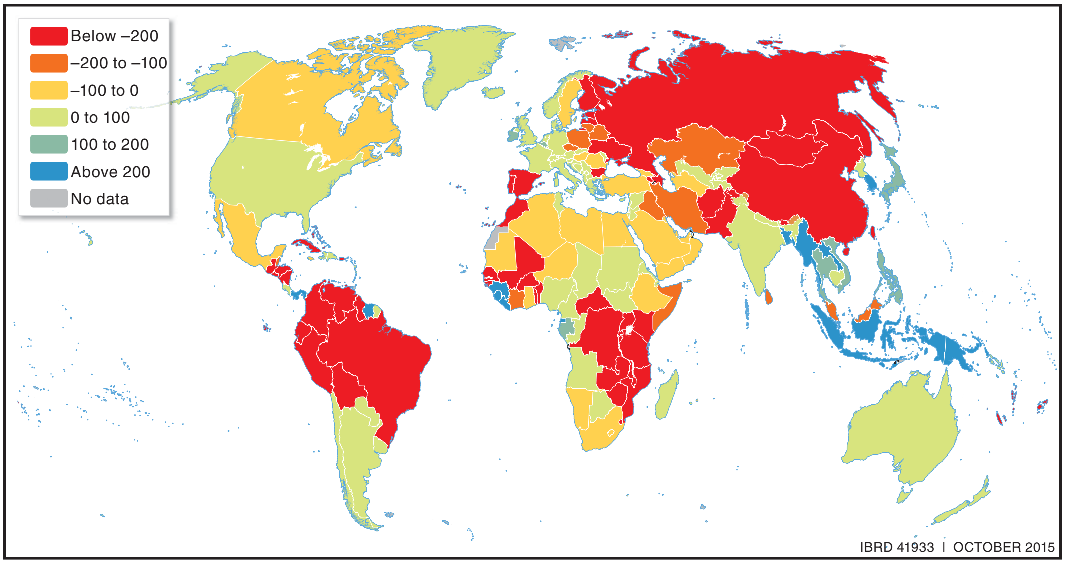
Droughts, Storms, Floods, and Changing Water Supplies

The consequences of climate change for the hydrological cycle could be strikingly uneven across time and space. The projections used in this report come from models that track 235 river basins and span the range of uncertainty—wet, dry, and normal.[2] The results are consistent with several other global climate models and do not significantly change across emission scenarios.

Uneven Impacts across Time and Space

On a global scale, the total volume of runoff will be relatively stable, suggesting that the amount of surface water globally remains fairly fixed throughout the next decades—a consequence of the global water cycle being a closed

MAP 1.1 The Spatial Distribution in Runoff Will Become More Uneven to 2050



Source: See World Bank (2015a) for other projections.

dynamic system.[3] But while changes in runoff will vary significantly across regions, and are subject to significant uncertainty, the spatial distribution of runoff will become more uneven across the globe (map 1.1). Many regions already experiencing water stress will experience even more scarcity, including much of the Middle East and North Africa, Central Asia, and Central America, all of which exhibit a consistent trend toward diminishing runoff. Other parts of Africa present a larger variation in runoff, with East Africa showing a significant decline by 2050, while southern latitudes do not exhibit significant changes until the second half of the century.

The declines in runoff matter most in areas with low baseline runoff and water availability. For instance, a 100 mm reduction in runoff is of less consequence when average rainfall is 3,000 mm a year, as in Colombia, than when it is about 300 mm a year, as in Chad.

No major variations in runoff are projected through parts of North America, the northern parts of Western Europe, and East Asia (excluding China). Notably, much of the decline in runoff is projected in the least developed countries, where access to water is most crucial for agriculture and energy.

Temperature changes are especially important in snow-dominated regions, determining the timing of snowmelt and the seasonality of water availability. Glaciers are expected to shrink and will store less water for release during warm periods, making water supplies less dependable. The effects on snow-fed rivers has been widely documented and publicized.

More Frequent Natural Disasters

Variable precipitation and extreme events are among the more disconcerting aspects of the climate challenge. The toll of water-related extreme events and natural disasters is high and growing in both frequency

BOX 1.1 Regional Risks of Climate Change[4]

Sub-Saharan Africa: low institutional capacity and high dependency on subsistence agriculture makes this one of the most vulnerable regions. Rainfed agriculture contributes nearly one-quarter of GDP and employs about 70 percent of the population.

East Asia and the Pacific: large concentrations of populations on coastlines and a large number of small islands leave this region one of the most exposed to water-related climate shocks.

Eastern Europe and Central Asia: poorly-designed infrastructure leaves this region ill-equipped to handle increasing flood risks, desertification, and changes in the flow of major rivers.

Latin America and the Caribbean: warming will dramatically affect ecosystems in the LAC region, especially the Amazon rainforest, threatening the livelihoods of those who depend on ecosystem services.

Middle East and North Africa: already the world's driest region, MENA will experience lower water availability and higher temperatures. The dependence on water intensive modes of employment such as irrigated agriculture are a concern in the context of further drying and increasing water demands.

South Asia: the large contribution of irrigated agriculture to food production and rural economies leaves this region highly vulnerable to predicted changes in the runoff of major rivers

Source: World Bank 2010b.

and intensity (box 1.1).[5] With warmer surface temperatures, seas fuel more violent storms, increasing the risks of floods and droughts. Severe storms, such as tropical and extra-tropical cyclones, can generate storm surges over coastal seas and extreme rainfall over land. The frequency of future tropical cyclones remains uncertain, but most models project higher precipitation rates and wind speeds.[6]

Flood hazards are projected to increase in more than half the world's regions, although this varies greatly for individual river basins. Disaster hotspots are magnified by the growth of coastal cities, where vulnerability to floods is high. While there is agreement across models on the broad regional and global trends, there is uncertainty about impacts at smaller spatial scales. Some models predict increasing flood hazards in parts of South Asia, Southeast Asia, East Africa, Central and West Africa, Northeast Eurasia, and South America.[7] In contrast, floods are projected to be less frequent in parts of Northern and Eastern Europe, Anatolia, Central Asia, Central North America, and Southern South America.[8,9]

Impacts on Groundwater

The planet's aquifers are a vast natural reservoir, containing about 30 percent of the available freshwater.[10] Groundwater storage provides a natural buffer against climate variability; it is thus vital not only for the economy but for a country's sustainability.

Climate change is expected to affect groundwater reservoirs, directly through changes in recharge patterns, and indirectly through increased demand, especially from irrigation, which today takes 70 percent of global groundwater withdrawals.[11] Groundwater recharge varies considerably, depending on prevailing climatic conditions. In general, in regions where total runoff is expected to decline (map 1.1), groundwater resources will also decrease.[12] Similarly, reduced surface water flows in regions that suffer from changes in snowmelt may be exacerbated by falling groundwater levels due to a shorter recharge season.

Climate change also brings risks to the quality of water in aquifers. Regions with higher temperatures may suffer from greater groundwater salinity as more water evaporates before it can reach deeper levels. Rising sea levels push seawater inland, and coastal aquifers shrink as rising demand drops groundwater tables. Although difficult to quantify, these trends suggest that coastal groundwater reservoirs will be under the most pressure in regions with declining runoff, where they will be needed the most.

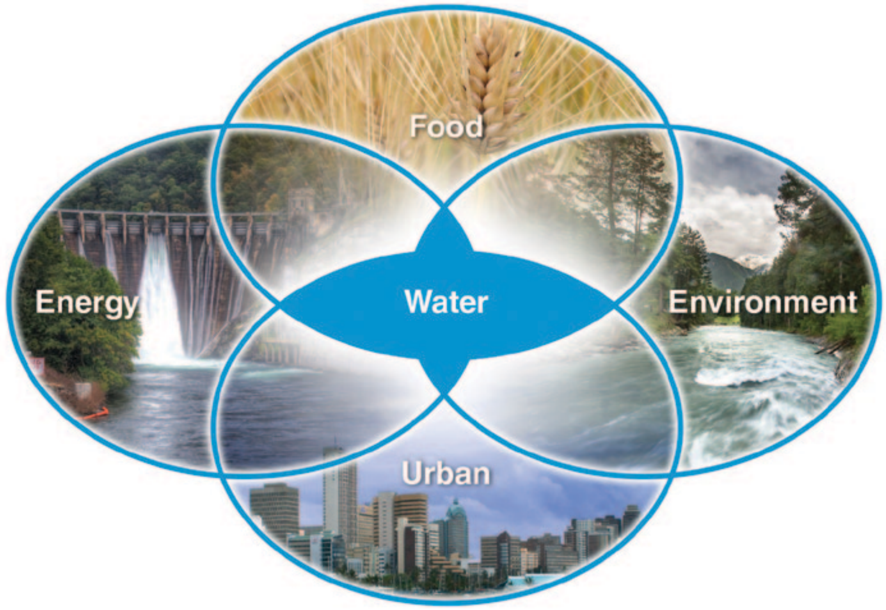
The increased variability that comes with climate change will inevitably raise reliance on underground freshwater supplies. If protected and managed along with surface water, groundwater can do much in adapting to climate change. Its widespread availability and typically large volumes—and thus long retention time and slow response—make it more naturally buffered against seasonal and inter-year variations in rainfall and temperature. Unlike surface storage, aquifers lose negligible amounts of water through evaporation and transpiration.

The Drivers of Demand: The Nexus of Farms, Cities, Energy, and the Environment

The coming decades will see a convergence of growing populations, rising incomes, and a changing climate. Demand for water will increase throughout all sectors of the economy, while, at the same time, water supplies will become more variable and less predictable. Indeed estimates suggest that within the next 3 decades, the global food system will require between 40 to 50 percent more water; municipal and industrial water demand will increase by 50 to 70 percent;[13] the energy sector will see water demand increase by 85 percent; and the environment, already the residual claimant, may receive even less.

The *expanded water nexus* is a way of conceptualizing and promoting more effective risk management and cross-sectoral climate policy to ensure water is utilized most efficiently (figure 1.1). The concept of studying the inter-linkages between water, climate, and economic sectors is not a new one. Indeed, the scientific community has been studying the "Nexus of Food-Energy and Water Systems" for nearly a decade.[14] This report takes a more expansive view, by extending the nexus to two other critical and integrated sectors- the urban sector, and the environment.

FIGURE 1.1 **The Water-Climate Nexus**



Dividing the Same Water between More Straws

The weight of evidence suggests that the problem of water allocation will become increasingly acute for governments across the globe. These growing pressures stem both from the direct effects of climate change as well as population growth and economic development that increase competition for a limited resource. Overall, barring significant increases in water efficiency (especially in agriculture), the world may face a shortfall in water availability of approximately 2,700 billion cubic meters by 2030, with demand exceeding current sustainable water supplies by 40 percent.[15]

In many regions, the gap between water demand and availability will exacerbate already severe stresses on water resources. Large portions of the world (virtually the whole of South Asia, the Middle East, and North Africa), exist in a state of near-permanent water stress, in which net withdrawals of surface and groundwater meet or exceed the available supply, meaning that no additional water is available for ecosystem use, or to meet future demand.[16] About 4 billion people—60 percent of the world's population—reside in these basins. Such stresses are clearly unsustainable and in the long run would threaten the integrity and productivity of aquatic ecosystems. At the same time there is much wastage in the system. Some cities, even in arid areas, lose more water through leaking pipes than they deliver to households.[17]

The challenge of managing water resources under climate induced stresses is therefore one of reconciling the mismatch between escalating demands for water and a finite and more spatially and temporally variable supply of water in ways that do not degrade the natural resource base upon which human and ecological systems depend. The remainder of this report is focused upon this fundamental issue.

An Uncertain Future

There is considerable uncertainty about long-term climate projections. Global circulation models have not been designed to project changes in the hydrological cycle, which is treated as just one element of a larger climate system. And this imprecision is compounded when models are extended to finer spatial scales. Forecasts and projections of extreme events are even more challenging, reflecting the statistical complexities of projecting extreme events and the limitations of the data.

Even so, there is broad agreement on the overall global trends across models. The primary challenge for decision makers is to plan for a more uncertain and hazardous future, where general trends are known with greater certainty than the precise nature and timing of the changes. Such circumstances put a high premium on adaptable and flexible approaches that can respond to new information and changing circumstances (box 1.2).

BOX 1.2 Decision-Making under Uncertainty

Uncertainty is intrinsic to climate change: there is ample evidence that the climate is changing but less confidence on precisely how fast or in what ways. Nor is there a full understanding of the social and economic consequences of these changes. Furthermore, the uncertainty about these issues is not always easily quantifiable in probabilistic terms: climate change brings *deep uncertainty* rather than *known risks*.

Despite these challenges, a number of methods have evolved to assist in decision-making under uncertainty. Uncertainty places a high premium on options that minimize regret across a range of possible outcomes. The robust decision-making process is one such approach. Applications begin with an existing or proposed project plan, explore vulnerabilities and sensitivities, and rank options for their sensitivity to changing conditions. Another is a decision-tree approach that uses judgments and sensitivity analysis to guide the process through various "decision nodes." It begins by assessing the relative performance and vulnerabilities of alternatives, using that information to describe scenarios, and then applying the information to answer specific questions arising during the decision-making process.

Other common approaches include "no-regret" measures that yield benefits even if forecasts are proven to be wrong. For example, controlling leakages in water pipes is a sound policy, regardless of how the climate changes. Another approach emphasizes reversible and flexible strategies. It is prudent to keep options open when the future is unknown. Urban planning falls into this category. A plan can adapt with the arrival of new information on risks. The option value technique is one variant that provides a more formal and rigorous way of assuring greater flexibility in decision-making.

In general, there is no universally accepted general methodology for assessing the significance of climate risks, and choices are often guided by pragmatism, available resources and information.

Notes

1. World Economic Forum 2015.
2. The Global Change Assessment Model (GCAM) is used as a tool that can track results from multiple GCMs. See World Bank 2015a for details.
3. Runoff is that part of the water cycle that flows over land as surface water instead of being absorbed into groundwater or evaporating. The flow is usually attributable to rainfall or snowmelt.
4. World Bank 2010b.
5. Arndt et al. 2010.
6. Intergovernmental Panel on Climate Change (IPCC) 2012.
7. Jiménez et al. 2014.
8. World Bank 2015a.
9. Jiménez Cisneros, Oki, Arnell, et al. 2014.
10. World Water Assessment Programme (WWAP) 2006.
11. WWAP 2012.
12. Jiménez Cisneros, Oki, Arnell, et al. 2014.
13. 2030 Water Resources Group 2009.
14. With support from the National Science Foundation, which has committed nearly $75 million toward investments in Innovations at the Nexus of Food, Energy, and Water Systems in FY2016. https://www.nsf.gov/about/budget/fy2016/pdf/37_fy2016.pdf
15. 2030 Water Resources Group 2009.
16. Mekonnen and Hoekstra 2016.
17. Kingdom Liemberger and Marin 2006.

Planting rice.

Chapter 2

A Brake on Prosperity and Progress?

Growing Populations, Growing Economies, and Growing Water Needs

In 50 years there may be two billion more people on this planet, and the world's population may exceed nine billion. And as countries grow more prosperous, their thirst for water rises. In many basins, especially in arid parts of the world, water is already over-allocated for much of the year and the basins are effectively closed to new users. Even where large water-storage facilities have been built, demand is so great that storage seldom reaches the desired capacity. Climate change is set to compound such challenges, intensifying extremes and accentuating scarcity when runoff declines. So it is no surprise that there are growing concerns about water's availability in the future.

The problem is not the adequacy of available water—it is the distribution and stewardship of water. Much of the world's water is used inefficiently by industry, agriculture, and cities even in arid areas; and much of it is wasted without economic benefit, often with negative environmental impacts.

Climate change is not expected to alter global supplies. Instead, the challenges are regional, due to the uneven distribution of water, and economic due to poor management of water resources. Without substantial reforms, water-related shocks and trends will converge to produce growing scarcity in some regions of the world and growing excess in others.

Water scarcity has commonly been seen as a technical issue. If water is in short supply in one region, the obvious solution is to obtain it from another where it is more abundant. But what is obvious may not always be prudent, and such supply-side solutions face economic and ecological limits.

Water has a low value-to-bulk ratio, which makes its transport across vast distances expensive and economically wasteful. So with climate change increasing the hydrological challenges, water management will require greater care and efficiency, recognizing not only the local needs for water but also its multiple values—as an economic resource, a human right, and the lifeblood of ecosystems. This chapter focuses on how water-related shocks and trends in water use under climate change is likely to affect regional economies.

The Pathways through which Water Scarcity and Stress under Climate Change Can Affect the Economy

Could a lack of water act as a brake on prosperity and economic progress under climate change? There are four primary pathways through which climate induced water shocks could impede development: First, if water is a scarce factor of production and is poorly allocated or inefficiently used, there could be impacts on broad economic performance—captured through metrics such as GDP growth, trade balances, and industry structure. Somewhat surprisingly there is limited understanding and knowledge of these links. In addition, water related natural disasters directly destroy lives and assets. The likely toll of future natural disasters is well documented with a litany of projected damage estimates. Next there are longer term impacts of water related diseases on health, nutrition, education and human capital with consequences for poverty and economic growth. These have been well documented. Finally, the conjecture that water related shocks ignite conflicts warrants closer scrutiny, especially because of its implications for water management. The remainder of this chapter examines these issues.

Water, Climate Change, and Economic Performance

A global economic model was developed for this report to shed light on possible impacts of water related climate impacts on the economy.[1] The model considers two scenarios that correspond to the Shared Socioeconomic Pathways (SSPs) that have been developed in the climate-change modeling literature (box 2.1). The SSPs are highly-stylized depictions of alternative

BOX 2.1 Climate Change and the Economic Effects of Water Deficits

Projecting future economic performance is a complex and hazardous endeavor. Future changes in economic structures, technological innovations, policies, political priorities, and consumer preferences cannot be known. Nor can the future path of greenhouse gas emissions be predicted with accuracy.

Recognizing the prevailing uncertainties, climate change scientists have constructed highly stylized development scenarios based on narratives termed Shared Socioeconomic Pathways (SSPs).[2] The SSPs describe changes in demography, policy, institutions, technology, economy, and lifestyles. The narratives are intended to serve as a general description of alternative futures that span a wide range of outcomes. The modeling described here considers two extreme scenarios as points of comparison. SSP1, "Sustainability," represents an optimistic outlook, and SSP3, "Regional Rivalry," embodies a rocky road in a world of high emissions, low adaptation, and limited economic progress.

Climate change will have impacts that encompass all areas of development—ecosystems, human health, agricultural yields, among others—all of which have been examined in the burgeoning modeling literature. The focus here is on the largely overlooked issue of the economic impacts of climate change through changes in water supplies.

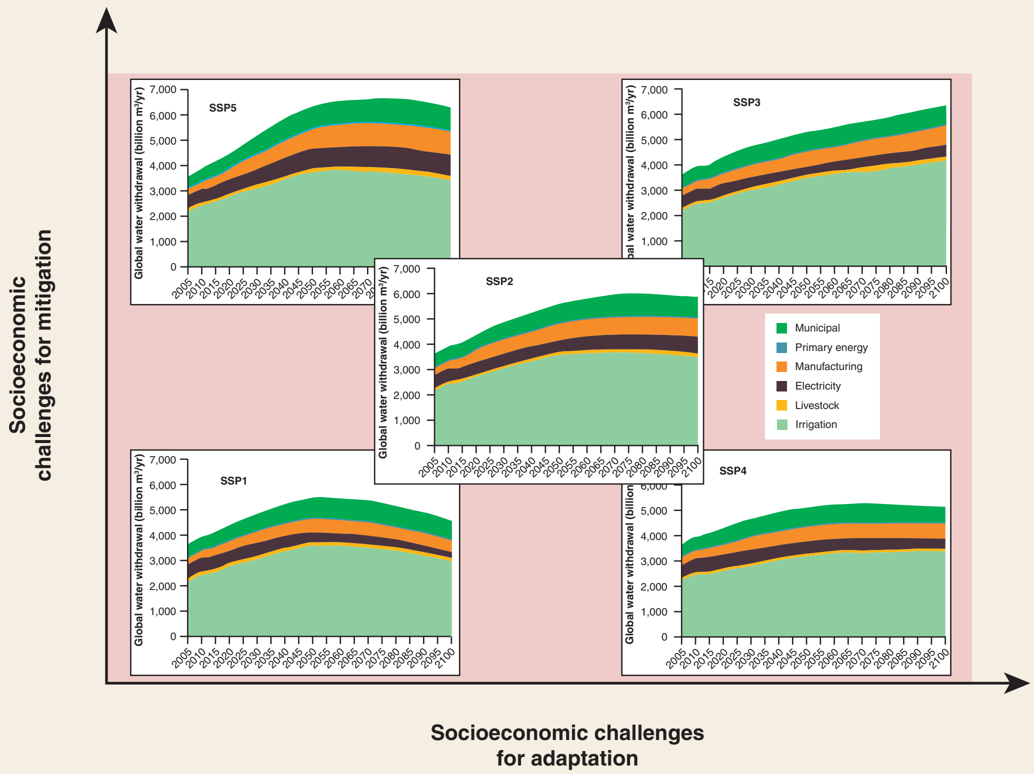
Since economic growth spurs water demand in rough proportion to the income it generates, there are legitimate concerns that expanding water deficits in some regions could constrain growth. To explore this issue, projections of water supply from a range of hydrological models underlying the projections in map 2 are incorporated in a conventional Computable General Equilibrium model for the SSP 1 and SSP 3 scenarios.

The analysis considers economic impacts under various broad policy regimes. The first is "business as usual," where water allocation policies remain largely unresponsive to changing levels of scarcity. This is modified by allowing for increasing shifts in allocation within and between industries to reflect the implicit value (shadow price) of water in the economy.

Simulations are performed using a Computable General Equilibrium model. The model approximates how economic sectors are inter-related, and can therefore estimate how a shock in one sector would reverberate through the entire economy. Water is treated as an input that is used in fixed proportions based upon exogenous allocations, that are varied to assess how economic performance changes with different allocation policies. It is assumed that water efficiency improvements that have been observed in the past in developed economies apply globally and continue through the simulation period. The model computes counterfactual equilibria for the world economy based on water supply and demand estimated for the SSPs shown in figure B2.1, resulting in estimates for future production, consumption, investments, trade flows, and many other economy variables.

BOX 2.1 Climate Change and the Economic Effects of Water Deficits *(continued)*

FIGURE B2.1 Water Withdrawal Based on Different Scenarios, by Sector



Source: O'Neill and others 2015.

Such models are not designed to forecast the future. As with all modeling exercises, the analysis is based on a litany of assumptions, driven by data availability and computational constraints. The exercise provides projections—the consequence of hypothesized scenarios in a stylized depiction of the economy, not predictions and forecasts. Nevertheless, such modeling exercises serve to improve understanding of the magnitude and direction of changes and to project whether alternative policies can either accentuate or mitigate the adverse impacts.

Regardless of which scenario is considered, the results demonstrate that a scarce water supply remains a significant obstacle to growth and development in the context of a changing climate. They also forcefully illustrates that prudent management of water resources is likely sufficient to neutralize some of the undesirable growth impacts.

global futures for demography, policy, the economy, and emissions. One of the scenarios represents a world of sustainability and optimism with low population growth rates, buoyant per capita GDP, low emissions, and thus little need for adaptation (SSP1). This is contrasted with a world of regional rivalry and high emissions that warrant greater adaptation (SSP3).

The model developed here is not intended to provide forecasts of GDP growth decades into the future—a seemingly impossible task. Instead, it seeks to improve understanding of the role of water in the context of a changing climate in a more populous world. It is based on a simplifying framework designed to isolate the role of water as a productive input in the economy.

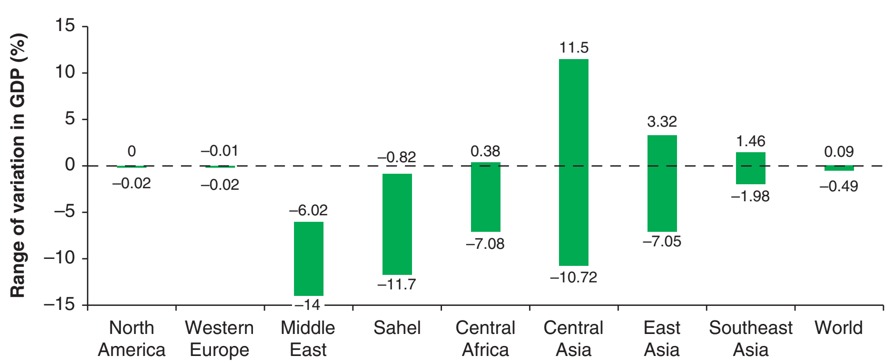
Increasing water demands resulting from increases in population, coupled with changes in the water supply, are projected to accentuate shortages in regions already experiencing some scarcity and water stress. The largest increases in water deficits are in the Middle East, North Africa, Central Asia, and parts of South Asia.

With water in short supply, there will be changes in what is produced, where it is produced, and the efficiency of production and water use. So, even local changes can be transmitted across the globe.

The impacts will depend on the policy regime, and effects can either be neutralized or exacerbated by policy responses. The analysis first considers a business-as-usual scenario where water is managed and allocated as it is under current regimes. In this scenario, water allocation does not respond to the growing shortages and changing comparative advantage of different sectors across the globe. The resulting changes in GDP are shown in the lower bounds of figure 2.1, which presents the worst projected outcome of SSP1 and SSP3.[3]

The economic consequences are highly unequal with the worst effects in the driest regions. The expected global damages are small relative to the expected global GDP in 2050: about 0.37 (SSP1) to 0.49 (SSP3) percent of global GDP in that year. But the global loss is a highly misleading estimate because, as the lower bounds of figure 2.1 illustrate, significant variations exist between regions. Western Europe and North America, where much global GDP is produced, experience negligible damages in most scenarios. The bulk

FIGURE 2.1 Climate-Related Impacts on GDP in 2050 (Ranges of Impacts Determined by Policies)



Source: World Bank 2015a.

Note: The figure shows the range that climate changes effects on water will have on GDP for selected regions. It incorporates effects from different growth scenarios (SSP1 and SSP3) as well as different policy scenarios (business-as-usual policies and policies that encourage better water allocation).

of losses are in the Middle East, the Sahel, and Central and East Asia, and the magnitude of losses is largely driven by the level of the water deficit. In the most arid regions, the projected percentage losses are large and imply that baseline growth projections cannot be met.

Other impacts are less visible, such as changes in trade patterns that cloud economic prospects in subtle ways.[4] The projections suggest that trade becomes distorted when countries in arid areas continue to produce water-intensive goods at ever-increasing financial and social cost, contrary to their natural comparative advantage.

But there is a silver lining. When governments respond to water shortages by boosting efficiency and allocating water to more highly-valued uses, losses decline dramatically and may even vanish. This is illustrated in the upper bounds of changes in figure 2.1 (note that the larger value between SSP1 and SSP3 is displayed). The upper bounds depict a world in which 25 percent of water is allocated to higher value uses. In most cases the losses from climate stress vanish and better water management even leads to growth rates that could be higher than those that would prevail in the absence of climate change and changes in policy. Improved water stewardship thus pays high economic dividends. There are however some regions of the world where more far-reaching actions would be needed. These are the extremely dry regions where scarcities are intense and the current allocation is far removed from the economically efficient outcomes, and hence require stronger policies and reforms to cope with deepening climate stresses.

The overarching message is that outcomes are driven by policy decisions, suggesting that prudent water-management policies can do much to secure growth, making people richer and thus more resilient to climate stresses. This often, but not necessarily, requires using market forces and prices to guide water allocation decisions.

The implication is that the benefits to managing water resources as a valuable economic resource are considerable. Water pricing can do much in this regard. Even if only a part of water use is allocated based on a price that brings supply and demand into balance, many of the problems of climate and socio-economic scarcity can be resolved.

Water that is provided free, promotes and condones overuse and waste. Countries that price water more cheaply also consume it more freely. Often, the most inefficient users of water are found in countries with the highest levels of water stress, where incentives are also lacking for prudent water use. More efficient water pricing, coupled with policies that safeguard the most marginal members of society, can therefore ensure that sufficient water is conserved and guarantee enough water to meet basic needs. As the Australian experience has demonstrated, market-based solutions, when complemented with policies that secure essential allocations for the environment and the world's poorest, can do much to assure greater efficiency of water use, higher levels of equity in its allocation, and long-term sustainability of the resource base.

A Brake on Economic Growth Will Mean a Brake on Poverty Alleviation

The model described in the previous section suggests that unless significant action is taken, water challenges due to climate change will significantly impair global economic growth. And even under favorable assumptions, some of the most fragile regions are expected to see growth declines, including the Middle East, the Sahel, and Central Africa. This is troubling not only from a wealth and prosperity standpoint, but also for the effect that this slow-down will have on poverty alleviation.

Past studies have shown that economic growth and poverty alleviation are closely tied, with the latter highly dependent on the former. Indeed, across all nations, a 1 percent increase in mean income has been associated with a 2 to 3 percent reduction in the poverty headcount ratio[5] (that is, the percentage of people within a country living below the poverty line). There is considerable heterogeneity in the magnitude of this link. It is known that poverty alleviation is much slower in economies that are more unequal, or have higher initial levels of poverty.[6] There are regional differences too. For instance, Sub-Saharan Africa tends to exhibit poverty rates that decline at a slower rate relative to the rest of the world, during periods of economic expansion.[7] It has been suggested that this may be due to SSA's heavy reliance on mining, which is a highly capital intensive industry and tends to benefit investors and managers near the top of the income distribution, rather than laborers at the bottom.[8] Nevertheless, it is clear that the large reduction in GDP growth that could occur due to increased water scarcity and variability, in the absence of prudent policy responses, will prevent millions of people worldwide from escaping poverty.

Of course, climate change will not only affect poor households via reductions in aggregate GDP, or through other economic benchmarks. Direct impacts on poor households, including an increase in prices, the destruction of assets, and a reduction in labor productivity, may impact the well-being of the poor significantly more than a slow-down in aggregate economic growth. Box 2.2 highlights the insights from a recent World Bank report, *Shockwaves: Managing the Impacts of Climate Change on Poverty*, which analyzes the specific challenges that climate change will inflict on the world's poor.

The Growing Economic and Human Impact of Extreme Events

Variability and rainfall extremes are hard to manage. Too much rain at once can generate storm surges and floods, capable of taking lives, destroying property, and through lingering effects, bring pestilence and diseases. In the other extreme, droughts can destroy entire harvests, wiping out the livelihoods of rural farmers, increasing food prices for urban residents, and making it more difficult to apply basic hygiene rules. Natural disasters often disproportionately affect poor households whose homes and assets

BOX 2.2 Climate Change's Effect on Poverty

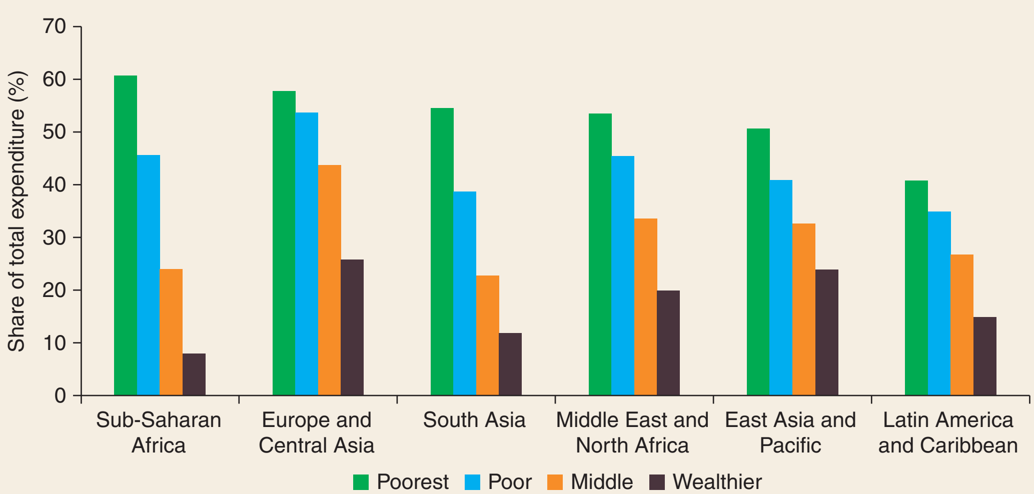
The World Bank's recently released report *Shockwaves: Managing the Impacts of Climate Change on Poverty* explores the interconnected goals of ending poverty, and addressing climate change. Climate change's impact on water distribution will affect the poor in three major ways: though its effect on agriculture, health, and natural disasters.

Nearly 78 percent of the world's poor, approximately 800 million people, live in rural areas and rely on agriculture, livestock, or aquaculture to sustain themselves and their families. With climate change expected to have dramatic effects on rainfall variability in many regions, farmers will be impacted more than perhaps any other group of people. Under high emissions scenarios, changes in rainfall patterns are projected to negatively affect crop yields globally, reducing them by up to 10 percent by 2030, and up to nearly 35 percent by 2080.[9]

If these projections are realized, agricultural production shocks will trigger significant increases in the price of food and food insecurity, for both rural and urban inhabitants. As poorer households spend a significantly larger share of their income on food (figure B2.2), they will be the most impacted. The magnitude of the changes in food prices due to climate change is highly uncertain. Without CO_2 fertilization, estimated food price changes due to climate change ranges from a 3 to 84 percent increase by 2050. With CO_2 fertilization however, the estimated range moderates significantly, changing to between a 30 percent decrease in food prices to a 45 percent increase.[10] Some farmers may benefit from these increases in food prices, increasing their profitability. Additionally, some agricultural laborers may see wages increase due to the increases in profit.

Increased water scarcity and variability will also lead to greater exposure to contaminated waters, less water available for sanitation, and increased disease burdens. These impacts will disproportionately affect poor households who may already lack adequate sanitation and reliable water supplies. Climate change will increase incidences of diarrhea and other waterborne diseases.

FIGURE B2.2 Poor Households Spend a Higher Share of Their Expenditure on Food and Beverages than Do Non-Poor Households



Source: Hallegatte et al. 2016.

BOX 2.2 Climate Change's Effect on Poverty *(continued)*

Diarrhea often occurs after the consumption of water which is contaminated due to flooding.[11] One case of diarrhea can cost a family $2 to $4, on top of the days lost at work or school, and it is unexpected healthcare costs such as these that are very often cited as the reason why households fall into poverty.[12]

Finally, floods, droughts, and storm surges will increase with climate change, and the world's poor will be the most exposed to their damage. As part of the Shockwaves report, a study was conducted on poverty-related exposure bias, and found that poor households tend to be more exposed to droughts and urban floods than their more wealthy counterparts.[13] Exposure bias to droughts is primarily due to the fact that the poor disproportionately rely on agricultural income, which is most at risk from droughts. Urban flood exposure bias likely occurs because urban space is scarce and so urban land markets will value flood-prone land lower, making it more affordable for poorer families. These exposure biases are expected to persist well into the future, with total exposure projected to increase due to climate change.

In addition to being more exposed to extreme events, poor households tend to lose a relatively higher share of their assets due to storms or floods.[14] This is partially because poorer households' assets tend to be more vulnerable to loss. In rural areas, much of household wealth tends to be in the form of livestock, which are highly vulnerable to droughts, storms, and floods. Housing stock also tends to be of lower quality, and more easily damaged or destroyed during storms.

are less robust and more vulnerable, and also tend to be located in higher risk areas. This vulnerability discourages investment in physical assets, which have the potential to be destroyed, and it can cause nutritional, health, and income shocks which tend to reduce human capital investments, particularly in children.

Whatever the projected frequency and intensity of floods and droughts, their economic impacts will almost certainly rise as the density of economic activity and people increases in areas of greater climate vulnerability. While the threat of more frequent and severe droughts looms large under climate change, floods are arguably exacting a more visible and perhaps an even more rapidly growing toll. Between 1960 and 1990, floods in Europe destroyed, on average, assets worth about $7 billion per year. If the trend continues—and trends may change—the damage under most climate scenarios is expected to double in Europe by 2080.[15]

Some extreme events directly linked to the hydrological cycle can have economic effects that are much greater and persist longer than expected. A recent study used meteorological data to reconstruct every country's exposure to tropical cyclones during 1950–2008.[16] It finds that national incomes decline after a disaster and do not recover within 20 years. This conclusion holds for both developed and developing countries. Income losses arise from a small but persistent suppression of annual growth rates spread across the 15 years following a water-based disaster. The results suggest that future cyclone activity would result in costs of about $10 trillion larger than previous estimates (in discounted present value). Another study found that it is the largest, most damaging natural disasters which have lasting impacts, but that these impacts can be subdued with better institutional quality, higher openness to trade, and higher financial openness.[17]

The Long-Term Economic Effects of Rainfall Shocks on Human Capital

There has been much research on the contemporaneous impacts of water scarcity and variability, climate change, and the intersection of the two; that is, how an increased future propensity for rainfall shocks will impact economic growth. However, there is also growing evidence that these water shocks may have much longer-term effects. This is particularly true when water shocks cause nutritional deficits or health impacts in young children, or income shocks which prevent families from investing in their children.[18]

As an example, in rural Vietnam, most families engage in rain-fed crop production- mainly irrigated rice production. Income is therefore heavily dependent on favorable rainfall conditions, and rainfall shocks often lead to significant income reductions for families. These income shocks can lead to nutritional deficits for developing fetuses and infants, which has dramatic consequences later in life. Children in Vietnam who experienced these shocks were shown to have delayed school entry, slowed progress in school, and lower height than their peers that did not experience this shock.[19] Similar effects have also been observed in rural India[20] and Mexico.[21]

This exposure to malnutrition and childhood illness as a result of drought can help perpetuate the cycle of poverty. Illnesses and chronic malnourishment can impact educational attainment, reducing future employment prospects. Where they impact childhood development and the central nervous system (such as severe cerebral malaria), they can have an impact on lifelong cognitive ability, leading to reduced future wages. Childhood stunting, which can be caused by repeated bouts with diarrheal diseases, is associated with long-term health and economic risks including reduced educational attainment, lower earnings, increased morbidity rates, and higher mortality rates.[22]

The idea that in-utero or infancy shocks like extreme drought could have long-term impacts was most prominently posited by David J. Barker[23], a British epidemiologist, and is now known as the *fetal origins hypothesis*. Mounting evidence shows the important role that early-life conditions can have on future success. A survey of rural farmers in Indonesia has shown that individuals, and particularly females, who experienced rainfall shocks during the first year of their lives achieved less education, earned less money, and married spouses who earned less money.[24] Recent evidence extends these results to middle class workers in Ecuador, where it has been found that individuals that experienced rainfall shocks, as well as hotter temperatures, while in-utero, had reduce formal sector earnings 20 to 60 years later in life.[25] These results show that climate change may have as yet underappreciated impacts on not only rural farmers, but also middle class workers from middle-income countries.

The Thirsty Origins of Migration and Conflict

Throughout history, humans have waged war to gain access to natural resources, including land, minerals, and even water. The first recorded water war occurred more than 4,500 years ago in modern-day Iraq, near the confluence of the Tigris and Euphrates rivers. Fought between the neighboring ancient city-states of Lagash and Umma, the conflict erupted when Lagash diverted the water supplies of its neighbor. History records other instances of violence over water. Drying events are thought to have fueled transboundary invasions in ancient China and political instability in historical Egypt.[26] Colonial conquests were often driven as much by a quest for territory, as natural resources.

Though much has been conjectured about a future of resource wars, today states rarely, if ever, fight over water alone. Arguably, this should come as no surprise. Wars are a costly endeavor with uncertain consequences, which renders dialog and cooperation a more attractive way to resolve disputes. As a result, cooperation and dialog over transboundary water resources is more common today than Malthusian resource conflicts. This is not to deny that water scarcity could act as a conflict risk multiplier in some cases. But more typically if disputes arise, they are mediated in ways that facilitate peaceful resolution.

While resource wars between countries may be uncommon today, tensions over water resources within countries are much more widespread. Episodes of drought and floods are often followed by spikes in violence, civil war, and regime change in developing countries. The strongest evidence is from Sub Saharan Africa where civil wars tend to erupt following periods of low rainfall.[27] In rural Brazil, land invasions are more common during drier years with more intense conflict in areas where land ownership is more unequal.[28] In India property related violence increases by about 4 percent when there is below average rainfall and communal riots become more frequent following episodes of floods.[29]

There are sound economic reasons to expect rainfall anomalies to cascade into violence. Droughts and floods typically generate poverty and accentuate deprivation especially in countries where agriculture remains an important source of employment. Poverty in turn alters the calculus of participating in conflict. Combatants have less to lose when customary sources of livelihood have been dwindled by droughts or floods, and they have more to gain by participating in violence that might beget a better future. The conflict vulnerability of a country to rainfall shocks typically depends upon the rainfall sensitivity of its income and its ability to provide protection and alternative sources of employment.

Rainfall shocks ignite conflicts in other ways too. Evidence from Africa suggests that by straining government budgets, their capacity and popularity decline, making regime change more likely.[30] Migration within and between countries, which tends to increase in areas facing water shocks, remains a potent and widely documented source of friction between locals and new arrivals across much of the world. Indeed, a decline in precipitation has been found to act as a “push factor” inducing much of the migration to cities.

The impact is particularly strong in Sub-Saharan Africa where a 1 percent reduction in precipitation is associated with a 0.59 percent increase in the urbanization rate.[31] The effects are more pronounced in cities with a manufacturing base that can absorb economic migrants seeking employment.[32] Similar trends have been observed elsewhere. In the Indian state of Gujarat when groundwater irrigation became less available or more expensive due to a declining water table, farmers migrated to cities instead of seeking alternative adaptation strategies such as shifts in cropping patterns or more efficient irrigation technologies.[33]

The increases in water variability and expanding water deficits that are predicted to occur due to climate change have the potential to increase the propensity for conflict. Building resilience to the more extreme precipitation events of climate change will become a more urgent priority especially in rainfall vulnerable areas.

The Way Forward: Implications for Policy

Water Allocation

Getting the distribution of water right will go a long way toward decoupling water use from economic growth. In many regions, water resources have been over-allocated, and climate change will compound the scarcity. If but a small part of water use were allocated to bring supply and demand into balance, many anticipated problems of climate and socio-economic scarcity could be resolved. Today, the marginal value of water for different uses varies greatly because the prices paid by industry, agriculture, and residential users are often unrelated. For example, in Arizona, water prices vary from $27 an acre-foot for agriculture to $3,200 an acre-foot for urban uses—so there is much suppressed demand in the cities.[34] While some of the gap could be explained by the difference in the nature and quality of the product delivered, most of it is a function of institutions that do not allocate water on the basis of explicit and transparent economic, distributional, or political criteria.

A fundamental rethinking of water rights and appropriate governance mechanisms is also needed. The focus could be on how water rights could be used not as a declaration of inviolate ownership, but as a flexible instrument to resolve water conflicts at the community, basin, regional, national, and global levels, while still protecting the needs of the poor. Adequate management and regulation— particularly of common groundwater aquifers—is essential to ensure that there is a mechanism for efficient allocation across water sources and uses. In this context, the emergence of sophisticated technologies to monitor, measure, and disclose water "performance" using objective metrics is an opportunity not yet realized.

The gains from addressing scarcity through markets, prices, or other economic instruments would be immediate. But the task will not be easy. It will often call for a fundamental reform of institutional and legal structures to address the impediments to allocating water to sectors and uses where demand and value added is greatest. It involves developing systems that are credible, trusted by all parties and assure fair compensation for transfers. This, in turn, requires an administrative entity with the capacity, knowledge and authority to monitor and measure water use and ensure compliance with the agreed rules of the game. In addition any change must overcome inherent political challenges. On the one hand, political leaders may be hesitant to expose the poor and key constituents like farmers to price increases. However, these challenges can be partly addressed through carefully-targeted assistance such as subsidies or block tariffs structures. But the past weighs heavily on the present, and the (often) wealthier water users who benefit from low water prices will naturally resist price reform. At times it may be necessary to directly compensate those who loose from new tariff structures, as in the case of Australia's reforms. This reality calls for transparent and equitable systems for compensation that may be needed to build a political consensus for reform.

Finally, to prevent increases in food insecurity, policies should be put in place which make it easier to import food, especially in countries with no comparative advantage in food production where water resources are being degraded in the attempt to force increases in food supply.

Water Proofing through Investment

While improving water allocation is essential to satisfying trends in future water use, providing security against water-related shocks requires investments in adaptation, especially if mitigation is limited. Adaptation will require both private and public action, with the public initially at least as large as the private to catalyze the process. In developing countries, the infrastructure gap for water storage, flood control, and energy supply is massive. Compounding the lack of infrastructure is inadequate investment in maintaining costly assets. Short-term savings on operations and maintenance are a false economy and can be counterproductive if they shorten the life of the asset. This is especially important in the water sector, where assets are expensive, capital-intensive, and long-lived (can last more than 100 years).

To protect the world's poor against natural hazards, developing countries need to be better able to predict when they will occur. This means investing more in hydro-meteorological, and early-warning systems, and putting the institutions in place which are capable of transforming a forecast into an actionable warning. Increasing the lead time of a forecasted storm or flood even by a few hours can help households mitigate the damage to their assets and can even help to save lives. Having more spatially granular forecasts is also important to help individuals determine the appropriate damage mitigating action they should take.[35]

Policy Choices under Uncertainty

But where uncertainty is high, as in projecting extreme events, it is wise to leave options open (box 1.1). Sinking all adaptation efforts into a single and costly project can prove wasteful, if the anticipated climate events do not eventuate. No-regret measures that provide benefits under a range of outcomes increase flexibility, as do modular approaches that can tailor responses to evolving circumstances. Soft policies, such as economic instruments and climate-informed plans, can be especially useful in such contexts. Some studies suggest that if Australia had introduced adequate water tariffs, water demand might have been managed to a level that no longer required the investments in costly desalination plants that now risk lying idle due to the expense of the water they produce.[36]

Notes

1. Details are in World Bank 2015a.
2. O'Neill et al. 2015.
3. In general, the differences in outcomes between the two SSPs are negligible, with the lower bound representing SSP1 in most but not all cases, as climate impacts differ across regions (see World Bank 2015a for the full set of figures).
4. These are discussed in the technical volume that accompanies World Bank 2015a.
5. Ravallion and Chen 1997.
6. Ravallion 2012.
7. Fosu 2015.
8. Christiaensen and Devarajan 2013.
9. Havlik et al. 2015.
10. Intergovernmental Panel on Climate Change 2014.
11. Watson, Gayer, and Connolly 2007.
12. Krishna 2007.
13. Winsemius et al. 2015.
14. Brouwer et al. 2007; and Carter et al. 2007.
15. World Bank 2015a.
16. Hsiang and Jina 2014.
17. Felbermayr and Gröschl 2013.
18. Almond and Currie 2011.
19. Thai and Falaris 2011.
20. Kumar et al. 2014.
21. Aguilar and Vicarelli 2012.
22. See Black et al. 2008; Victoria et al. 2008; and Maccini and Yang 2009.
23. Barker 1995.
24. Maccini and Yang 2009.
25. Fishman, Russ, and Carrillo 2015.
26. Inter alia Bai, Ying, and James Kai-sing Kung 2011 and Chaney 2013.
27. Miguel et al. 2004.
28. Hidalgo et al. 2010.
29. Inter alia Sarsons 2015 and Blakeslee, David, and Ram Fishman 2013.
30. Brückner, and Ciccone 2011.
31. Barrios, Luisito, and Strobl 2006.
32. Henderson, Storeygard, and Deichmann 2015.
33. Fishman, Jain, and Kishore 2013.
34. Olmstead 2013.
35. Malik et al. 2014.
36. Grafton and Kompas 2007; OECD 2013.

Rehabilitating Jakarta's waterways to mitigate flood risk.
© Farhana Asnap/World Bank. Permission required for reuse.

Chapter 3

Dimensions of the Water-Climate Nexus: The Drivers of Demand

The future will be thirsty. Growing populations, rising incomes, and a changing climate will converge to create unprecedented strains for the world's water resources. On the one hand, the world will experience a surge in demand for water; but on the other hand, under climate change it will experience a less reliable supply. Meeting the simultaneous increases in demand for water for food production, energy generation, urban growth, and ecosystem services will be impossible under business-as-usual.

Within the next three decades, demand for water from agriculture could increase by 50 percent, and for urban uses by between 50 percent and 70 percent.[1] Meanwhile, by 2035, the energy sector is projected to consume 85 percent more water.[2] These increased strains will create unprecedented conflicts between different water uses, and inter-connected risks between them. This chapter examines trade-offs between water uses and the key drivers of demand: food production, urbanization, energy, and the environment.

Meeting Food Security Challenges

Sustainably feeding more than 9 billion people by 2050 is perhaps the greatest global challenge of our time. By most estimates food production will need to double over this period. At the same time, the demand for meat, which consumes and pollutes large amounts of water, is increasing with income growth and rising nutritional standards. The agricultural sector already consumes over 70 percent of the available freshwater, and is the single largest anthropogenic water user. But over the next few decades, these already high water requirements are set to expand still further.[3] These demands will have to be met against the backdrop of shifting and often shrinking water resources, and amidst rapidly growing competition for water use in other sectors, including energy, environmental, and urban.[4] Nowhere are the trade-offs between these different water uses more acute than in the case of the global food system under climate change.

Climate Change Will Exacerbate Food Security Challenges

The basic challenge facing the global food system is that current approaches to increase food production, which rely on ever-greater inputs of land, water, and fertilizer, appear to be much less viable and suitable under climate change. The intensification of food production since the 1970's has achieved great success in feeding a rapidly growing global population. But this has often been achieved through methods and policies that lacked incentives for prudent use of inputs, resulting in the degradation of the natural resource base upon which future growth depends. There is also growing evidence that these impressive gains in yields are beginning to plateau in some areas.[5]

Even without climate change, meeting increasing water requirements would pose a substantial challenge for the global food system. In order to feed an additional 2 billion people by 2050 using current practices and technologies, the global food system would have to increase irrigation water withdrawals by about 5 percent annually. This is the equivalent of building a new dam about one-and-a-half times the size of the Aswan Dam every year.[6,7] Climate change will increase these already-high water requirements. Higher temperatures generally increase water requirements for both crops and livestock, in turn resulting in disproportionate impacts in areas dominated by rain-fed agriculture. Estimates suggest that in the South Asia region, farm-related income could decline by as much as 25 percent due to diminishing crop yields.[8]

Dependable water supplies are the single most important climactic factor in agricultural production,[9] and climate change will alter the amount of water available both in particular geographic regions, and seasons. While the magnitude of these effects is uncertain, estimates suggest that the cycle of flooding and drought associated with El Nino-Southern Oscillation events—which is similar to the type of increased variability that we might see due to climate change—likely results in crop yield variability of 15 to 35 percent, suggesting the potential for significant disruption.[10]

Models indicate that this effect is most pronounced in major river basins, including the Yangtze, the Ganges, and the Indus, that depend on seasonal meltwater from snowpacks and glaciers for the majority of their flow.[11]

Old Strategies for Increasing Food Production Will Become More Difficult

Traditional methods of increasing food production that have relied upon expanding land, water, and other inputs will become less viable under climate change. Land extensification, or the increase in land under cultivation, is quickly becoming unsustainable as the forest margin is exhausted and the risks to ecosystems accelerate.[12] And in a climate change context, significant extensification in areas of high rainfall is especially undesirable as it lowers the carbon sequestration potential of the world's tropical forests, thereby exacerbating climate change.[13]

Increasing irrigation from surface water offers a more direct means of adapting to the effects of climate change, but must compete with other human and environmental water requirements. Supplying more water to crops can help to ameliorate the effects of warming and buffer disruptions caused by increased variability in rainfall.[14] However, in many parts of the world, little additional surface water is available for irrigation, especially if environmental flows are taken into account. Increasing diversions of surface water is impossible in the increasing number of "closed basins" where virtually the entire annual flow is already appropriated for human use. In these and other highly-stressed basins, irrigation competes with other critical water uses, including energy production. Irrigation already accounts for about 90 percent of water use in many developing countries.[15] This creates difficult trade-offs. In the Blue Nile basin, for example, drier conditions mean that more water must be stored in reservoirs for hydropower production, leaving less water available for irrigation, despite increased agricultural water requirements.[16] Optimized dam management can ameliorate but cannot eliminate these trade-offs. Even in areas where additional water exists and can be stored for irrigation, the costs of doing so will inevitably increase over time as the more efficient and cost effective options are exhausted.

Where surface water supplies are unavailable, irrigators have turned to groundwater, where it is available.[17] Globally, groundwater accounts for approximately one-third of total water withdrawals, and approximately 50 percent of irrigation water withdrawals. However, much like surface water flows, much of the world's groundwater aquifers are already heavily exploited. Critically, from an integrated nexus perspective, groundwater abstraction requires approximately 30 percent more energy than surface water irrigation,[18] resulting in significantly higher greenhouse gas emissions. According to one estimate, groundwater pumping accounts for no less than 4 to 6 percent of India's total carbon emissions.[19]

While land and water constraints limit opportunities for increasing food production through extensification in some regions, techniques which increase food production through intensification can be damaging, if the off-farm impacts are ignored. Intensification, which involves increasing yields on a given plot of land, typically requires soil nutrients to be replenished with phosphorus or nitrogen based fertilizers. While these are essential for enhancing agricultural productivity, even small amounts of leeching are deemed to be harmful to water supplies intended for human consumption.[20] In some regions, particularly the great plains of North America, Western Europe, and East Asia, levels of phosphorus and nitrogen biochemical flows have already reached unsafe levels.[21]

The Geography of Vulnerability

Climate change will have the biggest impact on food security in regions which are already amongst the most insecure. Countries which have placed most available arable land under cultivation, face high demand for irrigation as well as other water uses relative to supply, and are already heavily dependent on groundwater, are likely to face the greatest challenges. Countries with large populations of smallholder farmers and weak institutions are also likely to be highly vulnerable.[22] On these measures, the countries of the South Asia and Middle East – North Africa regions are likely to face the most difficult trade-offs with respect to the food system and the other demands of water users. Because of its already high reliance on surface and groundwater irrigation,[23] South Asia has little additional water available to increase agricultural production or compensate for predicated climate-related shifts in the monsoon and runoff from the principal Himalayan rivers.[24] Across the Middle East and North Africa, meanwhile, the lack of surface flows and reliance on non-renewable groundwater reserves for irrigation makes agriculture especially vulnerable to predicted warming across the region.[25]

Changing Cities and Changing Climate

Cities are arguably the economic success story of this century. Accounting for over half the world's global population, they have been the engines of economic growth and generate about 80 percent of global GDP.[26] While cities offer immense opportunities for development and growth, they also bring risks and challenges. Today these areas account for about 30 percent of water used and return a large share of it to the system as wastewater, in a degraded state.[27] Globally, 456 million hectares of farmland can be found within a 20 kilometer radius of urban centers, an area about the size of the European Union.[28] But this is also a radius of resource depletion—with declining groundwater levels, polluted and "dead" rivers, denuded watersheds, paved floodplains, and deserts of natural biodiversity. Such impacts might seem warranted as an inevitable price for accelerated growth and prosperity in cities, but risks would emerge if this undermines the resource base that enables this growth.

As the world continues to urbanize the demand for water in cities is projected to increase by 50 to 70 percent within the next three decades, and urban residents—particularly the urban poor—become more vulnerable to the effects of climate change. One in four cities worldwide already experiences water insecurity.[29] Climate change adds to demographic and supply-chain pressures on cities, leading to fears of a perfect storm in which water shortages combine with periodic climate disasters to produce major social and economic disruptions.[30] The social and economic consequences of climate shocks on cities can be particularly devastating in low- and middle-income countries.[31] The annual global costs of adaptation for 2010–50 are estimated to range between $71.2 billion and $81.5 billion, depending on the climate scenario, and urban areas could bear more than 80 percent of these costs.[32]

In cities, as elsewhere, the effects of climate change are mediated largely through water. Cities are especially vulnerable to water-related climate shocks, even as the increasingly common pattern of fixed water supplies and rising demands is gripping cities across the world. Flooding events can degrade the quality of surface and groundwater, cause the loss of human lives and property, and disrupt the urban economy. Heat waves and variable precipitation reduce the availability and quality of water while increasing demand. Rising seas reduce groundwater availability due to salt-water intrusion and can permanently damage urban infrastructure.[33]

Impacts from Extreme Events—Slow and Rapid

The population affected by river floods is growing substantially, driven by both climate change and socio-economic change.[34] There are a litany familiar projections of urban vulnerabilities. The additional urban flood damages that take account due to climate change are projected to reach between $0.7 and $1.8 trillion by 2080.[35] In 2005, global flood losses were approximately $6 billion. These are projected to increase to $52 billion by 2050 due to projected socio-economic changes alone (increasing populations and incomes). With climate change, these losses may reach at least $1 trillion per year.[36] Sea-level rise can multiply the impacts of storms by creating devastating tidal surges, often aggravated by land subsidence caused by urban construction, groundwater extraction, and the alteration of sedimentation dynamics.[37] Jakarta illustrates what these threats could mean for coastal city populations (box 3.1).

Cities are also vulnerable to slow-onset droughts, whose frequency and intensity are expected to increase with climate change in many regions.[38] Droughts may reduce the availability of water for municipal and industrial use, energy (due to cooling water restrictions), and food (resulting in reduced crop yields). They may also contribute to heightened urban migration patterns and localized conflicts over scarce water. At the same time, urban water demands are likely to increase with higher temperatures as a result of increased demand for cooling. In California, the average annual cost of urban water scarcity (in forgone benefits) is estimated at $1.6 billion a year.[39]

BOX 3.1 Jakarta Faces Multiple Urban Water Challenges[40]

The city of Jakarta in Indonesia suffers from many water-related issues, including chronic flooding every year and extreme floods every few years. Despite these severe challenges, it still attracts a quarter of a million new residents every year. The 2007 flood, reaching 25 percent of the city, caused financial losses of $900 million.

Flooding has been blamed on deforestation in the nearby mountains, but the main causes lie closer to home: wetlands and rice fields have been paved over in defiance of urban-planning regulations. Drainage canals are blocked by garbage, the result of an ineffective disposal system. And while the city confronts a sea-level rise of 60cm or more over this century, unregulated and unsustainable groundwater extraction has already sunk coastal areas of the city by up to 4.5 m over the past 50 years. Northern parts of Jakarta are predicted to be 4 to 5m below sea level within 20 years, and floods would affect up to 5 million people. But Jakarta is not alone—this situation is shared by Bangkok and many other coastal or growing cities.

Water Availability and Urban Growth

The world is urbanizing at a rapid pace, and the most dramatic transformations are in low- and middle-income countries. By 2050, the number of urban dwellers is projected to grow by 2.5 billion people, with nearly 90 percent of the increase in Asia and Africa.[41] Without adequate urban planning, regulation, and development capacity, cities often expand through informal settlement into flood-prone areas, where dwellers are deprived of municipal water, sanitation, and flood protection (box 3.2).

With population growth, and to less extent climate change, the number of urban dwellers who live with seasonal water shortages is forecast to grow from close to 500 million people in 2000 to 1.9 billion in 2050.[42] This estimate may be a lower bound, since increasing competition between agricultural, industrial, and municipal water users will further strain cities. Urban populations are set to more than double by 2050 in the Middle East, North Africa, and South Asia. But modeling for this study shows that reduced freshwater availability and competition with other uses will reduce municipal water consumption per capita between 31 percent and 66 percent compared with the situation in 2015 under the SSP3 scenario (or 15 percent and 47 percent under SSP1).[43]

Water for Energy

The energy sector is a significant water consumer, especially for power plant cooling, mineral extraction and processing. In addition, return flows from energy processing and production facilities are a major source of water pollution. Overall, water withdrawals for energy production are expected to

BOX 3.2 Urban Adaptation Strategies Can Be Economically Beneficial

Few studies have rigorously analyzed the economics of urban resilience to water-related crises. But whether in Casablanca,[44] Copenhagen,[45] or Bangkok,[46] adaptation programs are less expensive than the damages they avoid.

Inexpensive strategies with high benefit–cost ratios could be priorities. They include early warning systems and more generally measures to improve access to flood-risk information, which can help urban planning, penalize investors supporting real estate development in unsafe areas, and facilitate the development of insurance markets. While the costs and uncertain benefits of adaptation may complicate the task of decision makers, many measures that contribute to climate change mitigation are also highly relevant in a pro-poor sustainable urban policy agenda, regardless of climate issues.

The paradigm shift that climate change imposes on cities will require large-scale political, technical, and financial mobilization. Three factors will be instrumental to achieving long-term water security objectives in cities. First is enhancing awareness among high-level policy makers about climate risks and the availability of economically sound adaptation options. Second is developing knowledge sharing and collaboration platforms for stakeholders managing or affecting the urban water cycle. And third is assuring adequate investment funding from multilateral development banks, governments, and the private sector. It will also be essential to support decision-making and demonstrate project relevance with robust economic analysis applicable to complex adaptation packages that include non-structural measures and cross-sectoral approaches.

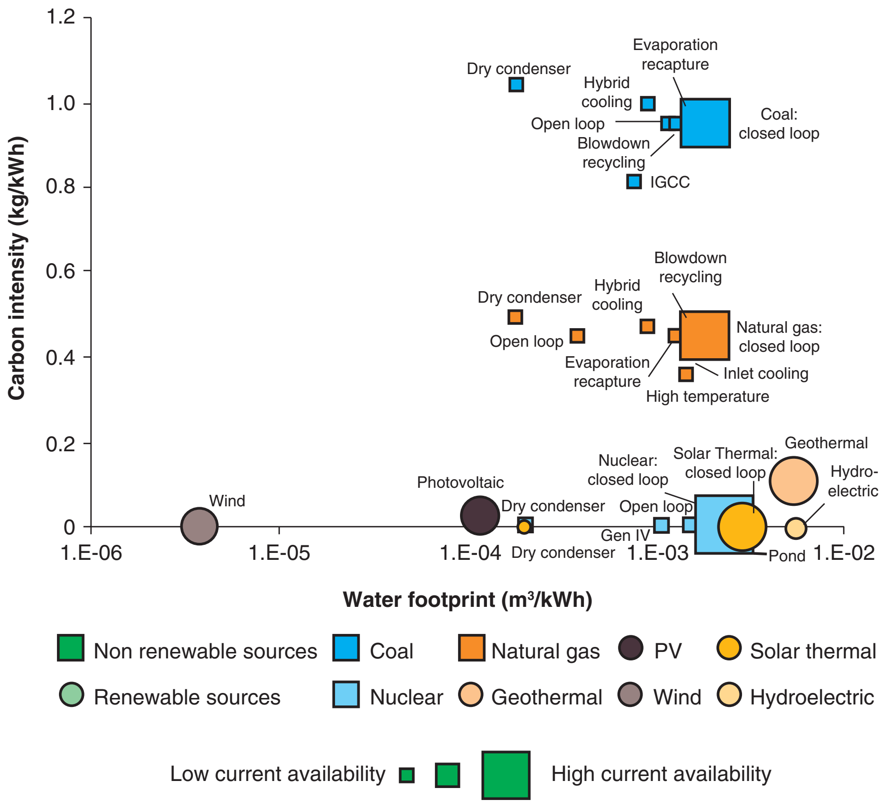
increase by 20 percent by 2035.[47] Additional demands are imposed by the significant energy inputs required to transport and purify water.[48]

Some cleaner sources of energy are surprisingly thirsty and utilize large amounts of water (figure 3.1).[49] Hydropower plants, which provide a reliable supply of low-carbon electricity for economic development, require large quantities of water to be stored in order to generate electricity. While integrated management can ease trade-offs, the objective of maximizing hydropower production sometimes entails lower water deliveries to farmers and disruptions to the flow of water to downstream ecosystems.[50] Carbon capture, utilization, and storage, meanwhile, is regarded as one of the most cost-effective mitigation strategies, but requires large quantities of water in the process of sequestering carbon.[51]

These inter-relationships create distinct trade-offs between the use of water and energy. In water-stressed regions, water withdrawals for energy competes with agricultural water uses, and may reduce the amount of water available to support ecosystem function.[52] Conversely, limited water availability may constrain the operation or expansion of thermal plants.

When surface flows become unavailable or insufficient, farmers are often compelled to increase their dependence on groundwater for irrigation, which

FIGURE 3.1 **Indicative Water Footprint and Carbon Intensity of Energy Production, by Source**

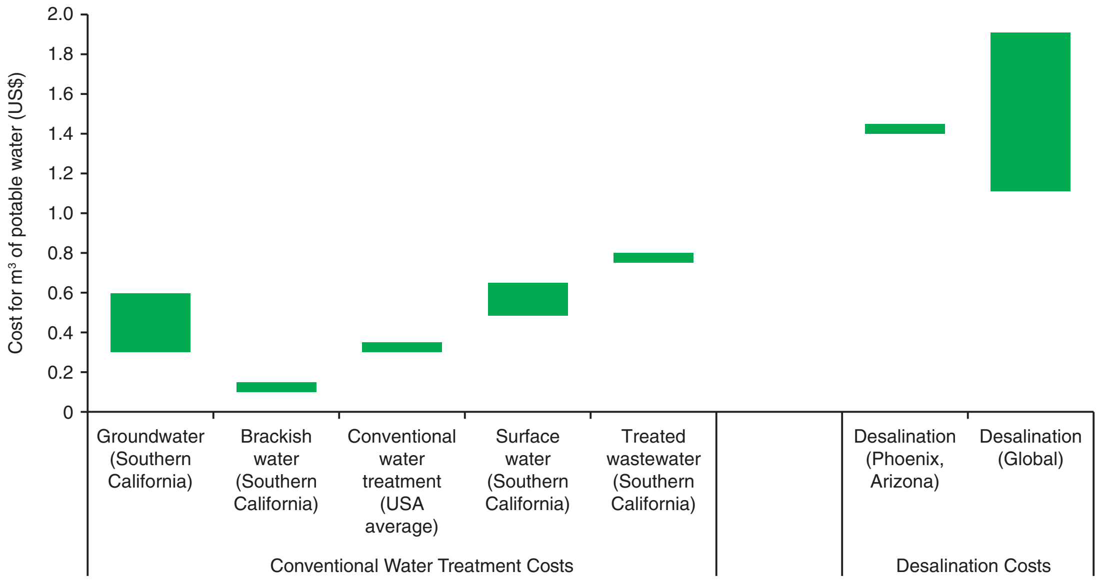


Source: World Bank 2010.

generates associated increases in energy use. Groundwater pumping requires about one-third more energy than conventional surface irrigation and relies on dirty sources of power like diesel-fueled pumps or coal-generated electricity.[53] Alternative technologies such as solar-powered pumps can reduce the pollution and greenhouse gas emissions associated with groundwater pumping, but do nothing to ease the growing pressures on aquifers worldwide. These trade-offs between energy and water production are usually hidden, and rarely do they figure into cost-benefit assessments. However, integrated planning and management of infrastructure and investment projects can identify synergies that reduce trade-offs between the uses of water for energy and other requirements.

Desalination and water recycling have emerged as important strategies for augmenting water supplies especially in cities in areas of low rainfall. But with current technologies these are not economically feasible options for lower value added uses. While there are significant variations, desalination typically requires up to 23 times as much energy as water withdrawn from surface sources such as lakes and streams and this translates into higher costs.[54] On average desalinized water costs about 4 to 5 times more than treated surface water (figure 3.2). As an example the total annualized cost of desalinated brackish water in Phoenix, AZ, is estimated at

FIGURE 3.2 **Indicative Cost of Water Production, by Source**



Source: World Bank estimates.
Note: Desalination calculated as an average of costs from 12 large urban areas around the world.

USD$1.49 per cubic meter; by comparison, surface water from the nearby Colorado River can be diverted at a meager cost of USD$0.32–0.65 per cubic meter.[55] The climate change impacts of desalination can be partly ameliorated by relying on renewable energy sources such as concentrated solar power, but these technologies add significantly to the already high cost of desalination.

Meeting Environmental Water Requirements

The water-related impacts of climate change are even more acute when environmental water requirements are taken into account. Natural ecosystems are too often the residual claimant of water resources, receiving only as much water as is left over from agricultural and other human uses and much of this is polluted. As the world grows thirstier and the global water footprint increases, it is often the planet's ecosystems which are the first to lose out. Estimates suggest that 20 to 50 percent of the total available water in each basin is required to maintain plant and animal life and sustain critical ecosystem services like water purification.[56] Temperature increases and shifting water availability associated with climate change are likely to cause ecosystem water needs to increase.[57] In large basins, such as the Yellow, Colorado, and Murray-Darling River Basins, humans already utilize virtually all available water for irrigation and urban use, leaving little available to maintain environmental flows.[58]

Assessing and providing for environmental water requirements has proven to be especially challenging. The most fundamental and common problem is that of measuring and determining environmental water requirements. Each waterway has a distinctive flow regime with a similarly unique set of floodplain, riparian, and instream ecosystems that often vary considerably along the length of a waterway.[59] Defining environmental water requirements is a complex and arduous process that includes modeling, experimental data collection, and habitat surveys along the length of the waterway.[60] Even more challenging, streamflow regimes and habitat types for many waterways are changing and are expected to change further as a result of temperature increases and river inflows changes (amounts and variability) as a result of climate change.[61] Box 3.3 summarizes the Australian experience which is often held as an exemplar of environmental stewardship. Decisions are further complicated by the need to vary environmental flows seasonally. The most important functions of environmental flows, such as maintaining water quality, triggering fish spawning, sediment transport, groundwater recharge, and wetland inundation, require periodic high flows.[62]

Balancing ecosystem needs with economic pressures remains amongst the most challenging tasks for water management decisions, particularly when it comes to determining what water infrastructure will be built, how it will be operated, and how much water can be abstracted for consumptive purposes. Some promising approaches do exist to alleviate these trade-offs.[63] Carefully-timed releases of water from storage dams and reservoirs, known as "pulses," can help maintain downstream ecosystems while providing sufficient water to meet irrigation and hydropower production requirements.[64] In other cases, infrastructure (for example, gates/regulators or pumps) are used to deliver water to floodplains at river flows below bankfull. These strategies illustrate that smart water resource management can partly mitigate the environmental impacts.

Almost 40 percent of the world's people reside in 275 transboundary river basins that span almost half of the Earth's land surface (map 3.1).[65] Accounting for 60 percent of the world's freshwater flows, transboundary rivers are ubiquitous. As a result the management of environmental flows is often further complicated by the need for international agreements to maintain environmental flows.

Policy Implications of the Nexus Approach

The primary message of the water-climate nexus is that trade-offs between water requirements for food and energy production, the environment, and urbanization under climate change are significant, and will require careful assessment by policymakers. However, the impact of these trade-offs can be ameliorated by taking several important steps.

The solutions in each sector largely fall into three categories: First there is a need to recognize the trade-offs across sectors to allocate water more wisely across sectors, Second to bring the burgeoning water deficits under control, incentives are required that reward prudent use and stewardship.

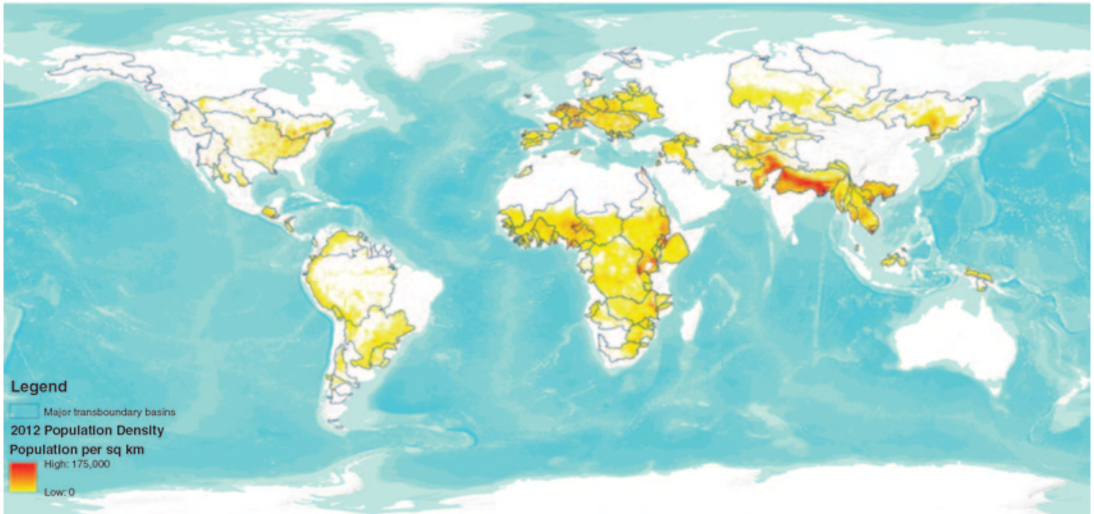
BOX 3.3 Environmental Flows—The Australian Experience

Attention has been given to environmental water requirements in Australia for over thirty years and the legal and institutional architecture has continued to evolve and strengthen. Environmental flows were a key element of the national water reform process formalized in the mid-1990s as part of broader micro-economic reforms across the country.[66] These recognized the environment as a legitimate user of water and required environmental water requirements to be determined "on the best scientific information available" and with "regard to the inter-temporal and inter-spatial water needs required to maintain the health and viability of river systems and groundwater basins." In 2004 these principles were reinforced through a National Water Initiative[67] that provided a national blueprint for water reform that was endorsed by all state governments. It called upon state governments to return of all rivers to sustainable levels of diversion, agreed actions for managing, measuring, planning, pricing, and trading water. The environment aspects of the reform were informed by a national assessment of the state of the rivers.[68]

Despite the far-sighted nature of the reforms, they failed to deal with the significant over-allocation of water in the Murray-Darling Basin—the heartland of irrigated agriculture in the country spanning four states and the Australian Capital Territory. The seriousness of the situation was highlighted by the decade-long "millennial drought" when the basin's extensive terminal lakes dried, the connected estuary suffered an ecological collapse, and iconic trees that were over 200 years old died due to a lack of water.

The Murray-Darling crisis catalyzed attention and willingness for new governance arrangements and a new approach to environmental flow determination, given the scale, complexity and economic and social significance of the problem. A new national authority for managing the basin replaced the prior cooperative arrangement. The authority has the responsibility to prepare a basin plan to ensure the return of all rivers and aquifers to sustainable levels, through the specification of "sustainable diversion limits". This required a major analytical effort over several years and extensive and difficult stakeholder consultations[69]. The science was contested and various independent reviews were used to assure quality and build stakeholder confidence[70]. Ultimately trade-offs were made to balance environmental outcomes with social and economic outcomes and the final aggregate sustainable diversion limits was set at about a 25 percent reduction in the average levels of water diversion. To make this feasible it was necessary to compensate losers and US$10 billion was made available. Around two-thirds of the money was used to purchase water entitlements from willing sellers on the water market, and one third was invested in water efficiency improvements in both public and private (on-farm) water distribution systems. The analytical approach used to guide this reform has now been recognized as new environmental flow method application to large scale regulated river basins, with diverse aquatic environments.[71]

MAP 3.1 The World's Largest Transboundary River Basins and the Populations They Support



Source: World Bank 2015a.

Third, technological remedies have an important role to play. New approaches and technologies (such as Climate Smart Agriculture), and infrastructure can ease supply constraints, protect assets and people as well as facilitate better demand management.

Food

Approaches that maximize benefits which cut across multiple dimensions of the water-climate nexus are needed to address water deficits. A smarter allocation of water across sectors will go a long way towards ensuring sustainable economic growth. Perhaps the most challenging but effective approach to enhancing efficiency and promoting more efficient water use is to provide incentives for more prudent use of water. The laws of demand and supply dictate that when water is provided more cheaply, it is used more wastefully. In many countries, pervasive and perverse subsidies promote the cultivation of water-intensive crops like rice and sugarcane[72] in arid areas. The increasing competition for water calls for policy instruments to signal scarcity and promote more prudent and sustainable water uses.

Water pricing is one, albeit often unpopular, mechanism for promoting more efficient water use. Water rights and water permits that give users the right to "rent" water is another instrument that recognizes the economic value of water and can provide incentives and signals to eliminate waste. The use of a water permit system in Australia has been credited with creating a system that endured a decade-long "millennium drought," for example. A policy of permits or prices coupled with safeguards to prevent regressive effects on the poor, and to provide for environmental water use would create the much needed incentive to promote more efficient[73], equitable, and sustainable production techniques.

Second, governments can help to close the large gap in agricultural productivity in some parts of the world where yields are often no greater than they were almost half a century ago; and in realizing the unexploited potential for better water management through improved allocation and better incentives for reducing wastage, over-use, and pollution. A related and critically important approach is Climate Smart Agriculture (CSA). CSA is an integrated approach combining policies, financing, and technologies designed to help food systems achieve a "triple win"—increasing productivity, enhancing resilience, and reducing greenhouse gas emissions.[74] CSA techniques range from planting crops suited to higher temperatures and longer droughts, to adopting practices such as alternate wetting and drying that minimize energy and water use while improving crop yields.[75]

CSA practices are aimed at simultaneously improving agricultural productivity while reducing vulnerability to increasing water scarcity. In the African Sahel region, where droughts are expected to intensify as a result of climate change, afforestation of degraded farmland improved crop yields by 15 to 30 percent while reducing the vulnerability of smallholder farmers to water scarcity.[76] CSA can be further enhanced through investments in new technologies such as heat-resistant crops, and can simultaneously reduce energy and water use while maintaining or increasing yields.[77] CSA is an example of the growing popularity of sustainable intensification strategies that seek to increase food production from existing farmland while minimizing pressure on the environment. It emphasizes that any efforts to intensify food production must be matched by a concerted focus on making it sustainable since failing to do so could undermine the capacity for future growth.

A challenge with these and other approaches that rely on training and information strategies is that adoption tends to be *slow and erratic* in the absence of incentives that induce changes in behavior. This is an old and familiar problem in development economics and is especially true of CSA-type technologies. Adoption of new methods are often slow when part of the benefits of the new approach are largely public while the costs (of adoption) are private. Policies are needed that can incentivize the adoption of new technologies, and create the impetus for adoption. The required approach would vary with circumstances. It may entail public investments, access to credit, insurance to address risk aversion, or payments for ecosystem services (PES) in the agricultural sector, or changes in input tariffs.[78]

Cities

Innovative approaches are needed to water-proof growing urban areas from both flood and drought risks. Projected changes in water availability during the lifetime of major infrastructure projects can no longer be based on historical trends.[79] To improve the robustness of system design, cities need a clear grasp of the available surface-water resources at basin level, the characteristics of local aquifers, and the associated climate-related risks. They can manage uncertainty and variability by diversifying water sources (if needed, with transfers from adjacent basins) and improving water utilities' preparedness. This would entail a variety of approaches such as increased water-storage capacity, insurance pricing, reducing water losses, reusing stormwater and greywater, and heightening awareness.[80] Adaptation to flood risks can reduce both the scale of events and their impacts on the city. The former can be achieved through improved land planning within the city and at basin level, balancing densification and impervious areas.

To mitigate the impacts of flooding, early warning systems can complement structural measures, such as drainage systems and dikes, and more restrictive enforcement of land use in flood-prone areas. Those structural measures need to take into better account a range of climate uncertainty in their design. Sustainable solid-waste management is essential to prevent clogging of drainage systems and catastrophic consequences from otherwise-benign rain events. When impacts are inevitable, insurance or safety nets should be considered, such as the Pakistan Citizen Damage Compensation Program.

Such approaches, referred to as integrated urban water management, function best when collaboration is strong among the state, local, and municipal governments in the metropolitan region, given their different purviews over the necessary interventions. Its application can also be facilitated in institutional settings by integrating the administration of key urban services (water supply, sewerage, drainage, wastewater treatment, solid-waste management, and slum upgrading) and water-resource and land-use planning (ecological zoning, protected areas, and public spaces).[81] Integrated water resource management (IWRM) approaches can also help to ensure that urban and agricultural water allocations provide for environmental flows.

Energy

Integrated planning is needed to assess the water supply implications of various forms of energy production. Trade-offs between water uses for low-carbon energy sources like hydropower can be partly mitigated by integrated management strategies to maintain minimum environmental flows and storage levels for irrigation. However, some renewable energy technologies, like concentrated solar power, consume significant quantities of water and intensify trade-offs. The rising water requirements of energy may also render what many perceive as a future panacea for water scarcity, desalination, counter-productive: current desalination technologies produce a substantial environmental impact, both in terms of brine production and greenhouse gas emissions, and are also significantly more expensive than traditional water provision. Given current technologies and costs, desalination is unlikely to be an economically feasible option for the large and expanding water demands of irrigated agriculture.

Environment

Unless environmental flows are protected critical ecosystem services may be irreparably degraded. Despite their importance, they remain the last claimant in the competition for water. Stewardship of natural assets calls for concerted efforts to assess and protect environmental water requirements in major water basins. As the Australian experience demonstrates, this task is both resource-intensive and politically challenging. Political will and recognition of the challenges is required to balance the needs of both current and future generations whose natural assets and resources are threatened by declining environmental flows.

The trade-offs between different water uses require difficult and contentious decisions, and most if not all countries will face considerable political obstacles to adopting these measures. But while adopting these reforms will be difficult, the costs of inaction are far higher. The future will be thirsty, but with the right reforms, governments can help ensure that people and ecosystems are not left high and dry in a more water-constrained world.

Notes

1. 2030 Water Resources Group 2009.
2. World Bank 2013.
3. Hanjra and Qureshi 2010.
4. Seckler et al. 1999; Khan and Hanjra 2009.
5. Pretty and Bharucha 2014.
6. Serageldin 2001.
7. Margat and van der Gun 2013
8. Appadurai et al. 2015.
9. Khan and Hanjra 2009.
10. Howden et al. 2007.
11. World Bank 2016.
12. Falkenmark et al. 2009.
13. Bonan 2008.
14. Doll 2002.
15. Bazilian et al. 2011.
16. Rodriguez et al. 2013.
17. Green et al. 2011.
18. Mohtar and Daher 2003.
19. Shah 2009.
20. Hart, Quin, and Nguyen 2004.
21. Steffen et al. 2015
22. Morton 2008.
23. Kumar et al. 2012.
24. Rasul 2014.
25. Pal and Eltahir 2016.
26. McKinsey and Co 2011.
27. World Water Council 2016.
28. Thebo et al. 2014 (Thebo, A.L.; Drechsel, P.; Lambin, E.F. 2014. Global assessment of urban and peri-urban agriculture: Irrigated and rainfed croplands. Environmental Research Letters 9: 114–122).
29. McDonald et al. 2014.

30. Beddington 2015; US Department of Defense 2014.
31. Revi et al. 2014.
32. World Bank 2010.
33. Intergovernmental Panel on Climate Change 2007.
34. Luo et al. 2015.
35. Organisation for Economic Co-Operation and Development (OECD) 2015, based on Winsemius and Ward 2015.
36. Hallegatte et al. 2013.
37. Tessler et al. 2015.
38. Revi, Satterthwaite, Aragón-Durand, et al. 2014.
39. Jenkins 2003.
40. World Bank 2015b.
41. United Nations Department of Economic and Social Affairs (UN DESA) 2014.
42. McDonald et al. 2011.
43. Based on United Nations Department of Economic and Social Affairs (UN DESA) 2014 and CGE model calculations in World Bank 2015a.
44. World Bank 2012.
45. City of Copenhagen 2011 and City of Copenhagen 2012.
46. Conable 2009.
47. Rodriguez et al. 2013.
48. Energy Sector Management Assistance Program 2012.
49. International Renewable Energy Association 2015.
50. Block et al. 2007.
51. Rodriguez 2016.
52. Rodriguez et al. 2013.
53. Mohtar and Daher 2003.
54. Mohtar and Dahar 2003.
55. World Bank estimates based on Zhou and Tol 2005 and Colley and Ajami 2012.
56. Smakhtin, Revenga and Doll 2004a and Smakhtin, Revenga and Doll 2004b.
57. McKechnie and Wolf 2009.
58. Smakhtin 2008.
59. Naiman et al. 2002.
60. Richter et al. 2003.
61. Arthington et al. 2010.
62. Lytle and Poff 2004
63. Opperman et al. 2015.
64. Arthington et al. 2010.
65. UN Water 2008.
66. Environment Australia 2004.
67. National Water Commission 2004.
68. Prosser et al. 2001.
69. Murray-Darling Basin Authority 2012.
70. Murray-Darling Basin Authority 2010.
71. Swirepik et al. 2015.
72. Anderson et al. 2010.
73. One of the most common proposed adaptations to water scarcity in agriculture, improving water use efficiency, can in fact have perverse consequences. Water applied to crops but not taken up by them helps to replenish the water table and is used by non-crop organisms that are themselves important to sustaining crop productivity. Indeed, some studies suggest that there is something like an "optimum level of inefficiency" that permits a portion of agricultural water withdrawals to contribute to environmental water requirements.

    Accordingly, agricultural water use strategies must ensure that these requirements are incorporated into overall water resource allocation.

74. World Bank 2015c.
75. Mushtaq et al. 2009.
76. World Resources Institute 2015.
77. Pender et al. 2009.
78. Swinton et al. 2007.
79. Milly et al. 2008.
80. Koundouri and Groom 2002.
81. SWITCH 2002.

Chapter 4

Conclusions and Policy Implications: Mitigating Water Shocks and Addressing Trends under a Changing Climate

The coming decades will see significant challenges in the water sector from both water-related climate shocks as well as trends. Changing trends in water availability, as well as an increase in extreme climate events, will coincide with a backdrop of an ever increasing thirst for water for productive, health, and environmental purposes. How the world responds to these water challenges will be pivotal in determining the planet's future growth path, and whether or not the world achieves the Sustainable Development Goals (SDGs). Although water only explicitly comprises one of the seventeen SDGs, the *expanded water nexus* framework demonstrates how all sectors of society are interlinked through the common currency of water, and how achieving nearly every one of the SDGs is dependent on solving the water problem.

Responses to the Water-Climate Challenge

Nearly a quarter of humanity already reside in water-scarce countries. If current water management policies persist, and climate models prove correct, water scarcity will proliferate to regions where it currently does not exist, and greatly worsen in regions where it does. These hydrological changes will have significant impacts on agricultural productivity as well as on cities where people and economic activity are concentrated. As water scarcity increases, ever more energy is needed for its extraction, treatment, and transport; while some sources of clean energy are often more water-intensive than dirtier alternatives. The primary message of the water-climate nexus is that trade-offs between water requirements for food and energy production, the environment, and urbanization under climate change are significant, and will require careful assessment by policymakers. However, the impact of these trade-offs can be ameliorated by taking several important steps.

Meeting these challenges will, in many regions, require unprecedented actions, significant investments in infrastructure, technology, and knowledge, and a radical rethinking of policies and institutions. There is no one-size-fits-all solution, and regional plans will require a flexible geometry which can adapt to the topology of the hazard, and local realities and characteristics.

In general, solutions can be categorized into three buckets: those aimed at increasing the supply of water; those designed to decrease the demand of water; and those which aim to reduce risks from water extremes by "climate proofing" valuable investments from natural hazards. There is no one-size-fits-all solution, however, and in practice, hybrid solutions will be needed, determined by country and regional risks and circumstances.

Increasing the Supply Of Water

Historically, the solution to increasing water scarcity was to increase the supply. The Ancient Romans, for instance, used enormous networks of aqueducts to move water hundreds of miles from areas of abundance, usually high up in the mountains, to their cities. The Ismailia Canal, built along the Suez Canal, was constructed in 1863 to bring freshwater from Lake Timsah to the city of Suez. Today, however, solutions like these are rare. Even though we only utilize a small fraction of the available freshwater on the planet, areas of abundance tend to be very far from, or inaccessible to, regions of scarcity.

Nevertheless, advancing technologies do offer opportunities for water supply expansion, and water resource recovery, in some regions. One such opportunity, particularly for large cities, is wastewater recycling. Wastewater recycling plants typically have two major drawbacks: they tend to be extremely energy intensive—in the U.S. they consume 2 percent of total electricity[1]—and they also generate a byproduct, known as sludge, which is difficult to dispose of in an environmentally safe way. Recent technologies, however, show promise for greatly alleviating these problems, making wastewater recycling a much more viable prospect for addressing water scarcity in cities. It has been shown that wastewater recycling can be accomplished at net-zero energy use. Biogas, a byproduct of the water treatment process, can be captured and used to offset the energy consumption of the treatment facility, resulting in net zero energy consumption.[2] At the same time, new uses for the sludge byproducts are being developed, including the processing into fertilizer, cement, or fuel.[3] These advances offer exciting opportunities not just for closing the water cycle, but also for mitigating carbon, reducing energy costs, and reducing environmental contaminants. Greater research is needed to determine the commercial viability and opportunities to scale up these new technologies.

Another means of increasing the water supply is desalination. Desalination has the potential to create a virtually limitless source of drought-proof, clean water in coastal areas. As detailed in Chapter 3, desalination is currently not economically viable, in many instances, for lower value uses. However, the cost of desalination, both in financial terms and in energy requirements, has fallen dramatically in the past decade, and as renewable energy technology advances, these costs may continue to fall. Desalination has the potential to offer back-stop protection against rainfall variability, while ensuring contamination-free water. Indeed, desalination may have the potential to revolutionize the water sector, but first there is a need to address the economic and ecological impacts of brine, the byproduct of desalination, and the impact of water intake on fisheries and aquatic biomes.

Finally, by far the most widely used method for increasing water supply is water storage, through the use of dams. Dams allow for the capture of runoff during periods of excess, which can be stored for release during periods of deficiency. They also have the added potential benefit of generating power, and flood protection. Globally, the stage is set for a tremendous and unprecedented increase in the number of dams, with numbers expected to swell by 16 percent by 2030, and storage volume expected to increase by about 40 percent.[4]

Supply side interventions, while essential, will not on their own resolve water management problems. History has consistently shown that when the amount of water supplied is increased and provided cheaply, this simply induces new demand. The laws of demand and supply dictate that when a productive, useful resource is provided for free (or almost free), it will inevitably be consumed in its entirety. As an example, new storage and irrigation infrastructure in arid areas, though essential, has spurred the cultivation of water intensive crops such as rice and sugarcane. The end result is an increased level of water dependence in arid areas that does little to ameliorate underlying scarcities or build upon natural comparative advantages. Investments in increasing water supplies must therefore be coupled with policies which promote efficiency and better allocate water resources.

Optimizing the Use for Water through Better Planning and Incentives

Growing populations and rising incomes are creating ever-increasing demands for water. In many parts of the world this growth in demand for water has been unchecked, with policies that have stimulated the over-use of water. This trajectory is unsustainable, however, and the supply of water is already approaching its ecological boundary in some regions. Ensuring water security in the future will therefore require more prudent demand side management.

Accomplishing this will require a significant shift in the way water is viewed. It will call for recognition that water is a scarce resource with significant productive value. This can be achieved through administrative decree or through economic instruments the deliver water to where it is most productive.

Allocations through water permits is one such instrument that gives users the right to "sell" or "rent" the water that is available to them. The result would be a win-win for both buyers and sellers as a transfer will occur only if the buyer and seller both anticipate a benefit from the transaction. The challenge with establishing such systems is the complex legal and institutional architecture that must accompany a credible system of water trading. Understanding how much water can be sustainably withdrawn in a certain region is a challenging task. This difficulty is multiplied many-fold in regions where climate change will vastly increase rainfall variability.[5] Determining the initial allocation of permits can also be a contentious process, particularly in countries with weak institutions where allocation may be (or have the perception of being) politically determined. Reforming water allocation in the agricultural sector faces even greater capacity issues.[6] Efforts to introduce water markets even in countries like Chile and Australia, where institutional capacity is generally high, have encountered substantial difficulties as a result of the need to establish total water availability, environmental water requirements, and provide clear legal entitlements to water use.[7]

Pricing is another instrument that could be used to guide the allocation of water for commercial uses. For municipal use, water pricing tends to be the simplest and most effective tool for moderating water use. Households are connected to a utility which can keep track of water use via a meter. High water prices tend to be effective at reducing municipal demand, and targeted subsidies or block tariffs can be strategically employed to ensure that the most vulnerable retain access to water and are not priced out of the market (see box 4.1). They could also provide the incentives for utilities to prevent wastage. When utilities are required to recover costs, they have a greater incentive to prevent revenue losses by fixing leaks in the system.[8] In fact, a staggering 32 billion cubic meters of treated water is lost to urban supply systems around the world each year through physical leaks in the pipes. Half of these losses occur in developing countries where customers already frequently suffer from interrupted supplies and poor water quality.[9]

Nevertheless, municipal water use is only a small fraction of total water use. Significantly more water is used for commercial purposes, particularly irrigated agriculture, where pricing is more complex. Water use for these purposes tends to be more inelastic than municipal water, making pricing less effective in reducing demand.[10] Further, agricultural water use is much more difficult to track than municipal water, particularly when farmers can drill into an aquifer and access groundwater, thus circumventing the higher prices.[11]

Attempts at water tariff reform face tremendous political, distributional, and institutional challenges. In many countries, providing free or low-cost access to water is seen as a basic responsibility of government, especially toward under-served rural and urban constituencies.[12] As a result, water price reform also requires extensive safeguards to avoid regressive effects on the poor. Under these circumstances, tradeable water permits can be a useful way

BOX 4.1 The Promise of Urban Water Price Reform

The experience of several countries and urban regions show that price reform can be a powerful driver of water use efficiency and conservation. Denmark instituted full cost recovery for urban water consumers in 1992, so that water prices were increased to reflect the full cost of providing water to end users. As a result, the real price of water increased by 54 percent from 1993–2004, reducing water demand from 155 liters per person per day to 125, one of the lowest levels in the developed world. The success of Denmark's price reform relies heavily on institutional capacity; the regressive effects of large water price increases for disadvantaged urban residents are buffered through the country's extensive social welfare system.[13] This example helps to illustrate the efficacy of demand-side responses to increasing water pressures under climate change. However, they also illustrate that substantial institutional capacity is required to implement demand-side measures in a way that protects the poor and promotes overall economic development.

of ensuring that water use remains below a certain threshold, and for rewarding those farmers who limit their water use.

Water price reforms such as these can also go a long way towards incentivizing the creation and adoption of water saving technologies. Climate-smart agriculture (CSA) has the potential to revolutionize the way food is produced. However, adoption tends to be slow largely because of misaligned incentives; the costs of CSA are borne by the farmer, but many of the benefits—including a reduced water footprint—are primarily public.

Finally, there are also opportunities to alter behavior and change thirsty consumption patterns through education, contextual cues, and using social norms to signal consent or disapproval. How people act and think often depends on what others around them do and think. The tools based on these behavioral nudges do not displace existing policy approaches that target incentives; rather, they complement and enhance them. There is limited use of these approaches in the sector and many of the emerging policy implications require further study.

Reducing the Impact of Extremes, Variability, and Uncertainty

Finally, the last challenge for ensuring a water secure world is reacting to and reducing the impact of extreme weather events, such as droughts, floods, and storm surges, and increased rainfall variability that is expected due to climate change. Opportunities for meeting these challenges often overlap with policies and investments which address water supply and demand. Indeed, reducing the amount of freshwater demanded relative to supply, and increasing the amount of water stored, will go a long way towards increasing resilience against highly variable rainfall, and the droughts and floods that the variability creates.

Mitigating the damage caused by extreme events will require large investments in technology and infrastructure. For coastal cities, such investments include seawalls and levees, and for cities along rivers, dams can also be effective tools for regulating river flows and preventing floods. These capital intensive investments come with significant risks, however. Once built, the investments are irreversible, and much uncertainty surrounds where they should be optimally placed and how large they should be. These investments must therefore be carefully researched and designed before commitments are made. Where uncertainty is high, modular options that allow for additions and reversals would be more suitable.

Other important investments include upgrading hydro-meteorological and early-warning systems. Increasing the lead-time of a storm can have tremendous benefits by allowing households to evacuate an area and move their belongings to higher ground. Better medium-term and seasonal forecasts can also help farmers make cropping and irrigating decisions, which can counteract some of the added uncertainty climate change will bring.[14] Nevertheless, forecasts are only useful if users have the ability to understand and incorporate them in decision-making. In some cases this will require building the institutions which have the capacity to transform a forecast into an actionable warning, and can communicate it to the local populations. In other cases, local communities must work with the relevant weather authorities to help them better understand what information is relevant and useful for local decision-making.

Another important, yet under-utilized tool in developing countries for responding to growing rainfall variability is crop insurance. Increasing farmers' access to crop insurance will not only protect households against falling into poverty or becoming food insecure when climate impacts destroy harvests. It will also incentivize farmers to invest in higher value crops and modern technologies by eliminating the catastrophic risk of losing a large investment if the harvest fails. In 2007, agricultural crop insurance premiums were less 0.3 percent of agricultural GDP in developing countries, significantly less than the 2.3 percent of agricultural GDP found in developed countries.[15] This gap suggests that developing countries are severely underserved, especially when accounting for the fact that rain-fed agriculture, a much riskier venture than irrigated agriculture, is much more common in developing countries.

Adaptation goals can often be achieved through better management of ecosystems and investments in natural capital, and at a fraction of the cost of physical and engineering solutions. Natural infrastructure (for example, forests, mangroves, flood plains, and rivers) not only serves as a source of protection and resilience, but is also required for sustainability—to assure future supplies of water. As the residual claimant, ecosystems receive the water that is left over from other uses, and water that is often polluted. This in turn disrupts river health, the ability to flush pollutants, and a host of other ecosystem services. As the world grows more crowded and thirstier, these problems and threats to ecosystems will escalate and investments in their protection will become more urgent.

But Will this Be Enough?

The solutions suggested here can go a long way towards preparing much of the world for a future of changing water trends, increased water variability, and increased scarcity. While there is indeed significant room for progress throughout much of the developing world, the question must be asked whether these prescriptions will be enough in some of the driest parts of the world.

Much of the Middle East, North Africa, the Sahel, and Central Asia, already extremely arid regions, are expected to become even drier in the coming decades. And some of these regions may see a decline in GDP due to a significant water deficit, even under positive water-policy regimes. Investments in new technologies for expanding water supplies and using water more efficiently will be vital, but may not be sufficient. These regions will need to take more robust measures to address water scarcity. The efforts would need to include policies that reduce the dependence on shriveling and more uncertain water supplies and de-couple water use from economic growth. Policies that anticipate the consequences of observed climate trends will be better prepared to respond to the complex challenges.

To a large extent, each country must also make its own decisions regarding the value of allocating water to different uses. Reacting to a changing environment and increased demographic pressures on water will be challenging but necessary for development. It will require large investments in infrastructure and technology, new policies to bring the cost of water in-line with its value, and better institutions, capable of managing this process in a fair and efficient manner. The costs of inaction will surely be greater than the challenges of more prudent water stewardship, particularly in the poorest and most water stressed regions of the world. Eliminating poverty, increasing prosperity, and meeting the Sustainable Development Goals will hinge on whether or not we solve this water problem.

This report highlights the relationship between climate change and the global water challenge, and offers several recommendations for how policymakers might adapt to a world shaped by water-related shocks and trends, and balance competing water use priorities. But in order to meet these challenges, all stakeholders in the global water sector, including governments, the private sector, and civil society, must join together to emphasize that every individual water user has a part to play. We all must become advocates for a more sustainable water future, and raise awareness to ensure all stakeholders understand their part in the global water challenge, and are empowered to play a role in addressing it.

Notes

1. http://css.snre.umich.edu/css_doc/CSS05-17.pdf
2. Chen and Chen 2013.
3. Buchauer and Huang, 2016.
4. http://www.gogeomatics.ca/magazine/mcgill-geography-researchers-map-global-impact-of-dams.htm#
5. Molden 2007.
6. Rivera 2015.
7. Bauer 1997; Turral et al. 2005.
8. Olmstead Hanemann and Stavins 2007.
9. Kingdom Liemberger and Marin 2006.
10. Molle and Berkoff 2007.
11. World Bank 2010.
12. Moore 2015.
13. OCED 2013.
14. Malik et al. 2014.
15. Mahul and Stutley 2010.

References

2030 Water Resources Group. 2009. Charting our Water Future: Economic frameworks to inform decision-making. McKinsey & Co.

Aguilar, A., & Vicarelli, M. (2011). El Nino and Mexican children: medium-term effects of early-life weather shocks on cognitive and health outcomes. Cambridge, United States: Harvard University, Department of Economics. Manuscript.

Almond, D., & Currie, J. (2011). Killing me softly: The fetal origins hypothesis. The journal of economic perspectives: a journal of the American Economic Association, 25(3), 153.

Anderson, Kym, John Cockburn, and Will Martin. 2010. Agricultural Price Distortions, Inequality, and Poverty. Washington, D.C.: World Bank.

Appadurai, Arivudal Nambi, Moushumi Chaudhury, Ayesha Dinshaw, Namrata Ginoya, Heather McGray, Lubaina Rangwala, and Shreyas Srivatsa. 2015. Scaling Success: Lessons from Adaptation Pilots in the Rainfed Regions of India. Washington, D.C.: World Resources Institute.

Araral, E. 2010. Reform of water institutions: review of evidences and international experiences. Water Policy Supplement 1, 12, 8–22.

Arndt, D. S., M. O. Baringer, and M. R. Johnson. 2010. "State of the Climate in 2009." Bulletin of the American Meteorological Society 91 (7): S1–S224.

Arthington, Angela, Robert Naiman, Michael McClain, and Christer Nilsson. 2010. "Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities." Freshwater Biology 55 (1): 1–16.

Bai, Y, and J Kung. "Climate shocks and Sino-nomadic conflict." Review of Economics and Statistics 93, no. 3 (2011): 970–981

Barker, D. J. (1995). Fetal origins of coronary heart disease. BMJ: British Medical Journal, 311(6998), 171.

Barrios, Salvador, Luisito Bertinelli, and Eric Strobl. "Climatic change and rural–urban migration: The case of sub-Saharan Africa." Journal of Urban Economics 60.3 (2006): 357–371.

Bates, B., Z. W. Kundzewicz, S. Wu, and J. Palutikof. 2008. "Climate Change and Water." Technical Paper, Intergovernmental Panel on Climate Change, Geneva.

Bauer, C. 1997. Bringing Water Markets Down to Earth: the political economy of water rights in Chile, 1976–95. World Development, 25 (5), 639–656.

Bazilian, Morgan, Holger Rogner, Mark Howells, Sebastian Hermann, Douglas Arent, Dolf Gielen, Pasquale Steduto, et al. 2011. "Considering the energy, water and food nexus: Towards an integrated modelling approach." Energy Policy 39: 7896–7906.

Beddington, J. 2015. "The 'Perfect Storm Revisited': Food, Energy and Water Security in the Context of Climate Change." Lecture at the Oxford Martin School, February 26. Oxford, UK.

Black, R. E., L. H. Allen, Z. A. Bhutta, L. E. Caulfield, M. de Onis, M. Ezzati, C. Mathers, and J. Rivera, Maternal and Child Undernutrition Study Group. 2008. Maternal and Child Undernutrition: Global and Regional Exposures and Health Co.

Blakeslee, D, and R Fishman. "Rainfall shocks and property crimes in agrarian societies: Evidence from India." Available at SSRN 2208292 (2013).

Block, Paul, Kenneth Strzepek, and Balaji Rajagopalan. 2007. Integrated Management of the Blue Nile Basin in Ethiopia. IFPRI Discussion Paper 00700, Washington, D.C.: International Food Policy Research Institute.

Bonan, Gordon. 2008. "Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests." Science 320 (5882): 1444–1449.

Brouwer, R., S. Akter, L. Brander, and E. Haque. 2007. "Socioeconomic Vulnerability and Adaptation to Environmental Risk: A Case Study of Climate Change and Flooding in Bangladesh." Risk Anal. Off. Publ. Soc. Risk Anal. 27: 313–26.

Brückner, M, and Ao Ciccone. "Rain and the democratic window of opportunity." Econometrica 79, no. 3 (2011): 923–947.

Buchauer, Konrad; Huang, Chi Rong. 2016. Final technical report Vol. 1 of Recommendations for urban sewage sludge management in China. Water Partnership Program. Washington, D.C.: World Bank Group. https://hubs.worldbank.org/docs/ImageBank/Pages/DocProfile.aspx?nodeid=26135926

Chaney, E. "Revolt on the Nile: Economic shocks, religion, and political power." Econometrica 81, no. 5 (2013): 2033–2053.

Carter, M. R., Little, P. D., Mogues, T., & Negatu, W. (2007). Poverty traps and natural disasters in Ethiopia and Honduras. World development, 35(5), 835–856.

Chen, S. and B. Chen. 2013. Net energy production and emissions mitigation of domestic wastewater treatment system: A comparison of different biogas-sludge use alternatives. Bioresource Technology 144: 296–303.

City of Copenhagen. 2011. http://international.kk.dk/aboutcopenhagen. Copenhagen Climate Adaptation Plan; accessed 10/19/2015.

City of Copenhagen. 2012. http://en.klimatilpasning.dk/media/665626/cph_-_cloudburst_management_plan.pdf. The City of Copenhagen Cloudburst Management Plan 2012; accessed 10/19/2015.

Colley H, Ajami N (2012). Key issues for desalination in California: cost and financing. Pacific Institute, Oakland.

Conable, Barber B. 2009. Climate Change Impact and Adaptation Study for Bangkok Metropolitan Region, Final Report. Washington, DC: World Bank. http://documents.worldbank.org/curated/en/2009/03/11164992/climate-change-impact-adaptation-study-bangkok-metropolitan-region-final-report-vol-1-3.

Christiaensen, Luc, and Shantayanan Devarajan. "Making the Most of Africa's Growth." Current history 112.754 (2013): 181.

Doll, Petra. 2002. "Impact of Climate Change and Variability on Irrigation Requirements: A Global Perspective." Climatic Change 54 (3): 269–293.

Energy Sector Management Assistance Program. 2012. A Primer on Energy Efficiency for Municipal Water and Wastewater Utilities. Technical Report, Washington, D.C.: World Bank.

Environment Australia. 2004. "The Council of Australian Governments' Water Reform Framework." Environment Australia. April 1. Accessed March 11, 2016. http://www.environment.gov.au/system/files/resources/6caa5879-8ebc-46ab-8f97-4219b8ffdd98/files/policyframework.pdf.

Falkenmark, M., J. Rockstrom, and L. Karlberg. 2009. "Present and future water requirements for feeding humanity." Food Security 1: 59–69.

Fishman, Ram, Meha Jain, and Avinash Kishore. Groundwater Depletion, Adaptation and Migration: Evidence from Gujarat, India. International Growth Center Working Paper, 2013.

Fosu, Augustin Kwasi. "Growth, inequality and poverty in sub-Saharan Africa: recent progress in a global context." Oxford Development Studies 43.1 (2015): 44–59.

Felbermayr, G., & Gröschl, J. (2013). Economic Effects of Natural Disasters: New Insights from New Data.

Fishman, R., Russ, J., & Carrillo, P. (2015). Long-Term Impacts of High Temperatures on Economic Productivity. Institute for International Economic Policy Working Paper.

Grafton, R. Q., and T. Kompas. (2007). "Pricing Sydney Water." Australian Journal of Agricultural and Resource Economics 51 (3): 227–41.

Green, Timothy, Makoto Taniguchi, Henk Kooi, Jason Gurdak, Diana Allen, Kevin Hisock, Holger Treidel, and Alice Aureli. 2011. "Beneath the surface of global change: Impacts of climate change on groundwater." Journal of Hydrology 405 (3–4): 532–560.

Hallegatte, Stephane; Bangalore, Mook; Bonzanigo, Laura; Fay, Marianne; Kane, Tamaro; Narloch, Ulf; Rozenberg, Julie; Treguer, David; Vogt-Schilb, Adrien. 2016. Shock Waves: Managing the Impacts of Climate Change on Poverty. Climate Change and Development. Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/22787 License: CC BY 3.0 IGO.

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. Nature climate change, 3(9), 802–806.

Hanjra, Munir, and M. Ejaz Qureshi. 2010. "Global water crisis and future food security in an era of climate change." Food Policy 35 (5): 365–377.

Hart, M. R., Quin, B. F., & Nguyen, M. (2004). Phosphorus runoff from agricultural land and direct fertilizer effects. Journal of Environmental Quality, 33(6), 1954–1972.

Havlík, Petr, et al. "Climate Change Impacts and Mitigation in the Developing World: An Integrated Assessment of the Agriculture and Forestry Sectors." World Bank Policy Research Working Paper 7477 (2015).

Henderson, V., Adam Storeygard, and U. Deichmann. Has climate change driven urbanization in Africa? Working paper, London School of Economics, 2015.

Hidalgo, F. D, S Naidu, S Nichter, and N Richardson. "Economic determinants of land invasions." The Review of Economics and Statistics 92, no. 3 (2010): 505–523.

Howden, S. Mark, Jean-Francois Soussana, Francesco Tubiello, Netra Chhetri, Michael Dunlop, and Holger Meinke. 2007. "Adapting agriculture to climate change." Proceedings of the National Academy of Sciences 104 (50): 19691–19696.

Hsiang, S. M., and A. S. Jina. 2014. “The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence from 6,700 Cyclones.” Working Report 20352, National Bureau of Economic Research, Cambridge, MA.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: Author.

Intergovernmental Panel on Climate Change (IPCC). 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report. Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. IPCC working group II contribution to AR5. Geneva: Author. www.ipcc-wg2.gov/AR5/

International Renewable Energy Association. 2015. Renewable Energy in the Water, Energy & Food Nexus. Abu Dhabi: IRENA.

Jenkins, M. 2003. “Using Economic Loss Function to Value Urban Water Scarcity in California.” Journal of the American Water Works Association 95 (2): 58–70.

Jiménez Cisneros, B. E., T. Oki, N. W. Arnell, G. Benito, J. G. Cogley, P. Döll, T. Jiang, and S. S. Mwakalila. 2014. “Freshwater Resources.” In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A, Global and Sectoral Aspects, ed. Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, 229–69. Cambridge, UK: Cambridge University Press.

Johansson, R., Tsur, Y., Roe, T., Doukkali, R., & Dinar, A. 2002. Pricing irrigation water: a review of theory and practice. Water Policy, 4, 173–199.

Khan, Shahbaz, and Munir Hanjra. 2009. “Footprints of water and energy inputs in food production—Global perspectives.” Food Policy 34: 130–140.

Kingdom, B., R. Liemberger, and P. Marin. “The challenge of reducing non-revenue water (NRW) in developing countries.” How the Private Sector Can Help: A Look at Performance-based Service Contracting, Water Supply and Sanitation Board Discussion Paper Series, Paper No. 8 (2006).

Koundouri, P., and B. Groom. 2002. “Groundwater Management: An Overview of Hydrogeology, Economic Values, and Principles of Management.” Groundwater, Volume 3. Abu Dhabi, U.A.E.: UNESCO-EOLSS. http://www.eolss.net/Sample-Chapters/C07/E2-09-07-00.pdf

Krishna, Anirudh. “The Stages of Progress Methodology and Results from Five Countries.” Reducing Global Poverty: The Case for Asset Accumulation (2007): 62–79.

Kumar, S., Molitor, R., & Vollmer, S. (2014). Children of drought: Rainfall shocks and early child health in rural India. Available at SSRN 2478107.

Kumar, M. Dinesh, M.V.K. Sivamohan, and A. Narayanamoorthy. 2012. “The food security challenge of the food-land-water nexus in India.” Food Security 4: 539–556.

Luo, T., A. Maddocks, C. Iceland, P. Ward, and H. Winsemius. 2015. "World's 15 Countries with the Most People Exposed to River Floods." Washington, DC: World Resources Institute. http://www.wri.org/blog/2015/03/world's-15-countries-most-people-exposed-river-floods

Lytle, D. A., & Poff, N. L. (2004). Adaptation to natural flow regimes. Trends in ecology & evolution, 19(2), 94–100.

Maccini, S. L., & Yang, D. (2008). Under the weather: health, schooling, and economic consequences of early-life rainfall (No. w14031). National Bureau of Economic Research.

Malik, A. S., Amacher, G. S., Russ, J., Esikuri, E. E., & Ashida Tao, K. (2014). Framework for Conducting Benefit-Cost Analyses of Investments in Hydro-Meteorological Systems.

Margat, J., & Van der Gun, J. (2013). Groundwater around the world: a geographic synopsis. CRC Press.

Mahul, Olivier, and Charles J. Stutley. Government support to agricultural insurance: challenges and options for developing countries. World Bank Publications, 2010.

McDonald, R. I., P. Green, D. Balk, B. M. Fekete, C. Revenga, M. Todd, and M. Montgomery. 2011. "Urban Growth, Climate Change, and Freshwater Availability." Proceedings of the National Academy of Sciences 108 (15): 6312–17.

McDonald, R. I., K. Weber, J. Padowski, M Florke, C Schneider, P A. Green, T. Gleeson, S. Eckman, B. Lehner, D. Balk, T. Boucher, G. Grill, and M. Montgomery. 2014. "Water on an Urban Planet: Urbanization and the Reach of Urban Water Infrastructure." Global Environmental Change 27 (July): 96–105. http://www.sciencedirect.com/science/article/pii/S0959378014000880

McKechnie, Andrew, and Blair Wolf. 2009. "Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves." Biology Letters 7 (2).

McKinsey Global Institute, (2011). "Urban world: Mapping the economic power of cities."

Mekonnen, Mesfin, and Arjen Hoekstra. 2016. "Four billion people facing severe water scarcity." Science 2: 1–6.

Miguel, E, S Satyanath, and E Sergenti. "Economic shocks and civil conflict: An instrumental variables approach." Journal of political Economy 112, no. 4 (2004): 725–753.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lattenmaier, and R. J. Stouffer. 2008. "Stationarity Is Dead: Whither Water Management?" Science 319 (1): 573–74.

Mohtar, Rabi, and Bassel Daher. 2003. "Water, Energy, and Food: the Ultimate Nexus." In Encyclopedia of Agricultural, Food, and Biological Engineering, by Dennis Heldman. New York: CRC Press.

Molden, D. 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan and International Water Management Institute.

Molle, F., and J. Berkoff. 2007. Irrigation Water Pricing: The Gap between Theory and Practice. Wallingford, UK: CAB International.

Moore, S. 2015. The development of water markets in China: progress, peril, and prospects. Water Policy 17(2): 253–267.

Morton, John. 2008. "The impact of climate change on smallholder and subsistence agriculture." Proceedings of the National Academy of Sciences 104 (50): 19680–19685.

Murray-Darling Basin Authority. 2012. Basin Plan. Accessed March 11, 2016. http://www.mdba.gov.au/basin-plan.

———. 2010. Science behind the Basin Plan. Accessed March 11, 2016. http://www.mdba.gov.au/basin-plan/developing-basin-plan/science-behind-basin-plan.

Mushtaq, Shahbaz, Tek Narayan Maraseni, Jerry Maroulis, and Mohsin Hafeez. 2009. "Energy and water tradeoffs in enhancing food security: A selective international assessment." Energy Policy 37: 3635–3644.

Naiman, Robert, Stuart Bunn, Christer Nilsson, Geoff Petts, Gilles Pinay, and Lisa Thompson. 2002. "Legitimizing Fluvial Ecosystems as Users of Water: An Overview." Environmental Management 30 (4): 455–467.

National Water Commission. 2004. "National Water Initiative." National Water Commission. June 25. Accessed March 11, 2016. http://www.nwc.gov.au/nwi.

OECD 2013. Water Security for Better Lives, OECD Studies on Water, OECD Publishing. http://dx.doi.org/10.1787/9789264202405-en

OECD. 2015. The Economic Consequences of Climate Change. Paris: OECD Environment Directorate Circle Project.

Olmstead, S. M. 2013. "Climate Change Adaptation and Water Resource Management: A Review of the Literature. Energy Economics (in press).

Olmstead, Sheila M., W. Michael Hanemann, and Robert N. Stavins. "Water demand under alternative price structures." Journal of Environmental Economics and Management 54.2 (2007): 181–198.

O'Neill, B., E. Kriegler, K. Ebi, E. Kemp-Benedict, K. Riahi, D. Rothman, B. van Ruijven, D. van Vuuren, J. Birkmann, K. Kok, M. Levy, and W. Solecki. 2015. "The Roads Ahead: Narratives for Shared Socioeconomic Pathways Describing World Futures in the 21st Century." Global Environmental Change (in press).

Opperman, Jeff, G. Grill, and J. Hartmann. 2015. The Power of Rivers: Finding balance between energy and conservation in hydropower development. Washington, D.C.: The Nature Conservancy.

Pal, Jeremy, and Elfatih Eltahir. 2016. "Future temperature in southwest Asia projected to exceed a threshold for human adaptability." Nature Climate Change 6: 197–201.

Pender, John, Claudia Ringler, Marilia Magalhaes, and Frank Place. 2009. The role of sustainable land management for climate change adaptation and mitigation in Sub-Saharan Africa. Washington, D.C.: International Food Policy Research Institute.

Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. Annals of botany, 114(8), 1571–1596.

Rasul, Golam. 2014. “Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region.” Environmental Science & Policy 39: 35–48.

Ravallion, M. (2012). Why don’t we see poverty convergence? The American Economic Review, 102(1), 504–523.

Ravallion, Martin, and Shaohua Chen. “What can new survey data tell us about recent changes in distribution and poverty?” The World Bank Economic Review 11.2 (1997): 357–382.

Revi, A., D. Satterthwaite, F. Aragón-Durand, J. Corfee-Morlot, R. B. R. Kiunsi, M. Pelling, D. C. Roberts, and. W. Solecki. 2014. “Urban Areas.” In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A, Global and Sectoral Aspects, ed. Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, 532–612. Cambridge, UK: Cambridge University Press.

Richter, Brian, Ruth Mathews, David Harrison, and Robert Wigington. 2003. “Ecologically sustainable water management: managing river flows for ecological integrity.” Ecological Applications 13 (1): 206–224.

Rivera, V. 2014. Tap Secrets: the Manila Water Story. Manila: Asian Development Bank.

Rodriguez, Diego J., interview by Richard Demania. 2016. Senior Economist, Energy and Extractives Global Practice, World Bank Group (March 6).

Rodriguez, D. J., Delgado, A., DeLaquil, P., & Sohns, A. (2013). Thirsty energy.

Sarsons, H. “Rainfall and conflict: A cautionary tale.” Journal of Development Economics 115 (2015): 62–72

Seckler, David, Randolph Barker, and Upali Amarasinghe. 1999. “Water Scarcity in the Twenty-first Century.” International Journal of Water Resources Development 15 (1–2): 29–42.

Serageldin, Ismail. 2001. “Assuring Water for Food: The Challenge of the Coming Generation.” International Journal of Water Resources Development 17 (4): 521–525.

Shah, Tushar. 2009. “Climate change and groundwater: India’s opportunities for mitigation and adaptation.” Environmental Research Letters 4: 035005–035018.

Smakhtin, Victor. 2008. “Basin Closure and Environmental Flow Requirements.” International Journal of Water Resources Development 24 (2): 227–233.

Smakhtin, Vladimir, Carmen Revenga, and Petra Doll. 2004a. “A Pilot Global Assessment of Environmental Water Requirements and Scarcity.” Water International 29 (3): 307–317.

Smakhtin, Vladimir, Carmen Revenga, and Petra Doll. 2004b. Taking into account environmental water requirements in global-scale water resources assessments. Comprehensive Assessment Secretariat, Colombo: Comprehensive Assessment Secretariat.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., & Folke, C. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223), 1259855.

Swinton, Scott, Frank Lupi, G. Philip Robertson, and Stephen Hamilton. 2007. "Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits." Ecological Economics 64 (2): 245–252.

Swirepik, J. L., et al. (2015) Establishing environmental water requirements for the Murray-Darling Basin – Australia's largest developed river system. River Research and Applications, DOI: 10.1002/rra.2975.

SWITCH. 2002. "SWITCH Approach to Strategic Planning for Integrated Urban Water Management (IUWM)." Freiburg, Germany: ICLEI European Secretariat. http://www.switchtraining.eu/fileadmin/template/projects/switch_training/db/event_upload_folder/103/SWITCHtrategyplanningapproach28october.pdf

Tessler, Z. D., C. J. Vörösmarty, M. Grossberg, I. Gladkova, H. Aizenman, J. Syvitski, and E. Foufoula-Georgiou. 2015. "Profiling Risk and Sustainability in Coastal Deltas of the World." Science AAAS (forthcoming). http://personal.cege.umn.edu/~foufoula/papers/efg_166.pdf

Thai, T. Q., & Falaris, E. M. (2014). Child schooling, child health, and rainfall shocks: Evidence from rural Vietnam. Journal of Development Studies, 50(7), 1025–1037.

UN Water. 2008. "Transboundary Waters: Sharing Benefits, Sharing Responsibilities." Thematic Paper. http://www.unwater.org/downloads/UNW_TRANSBOUNDARY.pdf

United Nations Department of Economic and Social Affairs (UNDESA). 2014. "World Urbanization Prospects: The 2014 Revision, Highlights." New York: UNDESA Population Division. http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf

US Department of Defense. 2014. FY 2014 Climate Change Adaptation Roadmap. Washington, DC: Author. http://www.acq.osd.mil/ie/download/CCARprint_wForeword_c.pdf

Victora, C. G., L. Adair, C. Fall, P. C. Hallal, R. Martorell, L. Richter, and H. S. Sachdev. 2008. "Maternal and Child Undernutrition: Consequences for Adult Health and Human Capital." The Lancet 371: 340–57.

Watson, John T., Michelle Gayer, and Maire A. Connolly. "Epidemics after natural disasters." Emerging infectious diseases 13.1 (2007).

Winsemius, H. C., Jongman, B., Veldkamp, T., Hallegatte, S., Bangalore, M., & Ward, P. (2015). Disaster Risk, Climate Change, and Poverty: Assessing the Global Exposure of Poor People to Floods and Droughts. World Bank Policy Research Working Paper, (7480).

Winsemius, H. C. and P. J. Ward. 2015. "Projections of future urban damages from floods." Personal communication to OECD.

World Bank. 2010a. Economics of Adaptation to Climate Change. Synthesis Report. Washington, DC: Author. http://siteresources.worldbank.org/EXTCC/Resources/EACC_FinalSynthesisReport0803_2010.pdf

World Bank 2010b. World Development Report 2010: « Climate-Smart » World Within Reach. Washington, DC: World Bank.

World Bank. 2012a. Adaptation au changement climatique et la résilience aux désastres naturels dans les villes côtières d'Afrique du Nord. Washington, DC: Author.

World Bank. 2015a. "The Forgotten Factor of Climate Change-Water: Technical Papers." Washington, DC: Author.

World Bank. 2015b. "Mainstreaming Water Resources Management in Urban Projects: Taking an Integrated Urban Water Management Approach: A Guidance Note." Unpublished mimeo. Washington, DC: Author.

World Bank/International Energy Agency. 2015c. Progress Toward Sustainable Energy for All 2015. Washington, D.C.: World Bank.

World Bank. 2016. Development Impact Notes. Turning Down the Heat, Washington, D.C.: World Bank.

World Economic Forum. 2015. Global Risks 2015 10th Edition. Geneva: Author. http://www3.weforum.org/docs/WEF_Global_Risks_2015_Report15.pdf

World Resources Institute (WRI). 2015. AQUADUCT Measuring and mapping water risk. http://www.wri.org/our-work/project/aqueduct

World Water Assessment Programme (WWAP). 2006. The United Nations World Water Development Report 2: Water. A Shared Responsibility. Paris, UNESCO.

WWAP (World Water Assessment Programme). 2012. The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk. Paris, UNESCO.

Zhou, Y., & Tol, R. S. (2005). Evaluating the costs of desalination and water transport. Water resources research, 41(3).

WATER
PARTNERSHIP
PROGRAM

WORLD BANK GROUP

SKU K8517