SECURING WATER, SUSTAINING GROWTH

Report of the GWP/OECD Task Force on Water Security and Sustainable Growth

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The Global Dialogue

The Global Dialogue for Water Security and Economic Growth is a joint initiative of the GWP and the OECD to promote and accelerate a transition to water security, by connecting policymakers and practitioners through global and country level consultations and through an expert task force analysis of the links between water security and sustainable economic growth.

About GWP

The mission of the Global Water Partnership (GWP) is to advance governance and management of water resources for sustainable and equitable development. GWP is an intergovernmental organisation and a global network of 13 Regional Water Partnerships, 85 Country Water Partnerships and more than 3,000 Partner organisations in 172 countries. The GWP network is committed to building a water secure world.

About OECD

The mission of the Organisation for Economic Co-operation and Development (OECD) is to promote policies that will improve the economic and social well-being of people around the world. The OECD provides a forum in which governments can work together to share experiences and seek solutions to common problems. We work with governments to understand what drives economic, social and environmental change. OECD work on water focuses on water economics and governance. It aims at facilitating the reform of water policies, so that they are better attuned to current and future challenges.

Source citation

This report should be referenced as:
Sadoff, C.W., Hall, J.W., Grey, D., Aerts, J.C.J.H., Ait-Kadi, M., Brown, C., Cox, A., Dadson, S., Garrick, D., Kelman, J., McCornick, P., Ringler, C., Rosegrant, M., Whittington, D. and Wiberg, D. (2015) Securing Water, Sustaining Growth: Report of the GWP/OECD Task Force on Water Security and Sustainable Growth, University of Oxford, UK, 180pp.

South Parks Road
Oxford
OX1 3QY
United Kingdom

ISBN 978-1-874370-54-3 (print)

ISBN 978-1-874370-55-0 (online)

Design and layout: One Ltd, 2015

Printer: Elanders, Sweden, 2015

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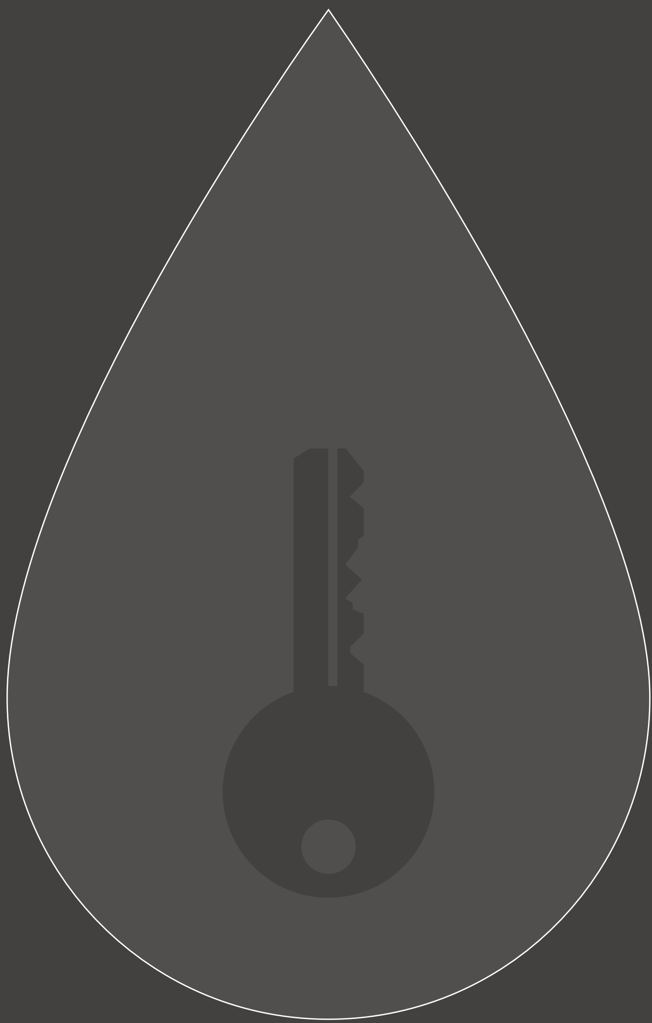


Acknowledgements

This Report* was prepared as part of the GWP/OECD Global Dialogue on Water Security and Sustainable Growth.

The Report is jointly authored by the Global Dialogue's Task Force. The members of the Task Force are: Claudia Sadoff, the World Bank (Chair); Jim Hall and David Grey, University of Oxford, UK (Co-Chairs); and (listed in alphabetical order) Jeroen Aerts, VU University Amsterdam, Netherlands; Mohamed Ait-Kadi, Global Water Partnership, Sweden; Casey Brown, University of Massachusetts, USA; Anthony Cox, Organisation for Economic Co-operation and Development, France; Simon Dadson, University of Oxford, UK; Dustin Garrick, McMaster University, Canada (Pathways Research Coordinator); Jerson Kelman, University of Rio de Janeiro, Brazil; Peter McCornick, International Water Management Institute, Sri Lanka; Claudia Ringler and Mark Rosegrant, International Food Policy Research Institute, USA; Dale Whittington, University of Manchester, UK, and University of North Carolina at Chapel Hill, USA; David Wiberg, International Institute for Applied Systems Analysis, Austria.

We gratefully acknowledge the leadership and oversight provided by the Global Dialogue's two Chairs: Angel Gurría, Secretary-General of the OECD; and HE Ellen Johnson Sirleaf, President of Liberia.

We recognize the Global Dialogue's sponsors, the Global Water Partnership (GWP) and the Organisation for Economic Co-operation and Development (OECD). We are grateful to the Danish International Development Agency (Danida) for their financial support of the Dialogue. We thank the Dutch Ministry of Infrastructure and Environment for its financing of case studies informing our work, and the CGIAR Research Program for Water, Land and Ecosystems (WLE) for supporting the crop modeling underlying parts of the Report.

Special thanks go to: Ursula Schaefer-Preuss, Ania Grobicki, Fraser MacLeod, Alan Hall, Noumbissi Tenku, Steven Downey, Sara Ehrhardt and members of the Technical Committee of the GWP; and to Xavier Leflaive, Kathleen Dominique, Gerard Bonnis, and Hannah Leckie of the OECD. Additional support from the World Bank and the Oxford Martin School is gratefully acknowledged.

We thank the Research Teams within many institutions, whose essential work of literature review, analysis, and modelling forms the foundation of the Report. These teams include: Franziska Gaupp, Kevin Wheeler, Simon Abele, Justin Rhodes, Yuuki Peters, University of Oxford, UK; Tingju Zhu, Gauthier Pitois, Ricky Robertson, Sherman Robinson, International Food Policy Research Institute, USA; Heather O'Leary, Ana Martine Melgaard, Oheneba Boateng, McMaster University, Canada; Hassaan Khan, Patrick Ray, University of Massachusetts, USA; Jane Zhao, University of North Carolina at Chapel Hill, USA; Lucia De Stefano, Complutense University of Madrid, Spain; Philip Ward, Brenden Jongman, VU University Amsterdam, Netherlands; Robert Nicholls, University of Southampton, UK; Jochen Hinkel, Daniel Lincke, Global Climate Forum, Germany.

We thank several individuals and institutions that generously provided access to invaluable datasets, including: Charles Vorosmarty, City University New York, USA; Richard Taylor, Tracy Lane, International Hydropower Association, UK; Marc Jeuland, Duke University; Amandine Pastor, Wageningen University, Netherlands; Hessel Winsemius, Deltares, Netherlands; Willem Ligtvoet, Arno Bouwman, PBL Netherlands Environmental Assessment Agency, Netherlands; Guy Hutton, World Bank, USA; International Water Management Institute, Sri Lanka; International Institute for Applied Systems Analysis, Austria.

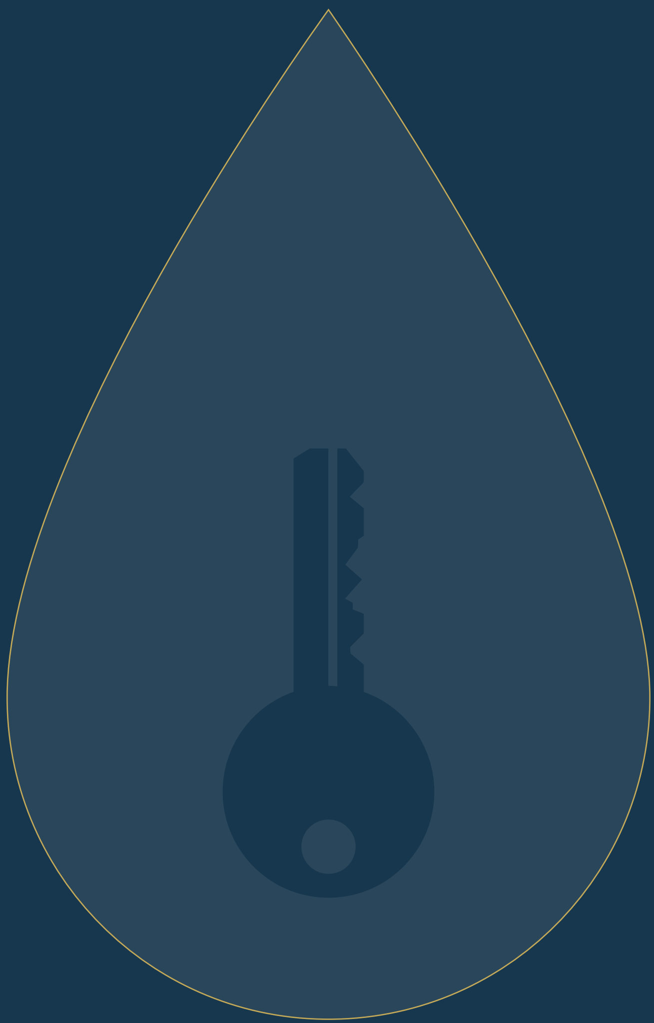
We acknowledge the information provided by 40 national consultations, carried out in 2013 and 2014 by the GWP network, with support from: the Swiss Agency for Development and Co-operation; the United Nations Development Programme (UNDP); and Danida. We recognize a consultation within India, sponsored by the OECD Knowledge Sharing Alliance.

The Task Force benefitted from comments received at three high-level meetings, held in Singapore (2 June 2014), Stockholm (1 September 2014), and Paris (27 November

2014). Participants in the meetings included Angel Gurría, Secretary-General of the OECD, France; Ursula Schaefer-Preuss, Chair of the Global Water Partnership, Sweden; Melanie Schultz van Haegen, Minister of Infrastructure and Environment, Netherlands; Chen Lei, Minister of Water Resources, China; Alok Rawat, former Secretary for Water Resources, India; Benedito Braga, President of the World Water Council, France; Choi Gyewoon, CEO, K-Water, Korea; Kapil Mohan, Water Resources Department, Government of Karnataka, India; Herbert Oberhaensli, Vice-President, Nestlé, Switzerland; Ania Grobicki, Executive Secretary of the Global Water Partnership, Sweden; Kim Chang-Gil, Research Director, Korea Rural Economic Institute (KREI), Korea.

We thank the Expert Advisers who shared their knowledge of river basins, aquifers, and cities across the world. Their help enabled development of the case studies and timelines of pathways to water security. We thank (in alphabetical order): Masood Ahmad (Indus); Rosalind Bark, Kevin Wheeler (Colorado River Basin); Chris Binnie (London); Don Blackmore (Murray-Darling River Basin); Lucia De Stefano (Ebro River Basin; Upper Guadiana Aquifer System); Ousmane Dione (Senegal River Basin); Michael Edmunds (Nubian Sandstone Aquifer system); Stephen Foster (groundwater; the Guarani Aquifer system); Ricardo Hirata (Guarani Aquifer system); Fernando J. González Villarreal, Jorge Alberto Arriaga Medina (Mexico City); Jerson Kelman (Sao Francisco River Basin); Anoulak Kittihoun, Ton Lennaerts (Mekong River Basin); Gail Krantzberg, Savitri Jetoo (Great Lakes); Michael Muller, Barbara Schreiner (Gauteng City complex); Maria Teresa Ore, Javier Chiong (Ica Valley); Robert Osborne (Apalachicola River Basin); Sanjay Pahuja, Aditi Mukherji (Ganges groundwater system); Mariya Pak Feuer (Aral Sea); Zhonghe Pang (North China Plain); Salman Salman (Nile River Basin); Bridget Scanlon (Ogallala Aquifer); Cecilia Tortajada (Singapore); Hong Yang (Beijing); Eelco van Beek, Marjolijn Haasnoot, Hans Middelkoop, Frans Klijn (Rhine River Basin).

Finally, we thank the following for undertaking essential tasks: Cheryl Colopy, Matthew Roberts (Editors); Karis McLaughlin, University of Oxford (communications and logistics); ONE Ltd, Oxford (design).



Executive Summary

Water security, sustainable growth, and well-being

For millennia, humankind has struggled to develop water resources for domestic water supplies, to provide irrigation, and to limit flood losses. This struggle to leverage water-related opportunities and manage water-related risks, while addressing social and environmental demands, is at the heart of water security.

Most of the world's developing countries remain relatively water insecure. Most developed countries invested heavily in water security, often starting early on their path to growth. These developed nations are now relatively water secure, but must continuously adapt and invest to maintain water security in the face of climate change, deteriorating infrastructure, economic development, demographic change, and rising environmental quality expectations.

Today, the challenge of water security is global, and growing. Achieving and sustaining water security, in both developed and developing countries, is likely to increase in complexity and priority – not only as climate change intensifies, but also as the demands of economic growth increase. The criticality of this challenge is reflected in the World Economic Forum's 2015 *Global Risks Report*, in which water is ranked as the global risk with the single greatest potential impact on economies over the next ten years. Its importance is also signalled by the proposed development of a dedicated Sustainable Development Goal for water.

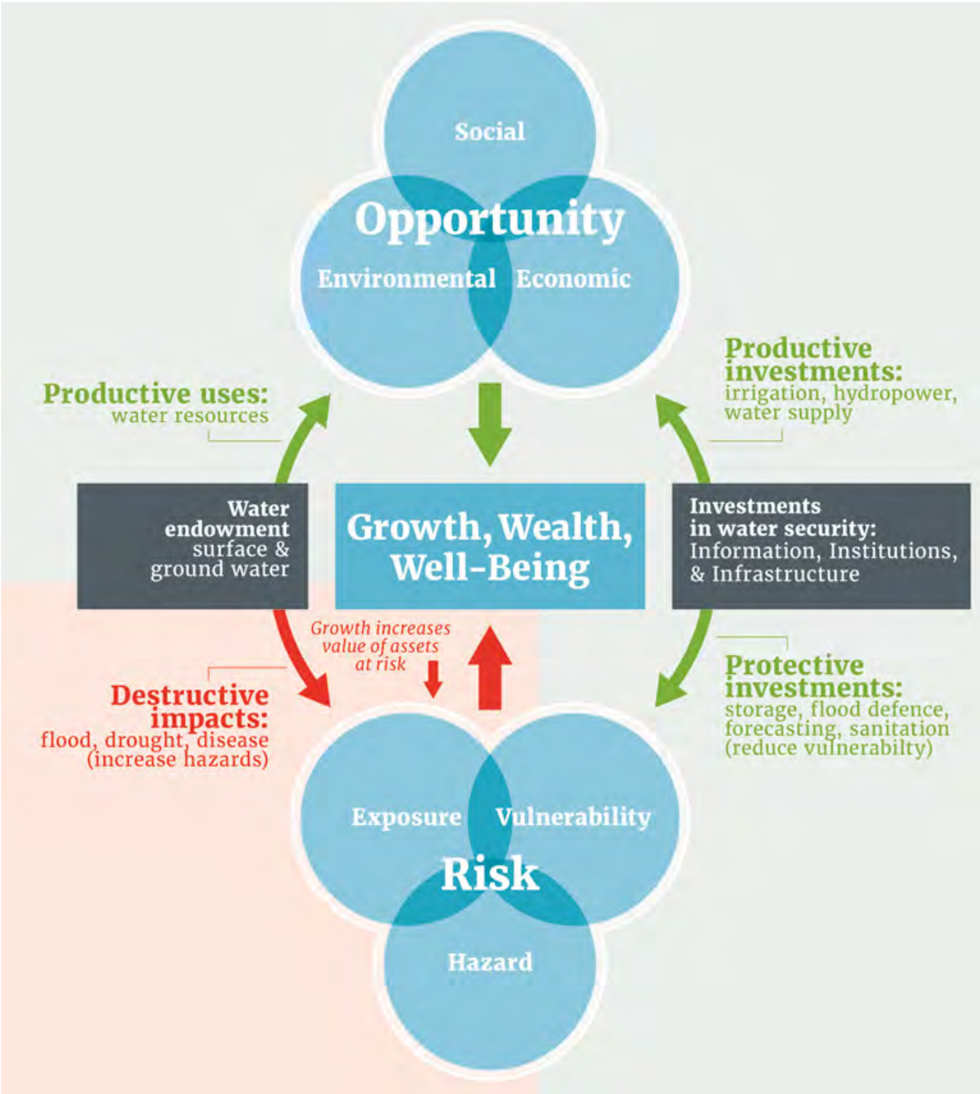
The objective of this Report is to promote sustainable growth and well-being, by providing empirical evidence to guide investment in water security. It seeks to: analyze the dynamics of water security and growth; quantify water-related risks and opportunities and their trajectories; and assess the experience of past pathways of investment toward water security. The Report focuses on growth: where, how, and how much, water security affects growth. The Report adopts a risk-based approach to identify the hazards and vulnerabilities of a lack of water security.

Water-related risks (such as scarcity, floods, access, and resource degradation) are growing, as population growth and economic growth put greater pressure on water resources – pushing more people and more assets 'into harm's way'. Water-related risks are also growing due to climate change, as water availability becomes less predictable, and as extreme weather events become more common. Where multiple water risks are present, the challenge of achieving water security will be compounded.

Although we focus on risks in this analysis, it must be emphasized that water is not only destructive – it is also profoundly productive. Water is essential to all life – and to households, agriculture, industry, energy, and transport. Thus, investment in water security is not only a matter of protecting society from specific water-related risks; it is an investment that supports economic growth and social well-being. While economic growth can enhance risks by increasing the value of exposed assets, growth also provides the resources needed to manage water and water-related risks. Growth enables investment in institutions (defined broadly to include agencies, rules, and incentives), information systems (hydro-meteorological, economic, and social), and infrastructure (natural and constructed), as well as investment into vital research and development of innovative technologies, and financial risk management tools.

Policies and infrastructure investments are needed to enhance water security; to allocate water between alternative uses; to deliver water at specific times, places, and prices; to ensure water quality; and to protect people and assets from water-related hazards. All of these can create opportunities and reduce risks for different regions, sectors, and communities. This, in turn, can have a profound impact on economic growth, inclusiveness, and the structure of economies.

Conceptual framework of the dynamic of water security and sustainable growth



Moreover, as the world globalizes, water-related risks that were once considered local supply limitations or weather hazards are increasingly seen as regional and global challenges. Globalization can help mitigate local water-related challenges through food trade, financial risk management tools, foreign direct investment, and cooperative disaster warning and response mechanisms.

Yet, the negative impacts of these risks can also be propagated through the global economy, and through social disruptions, population displacement, disease, and species and habitat losses.

Framing the water security challenge

Sustainable economic growth, wealth, and human well-being are at the heart of the Report's framing of the water security challenge. Recognizing the environmental, social, and inter-generational significance of water management, we have framed the water security challenge in terms of sustainable growth. Well-being is also a key element of this conceptual framing, as many of the values associated with water security are non-financial in nature, i.e., physical security, dignity, equity, ecosystem integrity, and recreation.

As illustrated in the conceptual framework diagram, a country's water endowment (i.e., water availability, quality, and variability) influences the level of investment needed to achieve a chosen level of water security. Investments to manage water resource endowments can modify this dynamic: moderating the effects of hydrological variability by providing reliable water delivery at acceptable prices, quantities, and quality; and by protecting lives and livelihoods against water-related disasters.

There is growing evidence that the endowment of 'hydrological complexity' is very different between most rich and poor countries. Most rich countries enjoy relatively manageable water endowments (i.e., 'simple hydrologies' providing relatively reliable, plentiful water resources), and have made the investments needed to manage these hydrologies. Many poor countries face 'difficult hydrologies', and hence require greater investment to achieve water security. These countries are often the least able to afford such investments, as the box shows.

Water security is not a static goal: it is a dynamic continuum that will alter with changing climates, growing economies and asset stocks, and resource degradation. As social, cultural, and aesthetic priorities and values evolve, water security will evolve with them.

Investing in water security

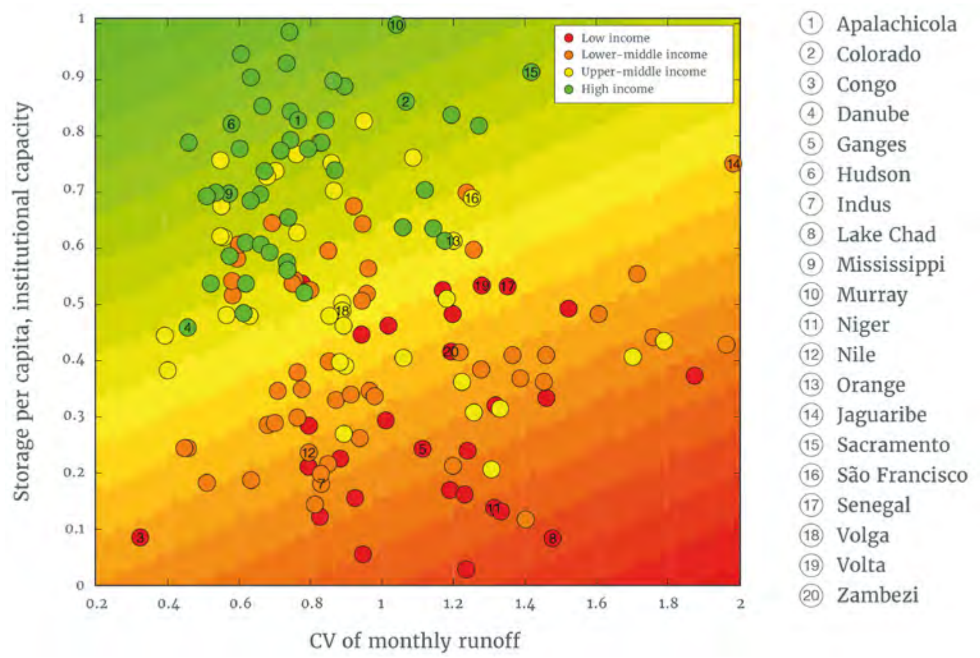
Not all water-related investments will be beneficial. Investments may be excessively costly, may not lead to the intended benefits, may result in harmful and perhaps unintended impacts upon people and the environment, or may close off more beneficial future investment opportunities.

Identifying the range of effects water security may have on economic growth – in a rigorous manner – is a challenge for several reasons. First, because water is such a pervasive input into so many economic activities, it is difficult to sort out statistically how water-related investments may affect any one of the many pathways leading to economic growth. There is no small irony here: because water is so important for so many reasons, it is difficult to actually show, statistically, the importance of water-related investments to economic growth. Second, the causal links between water-related investments on the one hand, and economic growth on the other, clearly run in both directions. Water-related investments can increase economic productivity and growth, while economic growth provides the resources to invest in institutions and capital-intensive water infrastructure. Finally, water-related investments can increase human well-being without also increasing national income or economic growth as they are conventionally measured.

At the project level, cost-benefit analysis is still arguably the best tool available to assess specific water-related investments. A good deal of work is being done to refine cost-benefit methodologies, in particular to take better account of environment and social costs; but the question of what constitutes 'good practice' remains a topic of debate. There is a clear need to identify and avoid poor investments in water security, and, even with its well-known limitations, cost-benefit analysis remains a necessary and useful tool to appraise specific water-related investments.

At the basin or state level, it is important to look beyond individual projects to dynamic, adaptive pathways and their impacts on economic growth, equity, and the structure of economies.

Economic growth, hydrological variability, and investment in water security



Note: The horizontal axis summarizes hydrologic variability. The vertical axis is a composite indicator of investment in infrastructure and institutional capacity. The dots represent all river basins with populations greater than 2 million, coloured to indicate high (green), middle (yellow), and low (red) levels of GDP per capita (using World Bank definitions). The coloured contours are a linearly interpolated surface reflecting the association between variability, water security investments, and GDP.

From: Hall et al. (2014).

This graphic illustrates the relationship between economic growth, hydrological variability, and investment in risk mitigation.

It shows that wealthy river basins (green dots, clustered in the upper left-hand quadrant) generally feature simpler hydrologies and larger investments in water security.

Poorer basins (red dots, clustered in the lower half of the chart) have invested less in water security, and many face complex hydrologies.

The investment required to transition from water insecurity to water security is greatest in those basins with highly variable hydrology (see coloured contour lines).

This requires performing cost-benefit analysis on sequences (or portfolios) of projects and carefully considering how pursuing a specific project may foreclose future options. It raises challenging problems of quantifying the wider benefits of water investments on the economy. Water policies and infrastructure investment decisions will have long-lasting impacts on development options across economies.

Finally, in finding the 'right' investments, it is essential to take special account of social, cultural, and environmental values; and to recognize that the impacts of water management decisions tend to greatly affect the poor, women, and the environment. Given this, multi-criteria evaluation techniques may be needed to supplement cost-benefit analysis. Regulations may be needed to ensure fulfilment of social imperatives.

A theoretical model of the dynamics of water-related risk, investment, and growth

To understand better the dynamics of investment in water security, we developed a growth model relating country wealth to investment in protective and productive water-related assets. Our theoretical analysis showed that when an economy is exposed to water-related risks there is a benefit attached to early investment in assets that mitigate those risks and protect productive assets. Countries that can make such investments protect their growth prospects from water-related threats and can therefore better harness the productive benefits of water-related investments. By contrast, in situations where hydrological hazards cause losses that affect other sectors of the economy, the economy can experience a significant water-related drag that limits the ability to harness water-related opportunities.

Nonetheless, we find that the trajectories of changing national wealth over time are strongly context-dependent. They rely on specific suites of policy choices and investment decisions. Where a country is heavily exposed to climate-driven losses (in particular, for example, where agriculture dominates), the likelihood of substantial feedbacks between water-related losses and national wealth is strong and we see situations in which a poverty trap is possible. In contrasting situations where the economy is more effectively disconnected from water-related losses – either through economic diversification or water-related policies, practices, and infrastructure that limit vulnerabilities – there is a much lower chance of experiencing water-related limits to growth.

Poor countries that are particularly vulnerable, because of difficult water endowments and agriculture-dependent economies, can become trapped in a cycle of economic losses and under-investment that inhibits growth. In order to overcome the water-related drag on growth, these countries will need targeted and sustained investment to protect their most important assets, seize their greatest water-related opportunities, and build resilience to water-related shocks.

In particular, the model reveals that even in an interacting hydro-economic system, the route from poverty to wealth is not best found through water-related investments alone. The fastest improvements in economic growth arise through investments in water-related assets that are combined with measures to create broad-based growth across multiple sectors of the economy.

An empirical analysis of the dynamics of water security and growth at the global scale

An econometric analysis (a fixed-effects panel regression) was performed across 113 countries, to determine whether there is empirical evidence of a statistically significant impact of hydro-climatic variables, including hazards, on countries' per capita GDP growth. This econometric analysis focused upon the effects of hydrological variability on growth in GDP. From this perspective on water security, countries whose economic performance is resilient to water security-related variables – such as runoff, floods, and droughts – are relatively water secure. Countries where growth is strongly correlated with these factors are relatively water insecure.

The findings confirm that water insecurity acts as a drag on global economic growth. Both our empirical and theoretical analyses demonstrates the importance of investment in water security for development – and the importance of development for investment in water security.

Water and water-related hazards have a statistically significant effect on economic growth that historically has been at least as important, and likely more important, than temperature effects. Runoff, which can be thought of as 'fluctuating annual water availability', was shown to have a statistically significant effect on annual economic growth. Drought and flood were also shown to have statistically significant negative impacts on growth. Together, they reflect the multiple ways in which water and water hazards affect economic growth. These results have important implications for economists assessing the potential economic costs of climate change. The results underscore that studies neglecting water may underestimate the economic consequences of climate change, especially in the most sensitive countries.

On drought specifically, an analysis was undertaken to calculate the cumulative effect of drought over time (1980-2012). The results showed the clear benefits of reduced drought impacts, and demonstrated how the effect of droughts can compound over a long period. In Malawi, for example, a 50 percent reduction in the drought effect led to a 20 percent higher per capita GDP at the end of the simulation. In the case of Brazil, the reduced drought effect (by 50 percent) led to GDP per capita that was 7 percent higher. The countries that stand to reap the greatest benefits from drought reduction were concentrated in the Middle East, Africa, South America, and Southeast Asia.

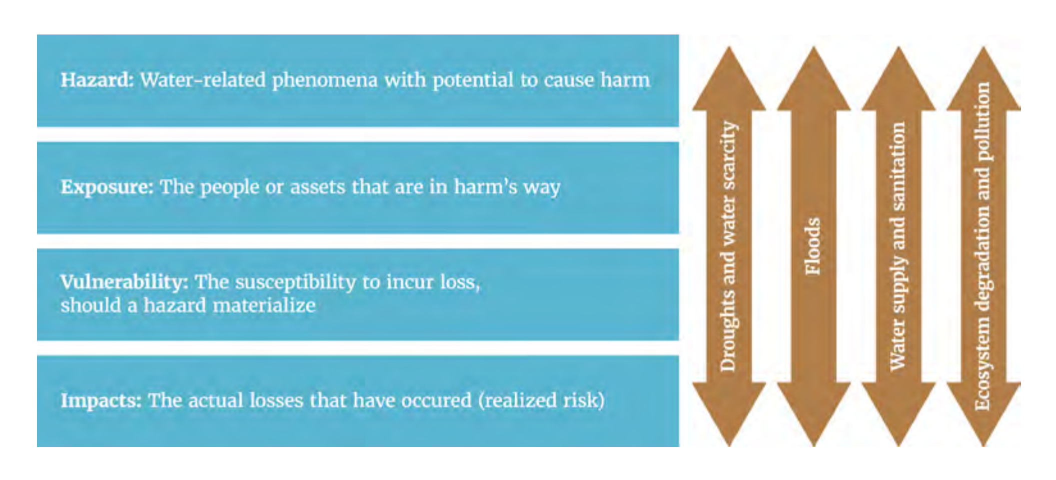
The effects of hydro-climatic variables on growth are strongest in countries that are poor (low income), and those that have high water stress (a measure based on per capita water resources), high dependence on agriculture (>20 percent of GDP from agriculture), or both. These countries tend to be concentrated in Sub-Saharan Africa and South Asia, along with a few countries in South America and Europe. The particular vulnerability of countries under water stress suggests that as water stress increases worldwide, managing water effectively will become significantly more important for sustaining global economic growth. And the OECD's baseline projections indicate that by 2050, 3.9 billion people will be subject to severe water stress.

The global status of water security

The impacts of water insecurity materialize through a wide range of different mechanisms for people, households, businesses, and communities. Water scarcity results in reduced crop yields, hydropower plant output, and thermal power plant cooling, which can subsequently push up food and energy prices. Floods damage homes and other floodplain assets, harm people, and disrupt businesses and supply chains. Inadequate water supply and sanitation increases mortality and morbidity, reduces labour productivity, and increases healthcare costs. Pollution and degradation inhibit ecosystems' capacity to deliver ecosystem services.

The analysis of risk involves quantification of hazards, exposure, and vulnerability. Records of the impacts of risks provide further (though often incomplete) evidence about the scale of risk. The language of risk provides a general framework within which the many facets of water insecurity can be incorporated. Analysis of risk provides evidence that feeds directly into cost-benefit analysis. However, quantification of risks is challenging, especially at a broad scale, so our risk estimates are uncertain and inevitably contain significant gaps, in particular in relation to impacts upon people and the environment, which are not readily monetized.

Overview of risk-based indicator framework



To assess the status of water security, we have analyzed water-related risks on a global scale, focusing upon four headline risks: (1) droughts and water scarcity; (2) floods; (3) inadequate water supply and sanitation; and (4) ecosystem degradation and pollution.

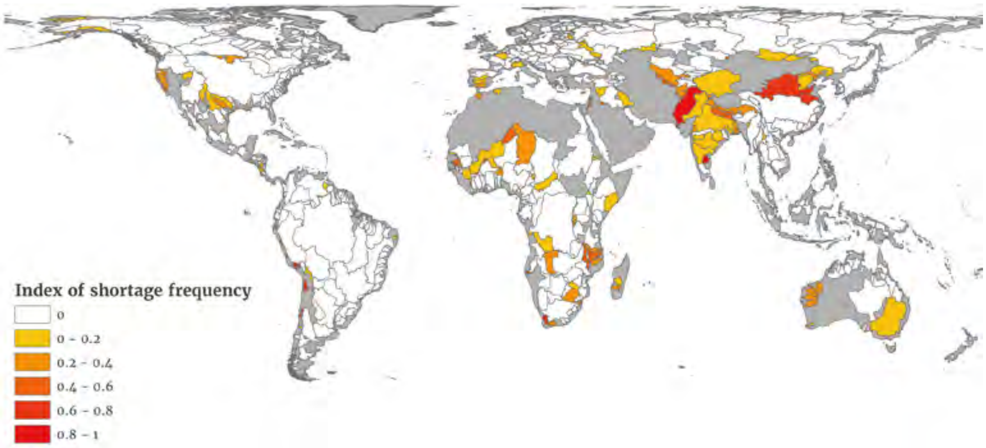
Water scarcity materializes through the interplay between hydrological variability, human demands for water (for agricultural, industrial, energy, and municipal purposes), and water infrastructure systems. Commonly adopted metrics of water scarcity quantify the balance between water availability and demand on average – overlooking seasonal variation in supply and demand, and the buffering effect that storage provides. We have developed a new aggregate model of water scarcity that operates on a monthly basis for every large river basin globally (see facing page).

Even taking into account the effects of investment in water infrastructure, the risks of scarcity are most severe in South Asia and northern China; and signicant risks of water shortage exist in all continents. The risks are increasing in all locations – and most notably in India and Pakistan, where demand for irrigation water in particular is projected to increase. Scarcity and hydro-climatic variability contribute to volatility in food crop production. This is particularly pronounced in Africa, but also notable in South America, Central Asia, and parts of Europe.

Our findings show that enhanced water security can help stabilize food crop production and prices. The probability of global wheat production falling below 650 million tons per year is reduced from 83 percent to 38 percent. And the probability that the price of rice could exceed US$400 per ton is reduced from 21 percent to 0.7 percent. The potential global welfare gain, from securing water to existing irrigators, was estimated at US$94 billion for 2010. This analysis does not capture the potentially significant benefits of additional investments in agricultural efficiency, or expansion in irrigated areas, that might be fostered by greater water security.

Floods are an extremely (and increasingly) damaging form of water-related hazard. Floods in Thailand during 2011 resulted in US$46 billion in economic losses, and US$16 billion in insured losses. Our global risk analysis estimates an expected annual flood damage of US$120 billion per year from property damage alone; with almost half of that economic risk in North America. By the 2030s, in the absence of adaptation, coastal flood risk is projected to increase by a factor of four; while fluvial flood risk could more than double. The risk estimates are sensitive to assumed flood protection levels – thereby demonstrating how important flood protection measures are in reducing vulnerability to flood risk. Sea level rise, subsidence, population growth, and economic growth mean that flood risk in coastal cities and estuaries will, in future,

Index of frequency of shortages of water available for use



Expected annual damage due to fluvial and coastal flooding

become particularly concentrated in coastal Asia. The greatest flood risks to people (in terms of the numbers exposed to flood risk) are now, and will remain, overwhelmingly located in Asia.

Inadequate water supply and sanitation continues to have the greatest economic consequence of all water-related risks. It also continues to be the most harmful risk to people, with diarrhoeal diseases resulting in 1.4 million premature deaths in 2010. The total global economic losses associated with inadequate water supply and sanitation, have been estimated by WHO at US$260 billion annually. Much of this loss reflects per capita estimates of the value of time spent fetching water, or walking to open defecation sites. The human impacts of inadequate water supply and sanitation are concentrated in South Asia and Sub-Saharan Africa.

Water-related risks to the **natural environment** arise from human interference in the aquatic environment: pollution, over-abstraction, and interruption of the natural variability of flow regimes; and interference in river, wetland, and coastal morphology. The threats are multiple, and they interact – undermining catchment and coastal systems' capacities to deliver ecosystem services. Taking a water security perspective, estimates were made to determine the frequency of failing to meet benchmark estimates of environmental flow requirements. In every continent, there are rivers whose water use patterns put aquatic ecosystems at risk – indicating that water insecurity is a global threat to environment. We have not sought to monetize these risks, as it is extremely complex and beyond the scope of this Report. The issue of environmental risk remains an important area for further study.

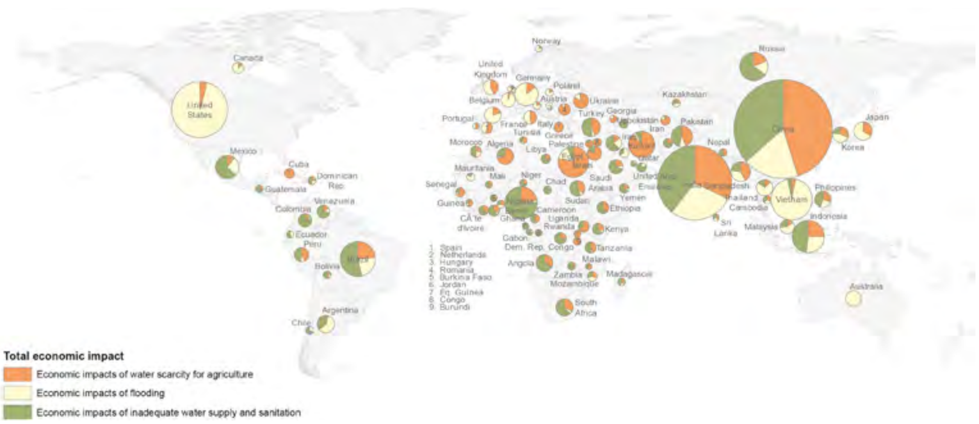
Our global analysis highlights hotspots of vulnerability, both in terms of anticipated economic impacts, and in terms of populations at risk:

- **South Asia** has the largest global concentration of water-related risks, including severe impacts across the full range of hydrological variability (droughts to floods), the largest global concentration of people without adequate sanitation,

Economic losses from inadequate water supply and sanitation

Relative economic impacts of water insecurity

Three economic risks have been standardized to the same total economic impact globally: (1) Water scarcity to agriculture; (2) Flood damage to property; and (3) Inadequate water supply and sanitation.



and growing environmental threats. India, with its very large population, is the top ranked country globally for the number of people exposed to water shortage, people at risk of flooding, people without adequate water supply and sanitation, and number of undernourished children.

- The exposure to flood risk in **East** and **Southeast Asia** is increasing rapidly. China and Vietnam respectively have the second- and third-highest economic risks of flooding, globally, led only by India. Vulnerability to water scarcity varies markedly across the region, with northern China being particularly challenged.

- As a proportion of GDP, the impacts of inadequate water supply and sanitation are greatest in **Sub-Saharan Africa** – the one region in which these risks are increasing. Africa also exhibits the greatest variability in crop production, highlighting African economies' sensitivity to hydro-climatic variability. This variability in food production, in turn, is reflected in high levels of child malnutrition. **North Africa** stands out in terms of the number of people, and percentage of the population, at risk of scarcity.

- The **United States** is estimated to have the greatest economic exposure to flood risk in the world, with expected annual property damage from fluvial and coastal flooding estimated at US$54 billion (0.3 percent of GDP). **Europe** and **North America** generally experience water security, with risks reduced to tolerable levels. Yet, flood risks are anticipated to rise in both Europe and North America, and various environmental risks are seen. Significant investments to maintain, upgrade and/or expand water supply and sanitation services, wastewater treatment systems, agricultural water management, and water management institutions, will be needed to sustain current levels of water security.

- **South America** experiences significant variability in agricultural yields. However, thanks to its relatively high potential for productivity-enhancing water-related investments, the region is expected to see the greatest global increase in food production (in percentage terms). In our econometric analysis, South America is also shown to be a region that stands to reap some of the greatest benefits from drought reduction.

This Report does not provide a fully monetized value for global water security. The range and nature of water-related risks do not lend themselves to consistent valuation, and some cannot be monetized with available data and methods. Thus, an aggregate value would not be defensible. However, taking the economic risks of water security that can be monetized as a lower bound, the scale of the challenge exceeds hundreds of billions of dollars annually.

The extent of 'upside' economic opportunities associated with water security are not always presented in this Report, because a risk-based approach does not capture these potential returns in full. Risk calculations focus on estimated losses of existing assets or expected losses of current production. Yet, investments in water security can create opportunities and incentives for precisely the kind of productivity enhancements, and additional investments, that generate growth.

Finally, the Report cannot provide advice on specific investments. No matter how large the global economic risks associated with water security might be, not all investments in water security will be beneficial. Moreover, investment in water security cannot eliminate water-related risks, but it can help to manage them to a tolerable level. As the Report shows, achieving water security requires a continuous process of sound decision-making founded on a basis of careful analysis at the local scale. There is no substitute for thorough appraisal of specific investments and investment pathways.

Relative economic impact of water insecurity per capita

Three economic risks have been standardized to the same total economic impact globally, and then divided by the national population: (1) Water scarcity to agriculture; (2) Flood damage to property; and (3) Inadequate water supply and sanitation.

Top ten countries for people at risk of water insecurity

Rank	Shortage Index: Total population at risk of frequent water shortages	Flood Index: Expected population flooded	Water and Sanitation Index: Total population lacking sanitation
1	China	India	India
2	Pakistan	China	China
3	India	Vietnam	Nigeria
4	Bangladesh	Bangladesh	Indonesia
5	Nepal	Myanmar	Pakistan
6	Algeria	Indonesia	Ethiopia
7	Saudi Arabia	Pakistan	Bangladesh
8	Uzbekistan	Egypt, Arab Rep.	Congo, Dem. Rep.
9	United States	Thailand	Russian Federation
10	Afghanistan	Nigeria	Tanzania

Colour scale is GDP per capita income classification:

Low income | Lower-middle income | Higher-middle income | High income

Top ten countries (with population greater than 1 million) for proportion of population at risk of water insecurity

Rank	Shortage Index: % of 2010 population at risk of frequent water shortages	Flood Index: % of 2010 population expected to be flooded	Water and Sanitation Index: % of 2010 population lacking sanitation
1	Israel	Vietnam	South Sudan
2	Pakistan	Mauritania	Niger
3	Jordan	Myanmar	Malawi
4	Turkmenistan	Bangladesh	Chad
5	Malawi	Guinea-Bissau	Togo
6	Nepal	Lao PDR	Tanzania
7	Guatemala	Cambodia	Madagascar
8	Guinea-Bissau	Mozambique	Benin
9	Saudi Arabia	Korea, Dem. Rep.	Sierra Leone
10	Lebanon	Somalia	Congo, Dem. Rep.

Colour scale is GDP per capita income classification:

Low income | Lower-middle income | Higher-middle income | High income

Pathways to water security

How have policymakers responded to water-related risks and opportunities? We examine historical pathways to water security, where pathways are defined as sequenced portfolios of investments in institutions and infrastructure underpinned by investments in information.

Pathways are dynamic: actions are taken in response to a changing context of risks, opportunities, and expectations; and in response to recurring patterns of challenges and responses. The triggers for action can come in different forms: gradual or chronic stress, variability, shocks, or combinations of major changes to multiple dimensions simultaneously.

Thirty-two cases were examined in order to reconstruct, analyze, and compare pathways to water security within different contexts. Eight illustrative cases are presented in this Report. The cases capture different configurations of water-related risks and patterns of investment in water security. In each case, specific risks, opportunities, and prior investments influence the priorities for action and the range of possibilities for achieving and sustaining water security. Timelines were created for these eight case studies in order to illustrate specific pathways. The timelines present political and economic events; water-related hazards and opportunities that may have acted as investment triggers; and discrete investments in information, institutions, and infrastructure.

The importance of context makes it difficult to generalize from specific experiences; however, we can identify some general lessons and insights for city, river basin, and aquifer contexts.

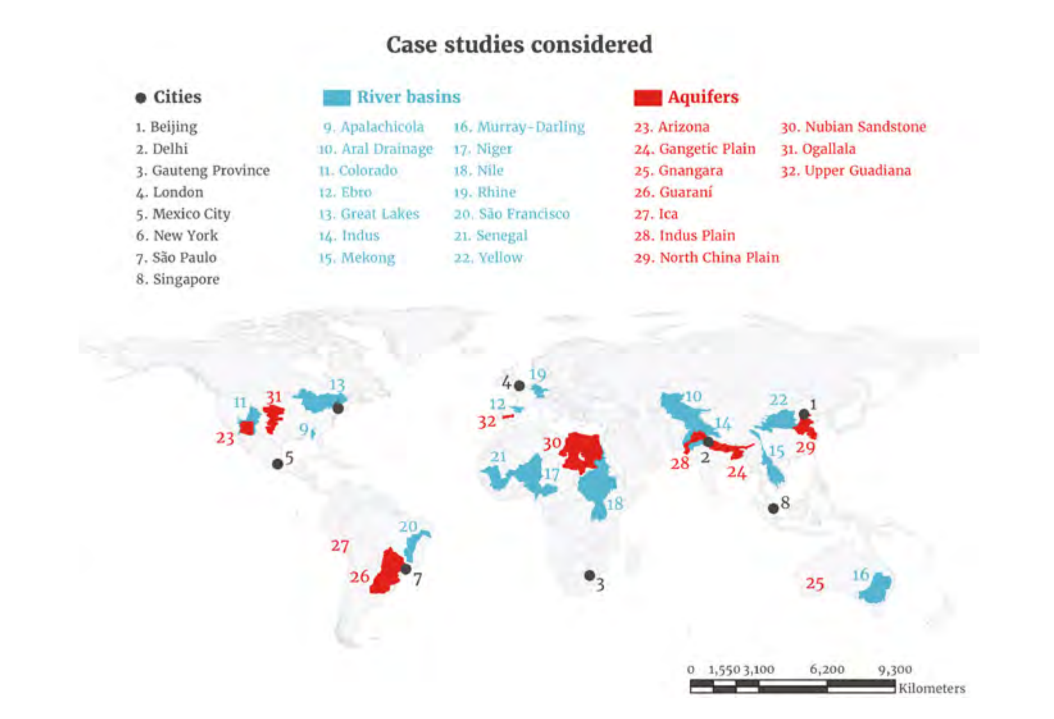
Pathways to water security: general lessons

The case studies show that institutions, information, and infrastructure can be interdependent and mutually reinforcing. Typically, they are complementary, yet sometimes they substitute for one another – depending on progress through a pathway, and local conditions. Generally, significant investment is needed in all three, as the full benefits of investment depend on their interaction.

Sequencing is strongly influenced by socio-economic and political context; and by the type and scale of risks faced and opportunities created. Ideally, investments in water security are based on robust information that provides a shared understanding of the system's dynamics and its dominant risks and opportunities. For example, in the Rhine River of northern Europe, agricultural and industrial development enabled economic growth, thereby placing increasing assets at risk from floods and water pollution. Systemic risks in the Rhine have spurred international cooperation coupled with efforts to define adaptation tipping points, coordinate national and international policies, adopt innovative approaches to flood management, and integrate risks and uncertainty into strategic planning, forecasting, and communication.

The cases also demonstrate the different factors motivating investment. Crises present both the need – and opportunity – for investment; but it is important not to wait for a crisis to plan and act. The triggers for investments in water security include: economic opportunities, chronic impacts and acute shocks, and both water-related and external factors, such as political changes, natural hazards, and international trends. In any given situation, multiple factors combine to trigger investment, producing a pattern of challenge and response. For example, a rapidly growing population in the Mexico Valley, combined with a sequence of natural hazards, land subsidence, political leadership changes, and financial crises have spurred both investment and institutional reforms in the urban pathway to water

Case studies of cities, river basins, and aquifers



Eight case studies are presented in the Report, selected from an analysis of 32 cases. They include: Mexico City, Gauteng Province, and Singapore (Cities); Colorado, São Francisco, and Rhine (Rivers); and the Guarani and Nubian Sandstone (Aquifers).

security in Mexico City. The late 1980s and early 1990s presented an 'avalanche' of triggers that provided a window for investment and reform: a major earthquake as well as protests about unreliable water supply and sanitation services prompted studies, construction of inter-basin transfers, and consolidation of water management responsibilities in the national water agency in 1989. The coincidence of financial crisis and political change led to efforts to decentralize water management, including incentives for private participation in water services, which have met with mixed success.

Finally, many historical investments have underestimated costs, overestimated benefits, and foreclosed alternatives. Water resources development can bring growth, but can also have negative consequences. What emerges clearly is that yesterday's innovation can become today's constraint, if there is not enough flexibility embedded in the system. This is illustrated by the experiences in semi-arid rivers like the Colorado, Murray-Darling, and Yellow, where historic development has led to river basin closure – meaning that downstream needs, water quality standards, and additional water demands cannot be met during all, or part, of a year. However, in some cases institutional innovations have been quite successful in re-aligning historic allocations with changing values and increasing demands, and embedding flexibility into water management systems. In the Murray-Darling, for example, despite a 70 percent decrease in the water available for irrigation during the 12-year Millennium Drought (in 2008-2009, as compared with the baseline 2000-2001 water year), the gross value of irrigated agriculture declined by less than 20 percent due to the existence of effective water markets that reallocated water among competing uses.

Pathways to water security: cities, rivers, and aquifers

The case studies reveal different patterns of triggers, water security investments, and economic activity across multiple contexts. Case studies and historic pathways are descriptive rather than prescriptive, as they reflect actual pathways not optimal pathways. Looking forward, decision makers will need to innovate and adapt, without being limited to the solutions adopted in the past. The case studies illustrate several challenges and opportunities for tailoring pathways in cities, rivers, and aquifers.

Cities

We examine pathways to urban water security in three contexts: mature cities in advanced economies; rapidly developing cities in emerging economies; and predominantly poor cities with rapidly expanding informal settlements.

Mature cities in advanced economies generally face the primary challenge of deteriorating urban water networks; and many face increasing vulnerability to floods, with high-value assets at risk. Innovation in water use efficiency and re-use, balanced with infrastructure investments to replace essential underground assets, may sustain water service levels. Innovation in these cities may influence – by example – the pathways undertaken by less advanced cities. For instance, the urban pathway to water security in Singapore has attracted significant international interest. Singapore's strong public utility enabled the implementation of strategic approaches to research, development, and long-term planning; with a wide range of infrastructure that includes reservoirs, desalination plants, wastewater collectors, and treatment and reuse technologies. There has been a strong commitment to demand management and full economic pricing of water for consumers. Singapore's water and wastewater services have become increasingly advanced in order to support its growing economy, which has enabled continued investment in these systems.

Rapidly developing cities in emerging economies often face inequitable access to water services, costly water technologies and delivery models, and rapidly rising numbers of people and assets at risk. Innovative institutional and infrastructure approaches will be needed to accelerate pathways to urban water security, ensuring universal water supply and sanitation access and integrated management of pollution and flood risks. For example, in the Gauteng Province of South Africa (which includes the cities of Johannesburg and Pretoria), rapidly growing human settlement in the headwaters of the relatively dry and variable Limpopo system has made investment in water security essential. The end of Apartheid in 1994 brought the political imperative to expand water services to peri-urban settlements. Extensive storage and transmission infrastructure has been developed in order to cope with climatic variability – designed and operated to achieve reliability levels of 99.5 percent for power, and 98 percent for urban supplies. Ninety-five percent of the Province's population has access to a safe water supply, although human settlement and industry impact on water quality.

Predominantly poor cities with rapidly expanding informal settlements face the greatest challenges. In these cities, generally-weak utilities deliver conventional water supply and sanitation services to only a small proportion of the population; and there is rapidly-expanding settlement, often in vulnerable watersheds and floodplains. In such cities, significant investment is needed in institutions, information, and infrastructure, to meet the challenge of designing and delivering universal, reliable coverage; as well as coverage that is cost-effective and context appropriate.

Rivers

We examine pathways to river basin water security in three hydro-climatic contexts: highly variable/monsoonal, semi-arid or arid, and temperate river basins and lake systems.

Highly variable/monsoonal basins typically experience extreme intra-annual variability, hydrological uncertainty, and often severe floods and droughts. In highly variable rivers, planning efforts and investment in water security have attempted to decouple economic growth from the impacts of climate variability and extremes. Basin-wide institutions, shared knowledge, and coordinated infrastructure have proven important for managing freshwater variability (e.g., through allocation rules, floodplain zoning, reservoir and aquifer storage and operations). In the Mekong River, for example, a major challenge now is to harmonize national development with transboundary interests. The Mekong River Commission has made a significant investment in the data and knowledge needed to strengthen basin-wide water security, and is exploring joint water resources management and development opportunities on the basis of this shared knowledge.

Arid and semi-arid basins face challenges of absolute scarcity and freshwater variability that can lead to heavy reliance on supply-side infrastructure and to ecosystem degradation. Robust and balanced pathways in these circumstances are likely to include innovative storage alternatives (e.g., aquifer storage), conjunctive use of multiple sources (e.g., reuse, rainwater harvesting), water use efficiency, and economic instruments to allocate scarce water.

Temperate basins tend to be more water secure, often with complacent dependence on existing infrastructure to manage risks. Innovative institutions and infrastructure can safeguard sustainable growth by mitigating water security risk and flood risk in particular, and enhancing environmental quality.

Aquifers

We examine groundwater contributions to water security pathways in two contexts: aquifers where significant surface water is available, and aquifers where society is dependent on groundwater for urban development and irrigated agriculture.

Aquifers where significant surface water is available often face challenges associated with localized overdraft and water quality deterioration, mainly due to urban use. This can result in future aquifer restoration costs as well as water logging and soil salinization, due to rising water levels caused by unplanned recharge (e.g., leaking water and wastewater networks). The Guaraní Aquifer System, for instance, is exploited mainly to meet urban water needs. In some cities that draw on this aquifer, groundwater levels have fallen by an estimated 30-40 meters since 1970, with a consequent increase in water supply costs and degradation of local rivers.

Aquifers where society is dependent on groundwater for urban development and irrigated agriculture generally face challenges of unregulated and intensive groundwater abstraction – resulting in declining water levels, deteriorating water quality, and land subsidence. The consequences of aquifer mismanagement are increased exploitation costs for major cities and irrigation developments, and deterioration of groundwater-dependent ecosystems. Investment in institutions and knowledge systems may facilitate sustainable groundwater development – with appropriate measurement technologies and regulatory tools including monitoring networks and models; quantity and quality regulations enabling reallocation and aquifer recovery; user involvement in groundwater management; and innovative infrastructure investments, including aquifer storage.

Toward strategic and adaptive pathways

Our analysis of case studies reveals cycles of adaptation in the quest for water security. At each stage, decision makers have had options at their disposal, and have made choices with a view to reaching goals. The evidence available to inform decision-making is always uncertain. While there is growing evidence of the relationship between water security and economic development, our analysis demonstrates that it remains scarce. The methodologies of systems analysis, decision analysis, and benefit-cost assessment – which are central to making strategic choices about investment in water security – have matured in recent decades. They provide the opportunity to shift from reactive management of the impacts of water security, to the pro-active management of risks.

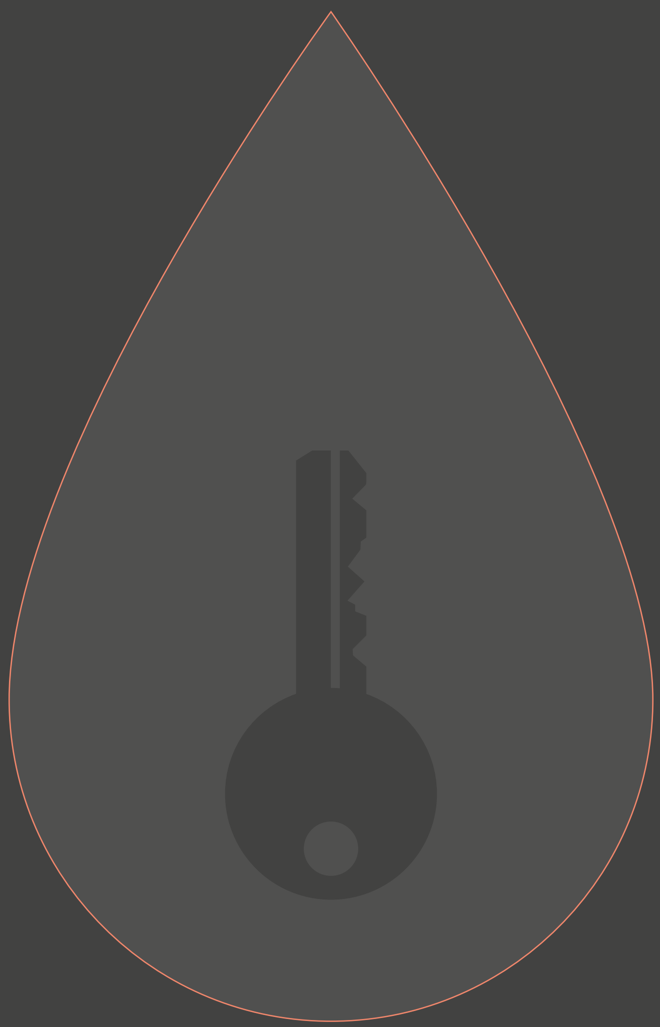
Looking forward

The profile of water security risks will change in the future, as countries invest and adapt. The headline risks examined in this Report all show increasing trends globally – with the important exception of water supply and sanitation. In addition, we found that the hydro-climatic effects on growth are stronger in countries with high water stress, and water stress will grow with population. By 2050, the OECD's baseline projections indicate that 3.9 billion people will be subject to severe water stress.

The impact of hydro-climatic variability on economic growth, however, does not need to increase. Policies and investments in water security can dampen the impacts of water risks. Our analysis has shown that economic impacts are particularly pronounced in countries with agriculture-dependent economies, low levels of mean water availability, low levels of access to safe water supply and sanitation, and rapidly increasing vulnerability to flooding.

Making better use of available water, ensuring reliable water quality and services, developing financial risk management products for periods of shortage or natural disasters, and promoting a transition to less agriculturally dependent economies, all emerge from the empirical analysis as potential mechanisms for de-linking economic growth from hydro-climatic variability, and providing greater water security.

Investment in water security can, therefore, help to safeguard growth against growing water-related risks. There will be many investment pathways to water security, but it is likely that successful pathways will share certain characteristics. They should be devised and assessed in terms of outcomes and tradeoffs among economic, environmental, and social criteria. Investments in physical infrastructure will need to be accompanied by sound water institutions, integrated into wider governance frameworks and improved information systems. As economies mature, emphasis will shift to making the most of existing resources and assets, and deploying innovative institutions and policy instruments. Investments should be developed in order to be robust to uncertainties; and to support adaptive management as risks, opportunities, and social preferences change. In addition, investments should be tailored to their context. All of this will require refined analytic tools, more holistic perspectives, innovation, and continuous monitoring, assessment, and adaptation.



Chapter 1: Introduction

‘Water … is the cause of life or death, or increase or privation, nourishes at times and at others does the contrary …’

Leonardo da Vinci, circa 1500

‘When the well is dry, we know the worth of water.’

Benjamin Franklin, 1746

Societies have always grappled with the elusive value of water. We see this in myths, literature, and art across the world. It is mobile, variable, and unpredictable. When you have enough water, it has little value. When you have too much, it can destroy. When you have too little, it can be priceless.

Human society has instinctively sought to limit the many risks that water brings. And, at the same time, to seize water's many opportunities for enhancing lives and livelihoods. This is evidenced by substantial investments over millennia in canals, reservoirs, aqueducts, and wells, and also in early water-related institutions and information systems. Each generation has faced this challenge of water security; future generations will confront added complications from climate change.
This effort to reduce water risk and seize water opportunities, to improve societal wealth and well-being, is the goal of water security.

Most developed countries have invested heavily in water information, institutions, and infrastructure systems. Today, they are relatively water secure, facing largely tolerable water-related risks. Most of the world's developing nations, however, are relatively water insecure.

In a future of rapid economic growth, escalating water stress, and climate change, the challenge of achieving and sustaining water security will be a priority in both developed and developing countries. This will likely entail large-scale and long-term investments that will require careful design, appraisal, and sequencing. Societies will need to make difficult choices regarding the allocation of resources among different growth-enhancing investments, and between the complex economic, environmental, and social trade-offs inherent in water resource management.

Concern over the growing global impact of water risks is reflected in the World Economic Forum's Global Risks 2015 Report, where water is ranked as the global risk with the greatest potential impact on economies and societies over the next ten years.

Its importance is also signalled by the proposed development of a dedicated Sustainable Development Goal for water.

The Global Dialogue on Water Security and Sustainable Growth 2013-2015

While intuition firmly points to the need for investment in water security, this intuition alone cannot tell policymakers which investments should be made, and how much investment is justified. Evidence is needed to guide the design, and scale, of water security investments.

The need for evidence – this need to provide an empirical basis for investing in water security – inspired the Global Dialogue on Water Security and Sustainable Growth.
The Dialogue was launched by the Global Water Partnership (GWP) and the Organisation for Economic Cooperation and Development (OECD) in 2013, with twin objectives:
to provide an evidence base for investment in water security and sustainable growth; and to undertake associated international and country-level consultations on water security and sustainable growth.

The Dialogue comprises:

A High-Level Panel

co-chaired by Mr Angel Gurría, Secretary General of the OECD, and Her Excellency Ellen Johnson Sirleaf, President of Liberia. The High-Level Panel leads the Dialogue.

A country consultation

process identifying the priorities and concerns of countries pursuing water security, with consultations held in some 40 countries.

A Task Force

comprising an international team of economists, scientists, engineers, and policy experts. This team leads the Dialogue's substantive analysis: developing empirical evidence to support the dynamics of water security and growth.

This Report

This Report presents the findings of the Task Force. The Report draws upon original research commissioned by the Task Force from the universities of Oxford, McMaster, University of Massachusetts, Manchester (UK), Southampton, Madrid and VU University Amsterdam as well as from the International Food Policy Research Institute, the Global Climate Forum, and Deltares. In addition, the Report has drawn upon expert advisers in the analysis of pathways case studies; and data and information provided by the City University New York, the International Hydropower Association, the International Institute for Applied Systems Analysis, the International Water Management Institute, the World Health Organization, and the World Bank. A listing of the many individuals contributing to this effort is provided in the Acknowledgements.

The Report provides evidence that promotes and guides investment in water security by:

- **analysing the economics of water security and growth**
- **quantifying water-related risks, opportunities and trajectories**
- **illustrating and assessing pathways of investment in water security.**

This work draws upon, and adds to, a growing body of literature on water security. However, it differs from most current work in several ways, by:

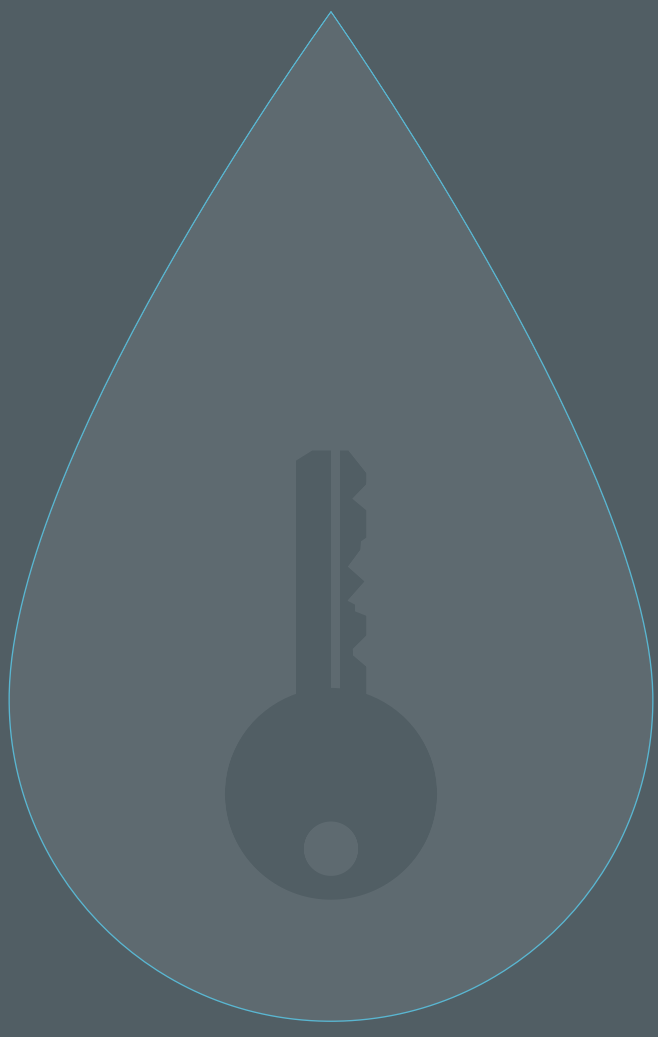
focusing on economic growth
asking where, how, and by how much water insecurity may limit growth

adopting a risk-based approach
assessing the hazards and vulnerabilities of water insecurity, and the growth opportunities that follow risk reduction

seeking empirical evidence
going beyond intuitive, qualitative, or subjective metrics

Although the best-available datasets have been used, hydro-meteorological monitoring systems will vary in network density across the world, data management and reporting systems will vary in quality, and consistency and comparability will always be a challenge in compiling global data.

The Report is structured as follows:
Chapter 2 explores the relationship between water security and sustainable growth. It provides a simplified conceptual framework, a theoretical model, and new empirical evidence of this relationship.
Chapter 3 examines the global status of water security, locating and analysing four 'headline' risks – both individually and collectively – to identify global risk and opportunity alignments, and 'hotspots'. **Chapter 4** identifies and assesses pathways to water security followed in representative cities, aquifers, and river basins across the world, and draws lessons for policymakers.
Lastly, **Chapter 5** provides the Report's conclusions.



Chapter 2: Water security, sustainable growth, & well-being

2.1 The water security challenge

Water-related risks exacerbate global economic, social, political, and financial challenges.

In 2010 and 2011, Russia, China, and Argentina experienced droughts, while Canada, Brazil, Pakistan, and Australia experienced floods, resulting in falling global grain and sugar stocks, and a doubling of prices for these commodities. Rapidly rising food prices caused riots in food-importing North African countries, aggravating existing social tensions as the 'Arab Spring' took hold. In Syria, by 2011 – following several years of drought, extensive crop failure, and massive losses of livestock – 2 to 3 million people had been driven into poverty. This poverty contributed to a mass rural exodus into economically depressed cities, deepening existing instability as the country descended toward civil war.[1] Thailand's 2011 floods killed 884 people, damaged 1.5 million homes, destroyed 25 percent of the rice crop and 7,500 industrial enterprises, and caused an estimated US$46 billion in financial losses.[2] The closure of industrial plants had impacts on global supply chains, triggering shortages of goods, such as computer hard drives and motor vehicles, that were felt across the world.

Water risks (such as scarcity, floods, water borne disease, and environmental degradation) are growing as population and economic growth put greater pressure on water resources, and push more people and assets 'into harm's way'. Water risks are also growing due to climate change, as water availability becomes less predictable, and extreme weather events become more common. Where multiple water risks are present (or 'co-located'), the challenge of achieving water security is compounded.

1 *Werrell and Femia (2013).*

2 *Aon Benfield (2012); Nabangchang et al. (2015); World Bank (2012).*

Moreover, as the world's economies globalize, water-related risks that were once considered local supply limitations, or weather hazards, are increasingly seen as regional and global economic challenges. Globalization can help mitigate local challenges in various ways. For example, utilizing regional and global food trade and aid networks during times of deficit may help ease food price fluctuations, and secure adequate food supplies. Economic impacts of hydrological uncertainties can also be countered through the increasingly global availability of weather-related financial risk management products and services – such as commodities futures and options, and crop- and weather-based insurance. Access to sophisticated regional and global severe weather forecasts, warnings, and response systems, can also help mitigate losses associated with hydrological uncertainties and extremes.

The negative impacts of water risks can propagate through the global economy as well, via severe water-related price shocks in food, energy, transport, and insurance; as well as from the unanticipated supply chain disruptions that may result from large-scale natural disasters, or from a lack of water availability as an input to production.

Environmental and social impacts of water-related risks can be widely felt in the form of species and habitat loss, social disruption, population displacement, and disease. Hydro-climatic extremes and water resource availability are increasingly seen as stressors or threat multipliers that aggravate existing challenges; challenges that relate not only to economic performance, but also to environmental management, social tensions, and political stability.[3]

3 *Scheffran et al. (2012).*

Yet, water is not only destructive: it is also profoundly productive. Water sustains human life, and the ecosystems upon which all living things depend. Water is essential for households, agriculture, industry, energy, and transport. Similarly, while economic growth can enhance risks (by increasing the economic value of assets at stake), it also provides the critical resources needed to manage water-related risks. Not only through investments in the institutions (defined broadly to include agencies, rules, and incentives), information systems (hydro-meteorological, economic, and social), and infrastructure (natural and constructed) needed to manage water resources and water-related risks, but also via investments in research and development of innovative technologies and financial risk management tools.

The goal of water security is to leverage the opportunities, and manage the risks associated with water and, in so doing, facilitate sustainable growth and enhanced well-being. The policies and infrastructure investments implemented to enhance water security will allocate water between alternative uses; deliver water at specific times, places, and prices; ensure water quality; and protect people and assets from water-related hazards. These actions will create opportunities, and reduce risks, for different regions, sectors, and communities, which, in turn, can have a profound impact on economic growth, inclusiveness, and the structure of economies.

Framing the water security challenge

Our objective in this chapter is to examine the effects of water security on wealth and well-being, and in so doing, to show how water influences – both positively and negatively – the things that people and societies value.

While the mandated focus of this report is the relationship between the management of water resources and changes in economic wealth (i.e., growth), we recognize that sound management of water and other natural resources is essential for environmental sustainability, social equity, and the quality of life of future generations. Thus, we frame the water security challenge in terms of sustainable growth. This concept of sustainable growth brings two important considerations to our analysis.

First, we explicitly recognize that considerations of well-being extend to future generations. Steps taken today to improve well-being, should not unduly compromise the well-being of future generations. Such considerations are germane to our study of water because, while water is a renewable resource, some of the interventions we make now in the aquatic environment may be difficult, perhaps impossible, to reverse in the future.

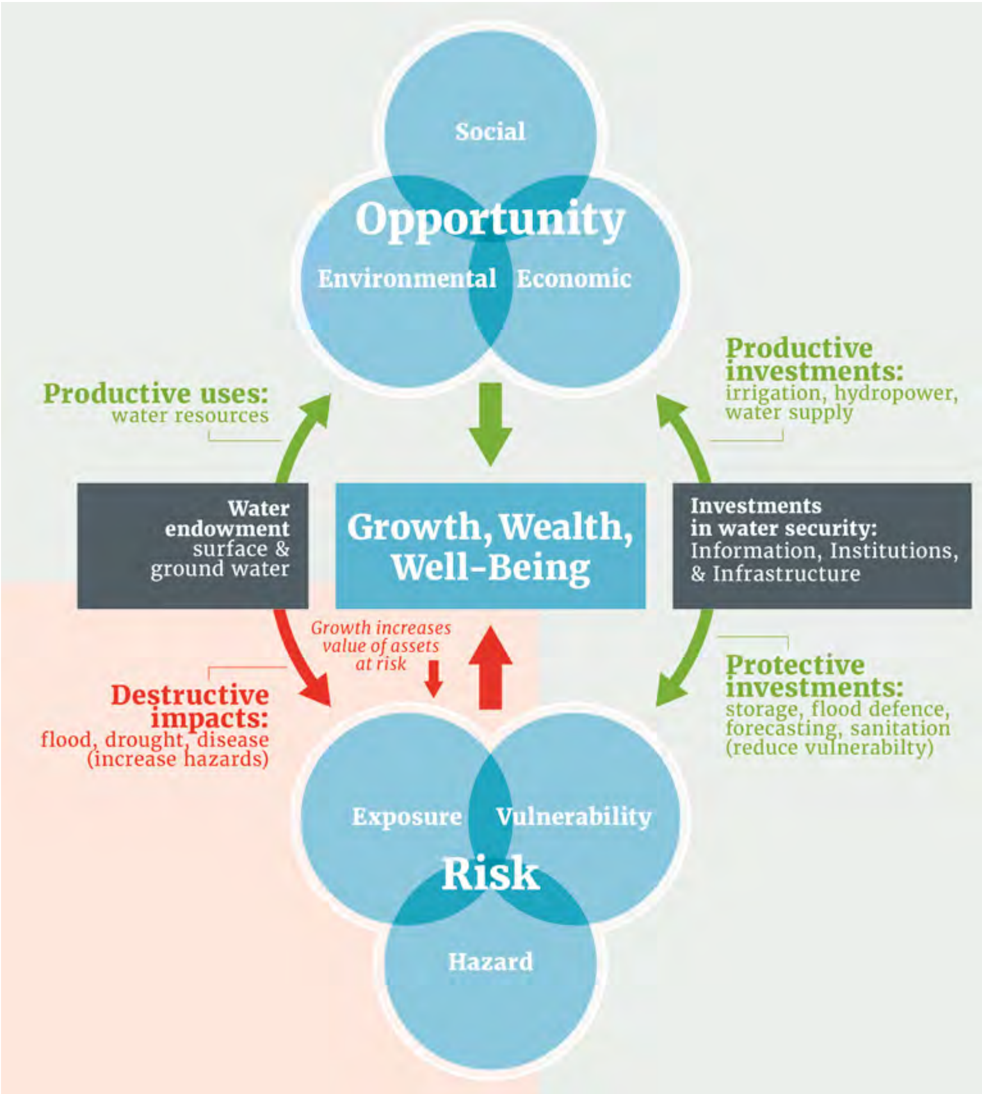
Second, our framing in terms of sustainability explicitly recognizes that there are multiple dimensions of well-being and prosperity, beyond material wealth alone. These dimensions include social, cultural, and environmental values, many of which are directly associated with the state of the aquatic environment. Therefore, the goal of improving the material wealth of societies must be negotiated within the boundaries imposed by the availability and sustainability of the water resource, and balanced with the cultural and spiritual values of water.

A schematic of this report's framing of the dynamic between water security and sustainable growth, is presented in Figure 1.

Sustainable economic growth, wealth, and human well-being are at the heart of this framing. Here, 'wealth' is considered to include both natural and human-made capital assets: recognizing that water security inherently speaks not only to the provision of water as an input to production, but also to sustaining water resources and freshwater ecosystems (including rivers, lakes, and aquifers) as assets of great economic, social, and environmental value. Well-being is a key element of this conceptual framing not least because many of the values associated with water security are non-financial in nature (i.e., physical security, dignity, equity, and leisure).

The flow of this dynamic starts with water endowments. A country's water endowment

Conceptual framework of the dynamic of water security and sustainable growth *(Fig 1)*



comprises the absolute level of its freshwater availability; the fragility or strength of its freshwater ecosystems; and, importantly, the variability of its hydrology. This is a natural endowment that will influence how much a country needs to invest to achieve a given level of water security. Countries with temperate climates and regular rainfall, large freshwater lakes, and reliably safe, accessible, and replenished groundwater aquifers (common characteristics, for example, of most of North America and Europe) will be able to achieve water security with comparatively less effort and capital investment. In contrast, greater effort and capital is needed in countries that are arid (such as many countries in the Middle East, northern Africa and western Asia; as well as most of Australia), or prone to significant hydrological variability and extremes (such as many countries in Sub-Saharan Africa, and in monsoonal southern and south-eastern Asia).

Where water is reliably available, economic opportunities are enhanced. Where water is unreliable or of inadequate quality, or where water-related hazards are present, there will be drags on growth.

Thus, water endowments create both opportunities for, and risks to, growth and well-being. Where water is reliably available, economic opportunities are enhanced. Where water is unreliable or of inadequate quality, or where water-related hazards (i.e., floods, droughts, or contamination) are present, there will be drags on growth.

Investments made in order to manage a national or regional water endowment can modify this dynamic, moderating the effects of hydrological variability by providing reliable water delivery at acceptable prices, quantities, and quality; protecting lives and livelihoods against water-related disasters; and protecting ecosystems from degradation. These investments might include the development of institutions (e.g., water rights, markets, pricing policies, and quality regulations), the sharing of information (e.g., extreme weather forecasts and warnings, and agricultural advisories), and the building of infrastructure (e.g., natural or human-made water storage, water supply and sanitation systems, and irrigation) designed both to leverage opportunities and to mitigate risks – often simultaneously.

Humans have strived to manage their water resources for over 10,000 years,[4] but the Industrial Revolution marked a dramatic shift in this effort. Across the industrializing world, portfolios of investments were built for water resource management, water supply and sanitation, and irrigation services. These investments systematically reduced water-related risks – leading to widespread water security in many parts of the world by the latter part of the twentieth century. Water risk is now largely tolerable for most people in developed nations, except when catastrophes strike, or where over-exploitation of the aquatic environment leads to unacceptable environmental impacts. Developing countries are now taking determined steps toward greater water security, too. Yet, many countries remain water insecure, particularly in Sub-Saharan Africa and Asia.

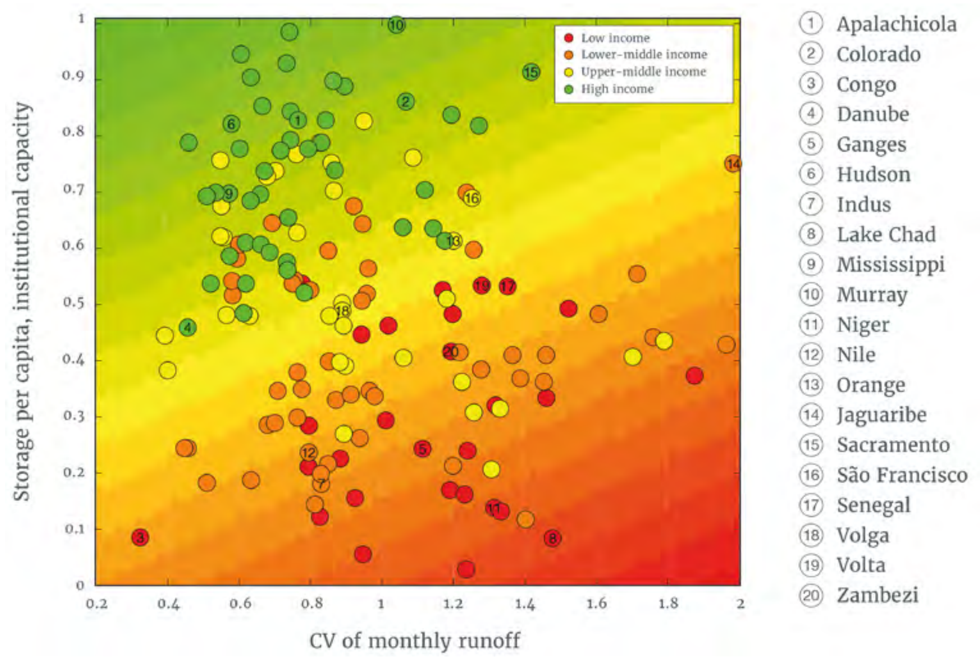
The importance of water endowments

There is growing evidence that the endowment of 'hydrological complexity' varies greatly between most rich countries on the one hand, and most poor countries on the other, even when their mean annual rainfall numbers are similar (see Box 1). 'Difficult hydrology' is a combination of unpredictable drought and flood extremes, plus high inter-annual and/or intra-annual variability (and associated unpredictability) of rainfall and runoff. Water security requires that this variability be managed, thereby ensuring predictable water supplies that are capable of meeting multiple, seasonally-changing demands, and also reducing potentially damaging extremes. In temperate regions (including most of the developed world), this variability is relatively low, and its management requires relatively less investment in institutions, information, and infrastructure. In tropical and monsoonal regions, including Sub-Saharan Africa and densely settled South and Southeast Asia, both inter-annual and intra-annual variability are very high.

Hydrological variability can be both good and bad. For example, the inter-annual variation in the flows of the Nile famously brought seven years of plenty followed by seven years of famine. Clearly, it would have been better if water-related investment had delivered 14 years of plenty. Yet, for millennia – in fact, until the nineteenth century – the annual Nile flood also washed excess salts from the soil, which was essential to the long-term

4 *Mithen (2012).*

Economic growth, hydrological variability, and investment in water security. *(Box 1)*



Note: The horizontal axis summarizes hydrologic variability. The vertical axis is a composite indicator of investment in infrastructure and institutional capacity. The dots represent all river basins with populations greater than 2 million, coloured to indicate high (green), middle (yellow), and low (red) levels of GDP per capita (using World Bank definitions). The coloured contours are a linearly interpolated surface reflecting the association between variability, water security investments, and GDP.

From: Hall et al. (2014).

This graphic illustrates the relationship between economic growth, hydrological variability, and investment in risk mitigation.

It shows that wealthy river basins (green dots, clustered in the upper left-hand quadrant) generally feature simpler hydrologies and larger investments in water security.

Poorer basins (red dots, clustered in the lower half of the chart) have invested less in water security, and many face complex hydrologies.

The investment required to transition from water insecurity to water security is greatest in those basins with highly variable hydrology (see coloured contour lines).

productivity of Egyptian agriculture. Without this inter-annual hydrological variability, irrigation in the Nile Valley would have been unsustainable. Moreover, ecological systems have adapted to existing hydrological (and climatic) variability, and species have evolved to accommodate these conditions. Anthropogenic changes to the variability of hydrological systems can alter ecosystems, and these changes may impose costs and benefits on the economy, and on the livelihoods of poor households.

Managing difficult hydrology requires major investments; yet, most countries with difficult water endowments are poor, and least able to make the needed expenditures (see Box 1). The few parts of the developed world with relatively high variability (including the western United States and Australia) made very large investments early in their development, and they continue to invest significantly in sophisticated institutions supported by advanced data collection and analysis. Many of these countries invested early in their development in infrastructure, including investment in dams and large storage reservoirs needed to secure intra-year and multi-year water supplies. As a result, their per capita water storage is up to two orders of magnitude higher than that of developing nations experiencing similar, or even greater, hydrological variability. It is important to recognize this inverse relationship between hydrological complexity and per capita wealth, and that pathways to water security will be more difficult, and more costly, in locations with complex hydrology.

It is important to recognize this inverse relationship between hydrological complexity and per capita wealth, and that pathways to water security will be more difficult, and more costly, in locations with complex hydrology.

It is also important to recognize that water security is not a static goal. In this report, we seek to identify which countries, river basins, cities, and aquifers are more or less water secure; but there is not a clear-cut dividing line, because water security is a continuum. Moreover, it is a dynamic continuum that will alter with changing climates, growing economies and asset stocks, and evolving social, cultural, and aesthetic priorities and values. Nevertheless, water security is not entirely subjective. Analyses of the investment pathways taken in a wide range of different societal, economic, and cultural contexts, reveals that historically, both good and bad choices have been made in the management of water resources.

2.2 The complex economics of water

The economic dynamics of water-related investments

To understand the complex economic dynamics of water-related investments, one must appreciate several distinctive facts about water.

First, the physical nature of the resource historically made water a largely local concern. Unlike electricity, water is heavy, and generally expensive to transport long distances. So, most water problems were tackled locally, and solutions were crafted to meet hydrological and financial realities at the local scale. In other words, the abundant water resources of Canada and Sweden cannot economically be transported to alleviate water shortages in Namibia or Yemen. While countries with chronic water shortages must, for the most part, find their own local solutions, there is an increasing trend to consider large-scale, long-distance water transfers. This includes transfers within countries (e.g., inside Pakistan, Libya, China, and India), and transfers between countries (e.g., from Turkey to Israel, and from Canada to the United States). The costs and complexities of these transfers can be very high.

Because water itself is typically extremely difficult to move long distances, strategies to manage water scarcity must often focus not on moving water as a factor of production, but rather on moving the products of water. This is the concept of 'virtual water'.[5] Although Canada cannot economically ship water to Ethiopia, it can ship wheat; this can ease the water demand/supply imbalance that Ethiopia faces as a consequence of water scarcity or variability. Because some 80 percent of the world's water is used for agriculture, global agricultural trade is an important part of the global solution to this local challenge.

The physical nature of both surface water and groundwater resources also ignores political boundaries. Many water problems cannot be tackled at the local level, or confined within the boundaries of a single administrative or political entity. For example, the 6,500 km-long River Nile flows through 11 nations, all of which have aspirations for its use. Such water problems are best tackled at a regional (rather than local) level; and they pose complex challenges, in part because states must choose whether to cooperate with their neighbours, or attempt to solve their water security problems alone. If states do not consider the consequences of their actions on their neighbours, then water-related investments cannot achieve their full economic, social, and environmental potential, and water-related political tensions and risks can increase.

Second, a distinctive feature of water is that, with the exception of certain sources of fossil groundwater, it is a renewable, common-pool resource subject to congestion, overuse, and degradation. Unlike coal or oil, when water is used, it is not 'consumed'. After it is used, a molecule of water continues through the hydrological cycle, and in due course, the resource will be replenished (more or less) in a way that coal or oil stocks cannot. The economic analysis of renewable resources is fundamentally different from the economic analysis of non-renewable resources. The analysis of renewable resources requires a focus on the sustainable use of the resource over time, aligning the rate of usage with the resource's natural capacity, and its timeframe for regeneration.

5 *Allan (2000).*

Despite the renewable nature of the resource, the natural supply of water from precipitation and runoff is variable and unpredictable; and the use of water can change the spatial and temporal availability of the renewable stock, as well as the quality of the resource. Such changes may impose additional costs on society, and these costs must be incorporated into the economic analysis of water-related policies and investments.

Third, water is not simply a commodity:[6] it has far-reaching social and environmental significance. In most societies, there are cultural and aesthetic values attached to water, springs, and rivers. These derive from belief systems dating back to antiquity, as evidenced by the construction of ancient structures such as riverside temples, fountains, stepwells, and gardens. Increasingly, access to water is seen as a human right. In many societies, a high value is also placed on the recreational opportunities provided by water, and the existence of free flowing rivers. In all places, the health of ecosystems is inextricably entwined with water management. As tangible as these factors are, they remain very difficult or controversial, to capture in economic terms.

Identifying the range of effects of water security on economic growth, in a rigorous manner, is a challenge for several reasons. In the first place, because water is such a pervasive input into so many economic activities, it is difficult to find convincing counterfactual situations to statistically substantiate how water-related investments affect economic growth. People must have minimum quantities of drinking water to live. Because water is a factor of production in all sectors, they will also need water to raise crops and animals, and to pursue economic livelihoods of all kinds. Water-related risks from variable supply, floods, droughts, and waterborne disease, may all adversely affect human well-being, productivity, and economic growth. There is no small irony here: because water is so important for so many reasons, it is difficult to statistically show the importance of water-related investments to economic growth.

Additionally, the causal links between water-related investments and economic growth, clearly run in both directions. Water-related investments can increase economic productivity and growth, and economic growth can provide the resources to finance capital-intensive investments in water-related infrastructure. A plot of water-related infrastructure and national income will show a strong positive relationship, but this tells us little about the relative magnitudes of the two causal links running in opposite directions. Work remains to be done to assess the degree to which water-related investments will enhance economic growth in individual cases.

... water-related investments can increase human well-being without increasing national income ...

Finally, water-related investments can increase human well-being without increasing national income or economic growth as conventionally measured. For example, the provision of piped water supplies will save households – and in particular, women and girls – from time spent collecting water outside the home. This is an improvement in quality of life that will not necessarily be reflected in national income statistics.

Overall, the literature suggests that the relationship between water and economic growth varies greatly with context. Some investments in water security will be attractive, while others will be undesirable, both in terms of economic returns on investment and in terms of the trade-offs between economic, environmental, and social values. The challenge will always be to determine the design, timing, and sequencing of investments in a particular location, so that they yield the highest returns.

6 *Boulding (1962).*

Appraising investments in water security

Not all water-related investments will be beneficial. Investments may be excessively costly, may not lead to the intended benefits, may result in harmful and perhaps unintended impacts upon people and the environment, or may close off more beneficial future investment opportunities.

Often, the benefits of large-scale water investments have been considered self-evident. For millennia, people have struggled to control water resources for irrigation, to limit flood losses, and to provide domestic water supplies. Would so much labour and treasure have been devoted to this task over such a long sweep of history, if the benefits were not large and important? But, the salient economic question is not just whether benefits exist: it is whether, and on what timescales, benefits exceed costs (be they economic, social, or environmental); how they compare to benefits from other investment opportunities; and how costs, benefits, and impacts are distributed across society.

Quantifying the costs and benefits of water-related investment is, in fact, increasingly difficult. Where water was reliably abundant relative to demand, the primary focus of economic analysis was determining the most cost-effective approach for delivering water to users. Investment capital was the fundamental constraint to delivering water; meaning that least-cost, supply-side engineering solutions became the usual approach to meeting water demands. There was, by and large, enough water for all users who were able to finance the infrastructure needed to access it. Projects tended to be appraised in strictly financial terms (without full regard to social and environmental trade-offs), and designed to achieve a limited set of objectives.

Today, capital constraints continue to limit investment, particularly in poor countries where water insecurity tends to be greatest. But, in addition, the quantity and quality of the water resources themselves are now increasingly becoming constraints on economic growth. As competition for water grows, both the 'opportunity cost' of allocating water to one use rather than another, and also the costs associated with water pollution, are becoming increasingly pronounced. It is, therefore, important to understand the full range of potential water uses if we wish to rigorously assess the economic benefits and costs of investments in water security; this is especially so relative to other priority investments competing for the same limited financial and water resources.

Investments intended to promote water security must increasingly address interrelated challenges with solutions that achieve multiple objectives.

As water resource constraints become more binding, and hydrological uncertainties grow due to climate change, it is also increasingly important for water planners to understand the complex inter-relationships among different water uses. Planners should incorporate feedback effects such as water quality and ecosystem degradation, and the dynamics of timing and sequencing, into analyses of investment costs and benefits. In a world of growing water scarcity, planning must increasingly take into account water resource constraints, and the impact one water use will have on another. In a globalizing world, the geographic extent of these inter-relationships expands, too.

Investments intended to promote water security must increasingly address interrelated challenges with solutions that achieve multiple objectives. As populations and economies grow, and as climate change makes weather less predictable and more severe, more people and assets are in 'harm's way', facing multiple risks. Thus, dams should be designed and operated to provide multiple benefits, such as flood control, power, and irrigation. Hydro-meteorological services should provide agricultural advisories, as well as storm warnings. The multipurpose nature of many water-related investments makes it important to assess the full range of risks and rewards in a given location, and to determine the most cost-effective interventions for managing multiple, often interrelated, risks; while also capitalizing on opportunities for investment.

Economic assessment of water-related investments is also complicated by the fact that they yield two conceptually different types of economic benefits. Investments can reduce the losses experienced as a result of water-related hazards, and at the same time, they can produce valued goods and services. Moreover, they can do this across multiple sectors and boundaries. Both the reduced losses, and the added value of productive water use, enter the cost-benefit analysis on the benefit side of the equation. For example, the benefits of dams include both flood and drought mitigation (reduced flood and drought losses), and hydropower generation (a 'valued good'). Similarly, piped water supply and wastewater connections yield health improvements (reduced losses), quality-of-life benefits, and aesthetic benefits from in-house plumbing (a valued service). Professionals in a particular discipline naturally focus on the type of outcome in which they have expertise, and tend to neglect or de-emphasize other valued outcomes. Thus, it is easy to overlook the full spectrum of economic benefits from water-related investments.

Finding the right water security investments

The 'right' investments in water security will always be context-specific. Investments will be set within specific institutional and cultural settings, economies, ecosystems, topographies, and hydrologies. They will be dependent on a common-pool water resource whose availability and quality can be affected both by other users, and exogenous climate shocks. All of this will influence project design and the magnitude and distribution of the benefits and costs of investments.

Many investments will be part of a larger infrastructure network such as a water supply and sanitation system, or a hydropower generation and transmission system. Network technologies are characterized by economies of scale, joint products, and positive externalities. These effects take economists into a world of increasing returns from investments, and are thus especially hard to quantify and value. The level of development of these broader systems will affect potential returns on new investments. Incremental expansions of mature systems, for example, will often be economically attractive; whereas the development of new systems that rely on extensive networks for economies of scale, can – in their early stages – appear to be poor investments.

In addition, the returns on many infrastructure investments will depend upon the strength of the institution that operates and manages it, as well as the human, financial, and information resources on which it draws. Investments in water security must therefore be designed holistically, in order to provide an effective balance of institutional, informational, and infrastructure financing.

Returns on large-scale, long-lived, networked infrastructure thus tend to be highly path dependent. In other words, they will depend greatly on the level of existing infrastructure stocks and their effective management. The breadth and complexity of these sorts of infrastructure investments often require significant complementary institutional capacity (and financial resources) for management, operations, and maintenance. In addition, they require robust information

Returns on large-scale, long-lived, networked infrastructure thus tend to be highly path dependent. In other words, they will depend greatly on the level of existing infrastructure stocks and their effective management.

and decision-support systems in order to facilitate ongoing adaptive management. This means that it is important to understand where a country sits on its pathway toward water security, and to assess portfolios of water-related investments within the context of that pathway.

Context will also influence the way in which water security investments are conceptualized: as 'upside' opportunities to secure potential growth, or as 'downside' risk management to secure continued growth. Developing countries with relatively low stocks of water security-related infrastructure tend to focus on the upside growth potential of investments; while developed countries, with relatively mature infrastructure stocks and significant accumulated assets at risk of water-related hazards, tend to focus on the downside risk management aspect of water security investments.

Whatever a policymaker's focus, it is important that risk and uncertainty are incorporated into the assessment of water-related investments. There are two commonly used approaches for appraising investments in water security that incorporate risk and uncertainty.[7] The first is an approach focused on risk management, structuring the question so as to find the least-cost method of achieving a tolerable level of water risk. In this approach, a policy objective is set (i.e., the level of risk the society deems to be tolerable), and the task is to find the investment or investments that most cost-effectively achieve the targeted level of risk. The second is a more economic approach, seeking to guide investment to the point where a marginal dollar invested in water security will return a marginal dollar in benefits, i.e., where marginal costs equal marginal benefits. Those benefits can include positive welfare benefits (e.g., the economic value of increased hydropower production), and also the benefit of risk reduction, which is the difference between the expected annual loss pre-investment and residual risk, i.e., the expected annual loss post-investment.

Both approaches conceptualize the water security challenge as a constrained optimization problem in which the timing, sequencing, and sizing of investments (and their operations) are chosen either to minimize costs (the 'tolerable risk' approach), or to maximize benefits (the 'economic' approach), subject to specific constraints. Both methods incorporate the economic opportunities from the productive uses of water, and the benefits from reducing the destructive aspects of water. In both formulations, constraints are used to characterize the biophysical realities of the hydrological system (such as the timing and absolute limits of water availability), and social prerogatives (e.g., relating to social preferences for maintaining environment flows, safeguarding water quality, meeting basic needs, and protecting cultural and natural heritage). In the 'tolerable risk' approach, constraints are also used to set 'tolerable risk' from water hazards, effectively mandating that investments achieve the level of benefits associated with pre-specified standards.

At the project level, cost-benefit analysis is still arguably the best tool available to assess specific water-related investments. A good deal of work is being done to refine cost-benefit methodologies; in particular, to take better account of environment and social costs, and to better accommodate uncertainties. Yet, the question of what constitutes 'good practice' remains a topic of debate. Cost-benefit analysis falls uneasily into a middle ground, where it is criticized both by proponents of intuition (who feel it is unnecessary to undertake detailed analysis), and by proponents of comprehensive modelling (who propose economy-wide models designed to capture system-wide effects of large water-related investments). Despite this discomfort, there is a clear need to identify and avoid poor investments in water security; and, even with its well-known limitations, cost-benefit analysis remains a necessary and useful tool to appraise specific water-related investments.

At the level of the river basin or the state, it is important to look beyond individual projects to dynamic, adaptive pathways (see Chapter 4), together with their impacts on economic growth, equity, and the structure of economies. This requires performing cost-benefit analyses on sequences (or 'portfolios') of projects, and carefully considering how pursuing a specific

7 *Hall et al. (2012).*

... it is essential to take special account of social and environmental impacts.

project in the present might foreclose options in the future. Water policies and infrastructure investment decisions will have long-lasting impacts on development options across economies, and the path-dependency of large-scale water infrastructure reinforces the importance of analyzing water development pathways.

Finally, in finding the 'right' investments, it is essential to take special account of social and environmental impacts. In many countries, the impacts of water management decisions will particularly affect the poor, women, and the environment. The poor are disproportionately affected by the destructive impacts of water insecurity, because they tend to live in areas more susceptible to weather-related disasters, they rely more on rain-fed agriculture, and they use more unprotected water sources. In the developing world, women and children are more likely to be affected by natural disasters than are men.[8] The poor, and women, also tend to be disproportionately constrained in terms of capturing the opportunities of water-related growth, because they hold fewer land and water rights. Environmental needs are generally the first water uses that fail to be met in times of scarcity, because few countries have formalized, enforced water allocations for ecosystems use. When water quality becomes degraded, it threatens the health of freshwater ecosystems and groundwater quality. As societies have gained wealth, they have consistently demanded greater environmental quality, suggesting that with growth will come greater demands for water quality, and for healthy ecosystems.

8 *Doocy et al. (2013); Neumayer and Plumper (2007); WP TWG (2010).*

2.3 A theoretical model of the dynamics of water-related risk, investment, and growth

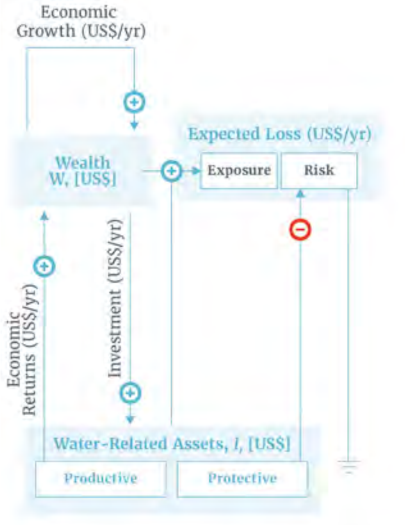
The need for investment – both to increase economic growth, and to mitigate water-related risks – is regularly cited as a policy priority. Yet, prior work to conceptualize the role of water-related investments has focused on these two objectives independently.

Policies and investments designed to improve water security should facilitate communities' access to the growth potential associated with the availability of adequate and reliable water supplies for municipal, agricultural, and industrial use; and at the same time, reduce communities' exposure to water-related risks such as floods, droughts, and water-related disease. To capture the dynamics of this interacting system, a growth model was developed relating country wealth to investment in both protective and productive water-related assets (see Figure 2).

As any economy grows, it generates income and builds wealth that can be invested in developing a stock of productive and protective water-related assets. In hazardous hydrological environments prone to extreme floods or prolonged droughts, water-related economic losses act as a drag on the rate of growth. Where countries have sufficient wealth to protect themselves from these hydrological losses (e.g., through investment in flood control, irrigation and storage, information systems, or strong institutions), robust economic growth is possible. On the other hand, poorer countries exposed to water-related hazards may struggle to recover from repeated debilitating losses, creating a vicious cycle where economic growth is repeatedly hampered by hydrological hazards.[9]

Similar dynamic behaviour has been described in other literatures linking environment and economics; and for some conditions, it is analogous to a poverty trap.[10] Indeed, there is an ongoing debate within development economics about both the prevalence or likelihood of poverty traps, and also the

Growth model relating country wealth to investment in protective and productive water-related assets *(Fig 2)*



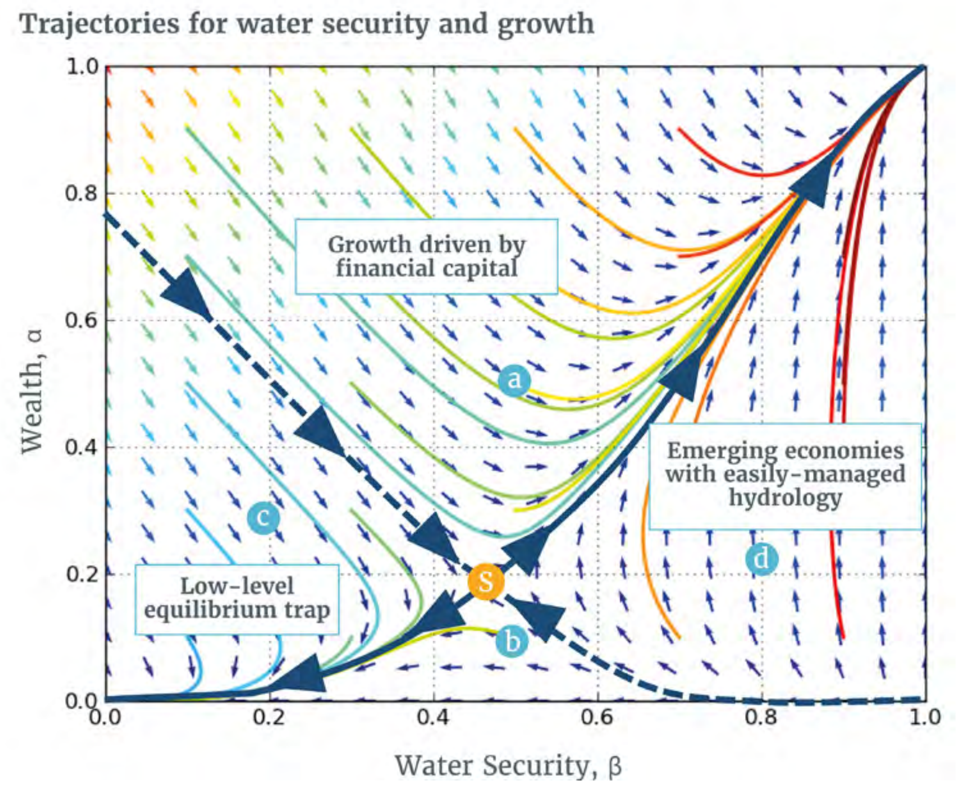
W_0 = wealth in the absence of water-related constraints
I_0 = investment required to achieve water security
(the point at which the next US$ invested goes elsewhere)

Hereafter, consider α = wealth as a fraction of W_0
And β = investment in water security to date relative to I_0

9 *Grey and Sadoff (2007).*

10 *Bonds et al. (2010); Dasgupta (2001).*

Theoretical dynamics of a water poverty trap *(Fig 3)*



Note: Direction field for the system depicting the relation between wealth and investments in water security (including natural endowments). The arrows indicate the direction of the rate of change of points in the domain. The colour of the arrow indicates the total magnitude of the rate of change (red = rapid; blue = slow). Bold blue lines with large arrows represent the convergent trajectories (solid) and the separatrix (dashed). The unstable saddle point is marked with an 'S'.

circumstances in which they might arise. The majority of work to date has concerned poverty traps at the household, rather than at the macroeconomic, level; and has not focused specifically on water security.[11]

The simple conceptual model presented in Figure 3 sheds some light on the debate, with specific reference to the water sector, showing as it does the complex and dynamic behaviour of an economy subject to water-related protective and productive investments. In countries where economic growth is restricted by the lack of available water resources, and when water-related losses are sufficiently frequent or large to derail sustained economic growth, a poverty trap can be a feature of the system of water, growth, and risk, as depicted in Figure 3. The actual existence of a poverty trap is, in practice, dependent on economic and environmental factors specific to an individual country.

Any point on Figure 3 will experience a trajectory of growth or decline that depends on its initial position, its 'water endowment' and context-dependent constraints and parameters. The prognosis for a country is promising if it begins at initial condition (a) in Figure 3. This initial situation reflects moderate wealth but only moderate water security, for example the western United States in the early twentieth century, or Israel in the mid-twentieth century.

11 *Dasgupta (2001); Sachs (2005).*

There is sufficient national wealth, making water-related investments possible. These investments come at the expense of investment in other sectors of the economy, and initially they are a drag on economic growth; but without them, further growth is hard to sustain. Once the initial investment is made, the amount of additional investment required to mitigate water-related risk is still significant, but can be allocated from the proceeds of growth in the wider economy.

The situation for a country that begins at initial condition (b) in Figure 3 is less encouraging. Here, the level of water-related endowment or investment is identical to the situation in (a) – perhaps owing to a similar level of unmanaged hydro-climatic variability, for example. However, the level of initial wealth is much lower. In this case, the lack of wealth seriously constrains mitigation of water-related losses and, after a period of stagnation, the economy is drawn into the poverty trap. Such an example trajectory is rarely seen in reality: these are locations in which large-scale, commercial agriculture is unlikely ever to have been viable. Such a trajectory is restricted by the presence of a poverty trap, and is investment-limited, so only an external injection of wealth (e.g., through overseas investment, or the exploitation of mineral resources) can shift the trajectory to one of growth.

The trajectory followed by a country that begins at initial condition (c) is not promising, either. This initial condition, in which water security is low and wealth is low represents the most perilous set of circumstances considered in the present analysis. With vulnerable water resources and modest wealth, an initial phase of investment drives an increase in water security. However, this investment depletes wealth to the point where growth is insufficient to compensate for losses incurred due to lack of water security. Modern examples of countries in this situation might include Niger and Chad.

Finally, the situation for a country that begins at initial condition (d) in Figure 3 complements initial condition (a), in the sense that its trajectory is one of growth, albeit the starting point is one of relatively low water-related risk, coupled with little wealth. Such a system might be typical of the eastern United States in the mid-nineteenth century, or of a northwestern European country in the mid-eighteenth century. During the initial phases of growth, water security is not a priority; the economy can grow without limits imposed by water-related risks. Indeed, the economy can afford to grow unencumbered by the need to invest in water security, instead allocating capital to opportunities in other sectors bringing higher rates of economic growth. Subsequently, the necessary level of investment in water security can be made from the proceeds of growth, providing that the impact is not so severe that it drags the trajectory across the divide, towards the poverty trap.

... developing and maintaining critical water security-related assets and institutions ... reduces the risk that a country's efforts to grow.. will be thwarted by regular water-related losses or water-related drags on productivity.

The location of the 'tipping point' (i.e., the point at which pressures will direct an economy either toward growth or toward poverty) will depend on the adequacy and effectiveness of water security-related investments compared to other investments in the wider economy. This finding implies that investing in the development, management, and operation of water-related institutions and assets can act to insulate a country from adverse water-related risk. In other words, developing and maintaining critical water security-related assets and institutions moves the country's growth trajectory away from the tipping point (S) in Figure 3, and reduces the risk that a country's efforts to grow in other sectors of the economy will be thwarted by regular water-related losses or water-related drags on productivity.

It is instructive to consider the effect of planned and unplanned interventions in the system of water security investments, risk, and growth. For example, climate change may lead to exogenous changes in water resource availability and variability. Such changes could lead to a requirement for greater investment to maintain the same level of risk, and in some cases, they would move the system closer to Figure 3's poverty trap. By contrast, technical advances in desalination, or the adoption of water-saving technologies, would lead to increased water security, and consequently move the growth trajectory away from the poverty trap. Because of the economy's potential vulnerability to exogenous factors, it is particularly important to identify and pay close attention to climate change adaptation measures within those countries that lie closest to the water-related poverty trap, for example, those countries with the highest water-related losses as a fraction of their GDP (see Chapter 3).

It is also possible to experience exogenous shifts in GDP due, for example, to the onset of war or the discovery of valuable natural resources. Such events may, in the former case, cause otherwise water-secure countries to descend into insecurity; in the latter case, increased access to capital may permit investment in water security that could place the country on a trajectory of growth. Whether such growth can be sustained depends on the amount of capital available relative to the costs of the necessary investments in water-related infrastructure. Some trajectories may require a substantial initial commitment of national wealth to the goal of reducing water risk before returns are seen. Historical studies from the Netherlands, the United Kingdom, and Germany have documented substantial public investment in water infrastructure in the nineteenth century. Those investments were stimulated by the requirements of private industrial producers, combined with the pressing need to simultaneously improve public health and reduce water-related risks, such as droughts and floods.[12]

This theoretical model of the dynamics between water-related risk, investment, and growth, suggests that the optimal growth strategy for minimizing the risk of falling into a poverty trap[13] requires a combination of both (i) investments in water-related infrastructure and the related investments required to ensure their productivity, and (ii) investments in other sectors, in order to stimulate broader economic growth. In other words, water-related investment is not a silver bullet that will result in inevitable growth and prosperity. Nonetheless, in areas with difficult hydrology, growth without adequate provision for water will leave a fragile economy vulnerable to water-related risks, and without the investment opportunities water security can bring.

... water-related investment is not a silver bullet that will result in inevitable growth and prosperity. Nonetheless, in areas with difficult hydrology, growth without adequate provision for water will leave a fragile economy vulnerable to water-related risks, and without the investment opportunities water security can bring.

12 *Brown (1988); Groote et al. (1999); Hassan (1985).*

13 *With respect to Figure 3, this would be a trajectory that is tangential to the bold blue lines that separate the trajectories of growth and decay.*

2.4 An empirical analysis of the impact of hydrological variability on growth

The connection between water security and economic growth is intuitively clear, but empirical evidence of this relationship is scarce.

Water-related hazards such as floods, droughts, and disease cause damage to an economy through the destruction of physical property and infrastructure, the loss of human capital, and the disruption of economic activities. These events are readily observed and undoubtedly have economic impacts. The dependence of agricultural production on reliable rainfall is similarly evident in many countries without significant irrigation investments.

Box 2 shows the relationship between growth (annual per capita economic growth, in percent) and annual runoff (spatially averaged) for Malawi, India, and China. Malawi shows highly variable economic growth, closely corresponding to the variability in runoff. India shows some correspondence between runoff and growth, amid a positive growth trend. Per capita economic growth in China shows a very stable pattern, with little correspondence to runoff variability. Thus, we see a range of relationships: suggesting that in some countries, hydro-climatic variability may have a strong effect on economic growth, while in other countries, a 'decoupling' can occur.

This highlights important questions about how water insecurity affects economic growth. Is the relationship between hydro-climatic variability and growth a causal relationship? Is it significant only in a very few countries with particular circumstances, or is it a global concern? Are the effects of hydro-climatic variability a sufficiently large drag on economic growth to justify investment or reforms? And, if so, what interventions and investments will be most effective in diminishing an economy's vulnerability to the harmful effects of water-related hazards?

The impact of hydro-climatic variability on economic growth

There are surprisingly few empirical studies addressing these important questions. Despite the recent interest in indicators of water security, no studies provide an empirical basis for identifying the drivers of water security. In particular, current definitions and indicators of water security are not empirically linked to economic growth.

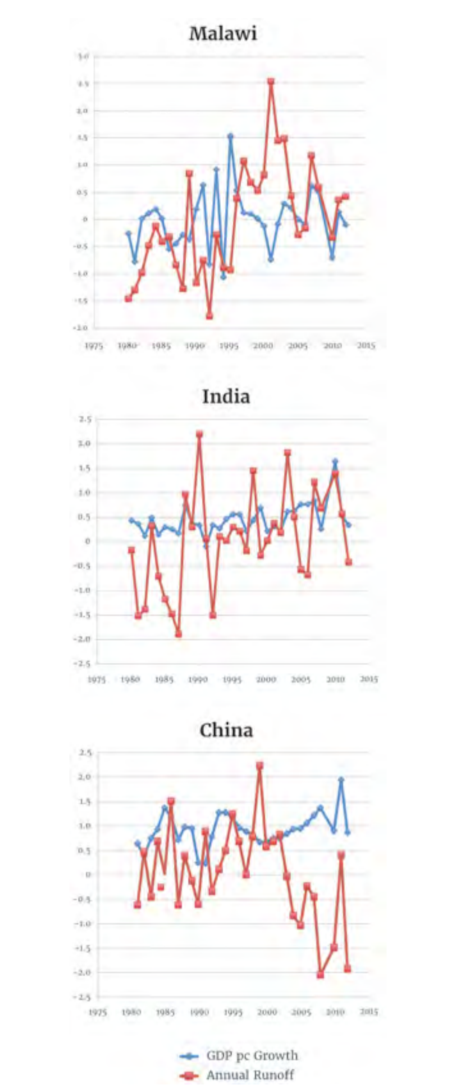
Early empirical studies of the relationship between infrastructure investments (not limited to water) and growth were subject to criticism in particular due to the problem of determining the direction of causality.[14] In other words, did infrastructure investment cause growth, or did growth lead to infrastructure investment? More recent work – using structural growth models to account for the feedbacks between investment and growth in the wider economy – has more clearly identified the substantial contribution of infrastructure to growth.[15]

14 *Gramlich (1994); Munnell (1992).*

15 *Esfahani and Ramírez (2003).*

Annual per capita GDP growth and annual runoff, for three countries. *(Box 2)*

These figures show the annual per capita GDP growth and annual runoff (standard normal units) from the period 1980–2012. Malawi shows highly variable economic growth, which often reflects the variability of runoff. India shows fairly consistent economic growth, with variability that exhibits some correspondence with runoff variability. China shows steady economic growth that, in the latter part of the period especially, shows little correspondence to runoff variability (i.e., a 'decoupling').



Looking more specifically at research on the relationship between hydro-climatic variables and economic growth, there is an emergent literature that establishes a link between climate factors and economic growth, for specific regions of the world.[16] Early efforts focused on the effect of changes in temperature on agricultural production[17, 18] and the wider economy.[19] More recent econometric analyses have considered variability in precipitation (i.e., rainfall, snow, sleet, and hail) in addition to temperature.[20] Precipitation extremes (rainfall variability, floods, and droughts) have been shown to have a statistically significant detrimental impact on different measures of economic growth in Sub-Saharan Africa;[21] and more recent analyses, using a global data set of country level per capita GDP growth, show that anomalously low or high precipitation has a negative economic effect; thereby providing evidence that variability in precipitation can indeed hinder growth.[22]

However, neither temperature nor precipitation alone can capture all of the ways in which water may potentially affect economic growth. While the recent recognition of the importance of precipitation is clearly linked with water-related impacts, it still does not account for land surface and temperature influencing the amount of water available for use in a given location; nor the occurrence of potentially harmful flooding. To address this, the Task Force's analysis used 'runoff' as one of several hydro-climatic variables to explain changes in per capita GDP growth. Runoff was estimated using a gridded model estimate of water accumulating at the land surface as a result hydrologic processes, e.g., by infiltration and evapotranspiration (see Box 3). As a result, the runoff variable captures both temperature and precipitation effects, and thus should provide a better indicator of water available

16 *Fankhauser and Tol (2005); Seo et al. (2009).*

17 *Mendelsohn et al. (1994).*

18 *Schlenker et al. (2006).*

19 *Nordhaus (2006).*

20 *Deschênes and Greenstone (2007).*

21 *Brown et al. (2011).*

22 *Brown et al. (2013).*

Specifications of the econometric analysis *(Box 3)*

The analysis of the effect of climate and water-related hazards on economic growth was conducted using a fixed effects panel regression model, with individual and year fixed effects. Country fixed effects were used to control for omitted variables that vary across countries (e.g., other aspects of geography, culture, and institutions). Year fixed effects controlled for factors that might vary over time, but affected all countries in much the same way.

This specification helped adjust the model for global shocks to the economy, such as the global financial crisis of 2008-9. The standard errors on the coefficients estimated through the model were obtained through robust covariance matrix estimation, in order to account for heteroskedasticity and serial correlation. The standard errors are clustered at the country level. The specifications of the model are shown below:

$$Y_{it} = \beta X_{it}^{exo} + \alpha_i + \gamma_t + \varepsilon_{it} \quad \text{i= 1,...,113 and t = 1980,...,2012}$$

Where Y_{it} represents the dependent variable (per capita GDP growth) of country i at time t, β is the regression coefficient for each independent variable, X_{it}^{exo} represents the exogenous independent variables (hydro-climatic indices for basin i at time t), α_i is the basin fixed effect meaning that it represents the time-invariant aspects of basin i, γ_t represents the year fixed effects, and ε_{it} represents the time-variant factors. This model was used for all panel regression results.

Observations of precipitation, including a measure of meteorological drought, plus temperature, are also included in the analysis. In total, nine hydro-climatic variables were used as independent predictors in a fixed effects panel regression. These variables were: (i) mean annual precipitation; (ii) mean annual temperature; (iii) the squared mean annual temperature (to account for non-linear effects); (iv) mean annual runoff (streamflow); (v) drought and excess precipitation, positive thresholds (WASP+1); (vi) drought and excess precipitation, negative thresholds (WASP-1); (vii) runoff, positive thresholds (WASR+1); (viii) runoff, negative thresholds (WASR-1); and (ix) percentage of area under flood in each country.

While precipitation is generally indicative of water availability, it does not account for the effects of evapotranspiration, which is a function of temperature and soil moisture; and which can be particularly significant in the semi-arid tropics. To account for these evapotranspiration effects, runoff data were introduced to an econometric analysis of economic growth for the first time; the runoff data being taken from a model output of the MacPDM gridded hydrologic model.[23] In addition, the use of monthly precipitation data is not generally a viable representation of flood hazard, which is expressed at shorter timescales in most cases. This study therefore introduced a flood hazard metric based on a new global model of flood hazards by Winsemius et al. (2013).

The analysis was conducted at the national (country-level) scale. Precipitation, temperature, and runoff variables are standard normal variates; thus, a unit increase in the variable above the mean (i.e., one standard deviation) implies a change in annual per capita GDP growth rate (%) equal to the value in the table. Extreme variables (WASP and WASR) are fractions of a country in the given state. These regression coefficients represent the reduction in per capita GDP growth rate (%) when the fraction of the country in the extreme state is equal to 1.

23 *Arnell (1999).*

... countries whose economic performance is resilient to water security-related variables such as runoff, floods and droughts, are relatively water secure. Countries where growth is strongly correlated with these factors are relatively water insecure.

for use. In addition, to better represent the potential effect of hydrologic extremes, thresholds were used to designate the fraction of a country in an extreme state of runoff or precipitation. As Box 3 shows, the variables are inevitably correlated, but together they create a representative summary of the hydro-climatic conditions in a particular country.

To determine whether there is empirical evidence of a statistically significant impact of hydro-climatic variables, including hazards, on per capita GDP growth on the countries of the world, and to help identify the key drivers of those impacts, we performed an econometric analysis (i.e., a fixed-effects panel regression) across 113 countries (see Box 3).

As Box 3 indicates, we found it useful to conceptualize water security as 'protection from water-related drags on economic growth'. By this definition, countries whose economic performance is resilient to water security-related variables such as runoff, floods and droughts, are relatively water secure. Countries where growth is strongly correlated with these factors are relatively water insecure. The work presented here comprises the most complete economic assessment to date of the effects of water-related hazards on economic growth, and includes variables never previously incorporated, such as runoff and flood hazard.[24]

We note that there are also hydro-climatic effects on waterborne disease, and these water and sanitation-related impacts will also affect growth.

Using this model, runoff was revealed to have the most highly statistically significant effect (at a 99 percent confidence level) on annual economic growth, of all the variables examined. The variable used for runoff is representative of the general availability of water; separate variables are used for flood (Weighted Anomaly Standardized Runoff, or WASR) and drought (Weighted Anomaly Standardized Precipitation, or WASP) extremes. Runoff has a positive relationship with growth that indicates that greater water availability has a significant and positive causal effect on economic growth. The positive nature of the effect was not surprising, but the strong statistical significance with the 113-country data set suggests that the temperature and precipitation effects reported in earlier studies are indeed related to water availability.

Drought[25] (WASP) was shown to have a statistically significant (95 percent confidence level) negative impact on economic growth as well, which is consistent with previous studies. The magnitude of the effect depends on the characteristics of each country. On average, a major drought (affecting 50 percent or more of a country's area) was found to reduce economic growth (as measured by per capita GDP) by about half a percentage point in that year (e.g., reduced from 3% to 2.5% per year).

Flood extent (WASR) was also found to have a negative association with per capita GDP growth (at a 90 percent confidence level). Although it is widely recognized that floods have episodic negative effects, this analysis clearly demonstrated the extent to which these individual events can accumulate to affect economic growth in significant ways.

24 *Winsemius et al. (2013).*

25 *Drought was defined in two ways: using a variable based on precipitation (Weighted Anomaly Standardized Precipitation, or WASP) and a similar variable based on runoff (Weighted Anomaly Standardized Runoff, or WASR). These variables are defined in Brown et al. (2011). For most of this analysis, the WASP-1 variable was used to represent drought.*

Overall, the results show a strong connection between water availability and economic growth in a global dataset. The effects will vary among individual countries: strong in some, yet insignificant in others. This corresponds with earlier studies, but provides greater substantiation of the relationship because it examines multiple measures that better characterize the complexities of hydro-climatic variability and water availability. Previous studies of these relationships have been based on precipitation and temperature. Here, in addition, runoff and a flood metric have been included, and both were found to be statistically significant.

The statistical significance of multiple hydro-climatic variables does not imply that economic growth is solely determined by water, and water-related hazards. The magnitude of the effect on economic growth across the entire data set is small,[26] because there are many factors that affect economic growth. However, in some countries the effect may be quite large. The results are best interpreted as showing that water availability and water-related hazards, such as floods and droughts, act as a drag on growth, or a 'headwind', reducing the economic growth that would have occurred if not for these effects.

This empirical evidence of the relationship between water and economic growth also has important implications for assessing the potential economic costs of climate change. Water-related impacts of climate change will be significant, and studies that neglect the impacts of the availability of water and water-related hazards will underestimate the economic consequences of climate change. Previous economic studies of the effects of climate change have focused primarily on temperature. Here we see that historically temperature is not statistically significant, but the effect of runoff (which reflects the general availability of water and thus is temperature related) and water-related hazards are. Without taking into account hydrological variability, the economic returns on adaptation investments made to improve water security are likely to be underestimated.

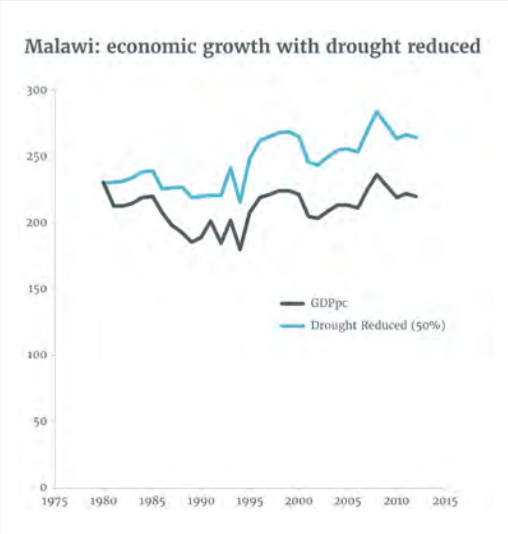
Overall these findings indicate that, on average, global economies are vulnerable to changes in the availability of water and water-related hazards, and that water insecurity acts as a drag on economic growth. Water security is therefore not only an investment in protecting communities; it is an investment in enabling growth.

Looking more specifically at the economic impacts of drought, an analysis was undertaken that builds on earlier studies and looks at which countries are most severely affected by drought (see Box 4). The analysis focused on the difference between countries' economic growth rates in drought years and in all other years. This allowed isolation of the drought effect. Simulations were conducted to represent the growth in countries with and without the drought effect present. This enables us to visualize the cumulative effect of drought over time. The difference between the drought growth rate and non-drought growth rate reflects the degree to which a country was affected by drought, while accounting for its baseline growth rate. Based on this simulation analysis, one can determine which countries would most benefit from a reduction of the drought effect in terms of economic growth rate. The results showed that in Malawi, for example, a 50 percent reduction in the drought effect led to a 20 percent higher per capita GDP at the end of the simulation. In the case of Brazil, the reduced drought effect led to GDP per capita that was 7 percent higher.

The results showed a very clear negative association between drought and average economic growth rates globally, confirming that droughts produce a drag on global economic growth. Simulations that determined the benefits of reduced drought impacts also demonstrated that the effect of droughts may compound over a long time period. A visualization of the simulation results is presented in Box 5. These simulations showed that the countries that stand to reap the greatest benefits from drought reduction were concentrated in the Middle East, Africa, South America, Central Asia, and South and Southeast Asia.

26 *From an econometric standpoint, this is a positive attribute because it shows that the model is not over-specified.*

Simulation of reduced drought effect on economic growth
(Box 4)

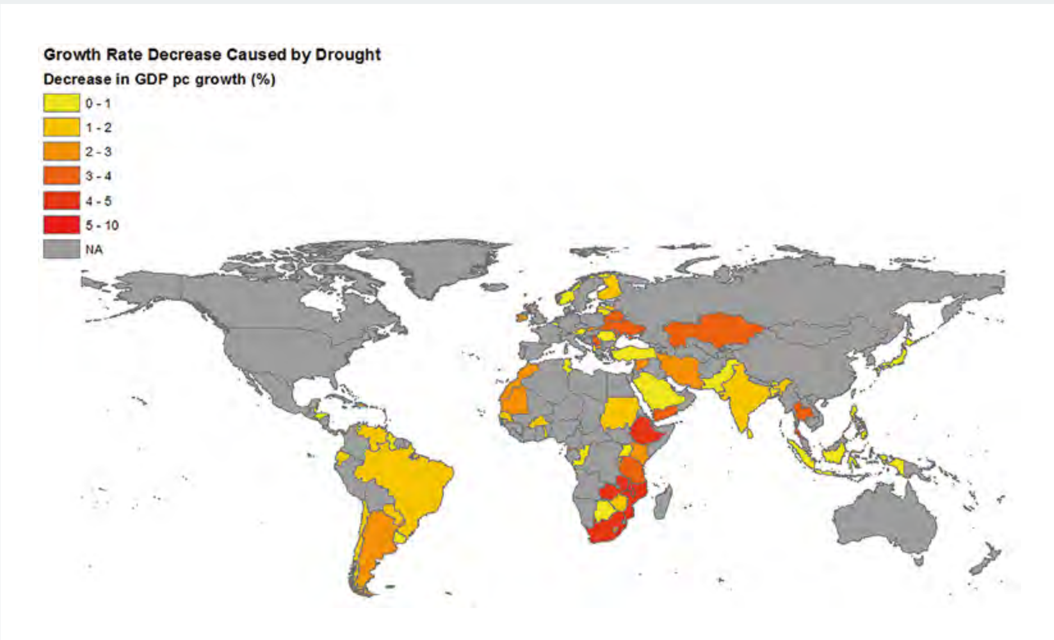


In order to demonstrate the growth effects of the economic drag caused by drought, a simulation was performed assuming reduced drought effects. The results for Malawi are shown here.

The growth rates in drought years were replaced with growth rates calculated assuming a 50% reduction of the drought effect (i.e., the difference between growth in drought and non-drought years, divided by 2). The new series of growth rates was used to simulate economic growth for a 30-year period, beginning in 1980.

Countries with the largest reduction in growth due to drought
(Box 5)

This map shows the countries with the largest difference in economic growth between drought years and non-drought years. Here, drought is defined as >30% of a country's area with rainfall below the drought threshold. The calculation uses the average of the difference between the growth rate in years when drought occurs, and the growth rate in all other years. Countries in grey show little difference – or even higher growth – during drought.



Results from fixed effects panel regression on country level per capita GDP growth (1980-2012) from 113 countries, conditioned on human water stress, and % GDP from agriculture *(Table 1)*

	Human Water Stress		% GDP from Agr		
Climate Variables	> 0.8	< 0.8	> 20%	< 20%	All Obs
Annual Precipitation	-0.57 (0.14)	0.01 (0.73)	-1.57 * (0.04)	-0.16 (0.52)	-0.40 (0.10)
Temperature	0.07 (0.771)	-0.122 (0.491)	-0.425 (0.247)	0.044 (0.746)	-0.09 (0.50)
Temperature (^2)	-0.086 (0.651)	-0.177 ‘ (0.081)	-0.243 (0.132)	-0.127 (0.221)	-0.14 (0.138)
Annual Runoff	0.685 * (0.037)	0.214 (0.376)	1.446 * (0.036)	0.454 * (0.032)	0.567** (0.005)
Meteo. Drought (WASP-1)	-1.878 ‘ (0.075)	0.039 (0.962)	-2.898 * (0.017)	-0.791 (0.214)	-1.152* (0.044)
Meteo. Flood (WASP+1)	1.115 (0.249)	-1.106 (0.298)	2.705 (0.298)	-0.231 (0.737)	0.284 (0.685)
Runoff Drought (WASR-1)	1.819 ‘ (0.090)	0.82 (0.449)	4.537 ‘ (0.085)	0.936 (0.143)	1.58 * (0.019)
Runoff Flood (WASR+1)	-1.549 ‘ (0.083)	-0.15 (0.871)	-2.611 (0.141)	-0.91 (0.174)	-1.021 ‘ (0.086)
Observations	1221	2112	891	2574	3729
Country	37	64	27	78	113

Note: Values indicate the regression coefficient for each variable (p-value in parentheses). Negative coefficients indicate negative effects on per capita GDP growth. The analysis focusing on water stress grouped countries based on the Human Water Stress (HWS) index. This measure, which is roughly equivalent to available water resources per capita, was obtained from the HWS data set developed by Vörösmarty et al. (2010). The subsets were created using a threshold on the conditioning factor, to divide the countries into two sets: respectively, those with values above and below the threshold. The threshold was selected based on break points in the empirical probability distribution of the conditioning variable. A threshold level of 0.8 was selected to separate countries, where a higher score means greater pressure on water resources. An agriculture-dependent economy was defined as one in which more than 20% of GDP is derived from agriculture. The threshold was predicated on the empirical probability distribution of the conditioning variable. The categorization is based on year 2012 values. The flood variable was not available for these regressions.

Significance levels: * 99.9%; ** 99%; * 95%; ‘ 90%**

Fixed individual and annual effects panel regression results for countries, by income classifications *(Table 2)*

	Country Classification			
Climate Variables	**LI**	**LMI**	**UMI**	**HI**
Annual Precipitation	-1.142 (1.066)	-0.879' (0.497)	0.234 (0.596)	-0.314 (0.316)
Temperature	-0.72 (0.623)	-0.367 (0.302)	-0.355 (0.216)	0.065 (0.172)
Temperature(^2)	-0.306 (0.233)	-0.176 (0.270)	-0.061 (0.109)	-0.0114
Annual Runoff	0.956 (1.156)	0.506 (0.363)	0.439 (0.499)	0.460 ' (0.263)
WASP-1	-3.430' (1.986)	-1.975 (1.654)	2.217 (1.360)	-0.929 (0.578)
WASP+1	1.597 (2.241)	1.873 (1.879)	0.652 (2.275)	0.04 (0.914)
WASR-1	6.192 (3.814)	1.56 (1.655)	-1.469 (1.127)	1.421' (0.725)
WASR+1	-1.762 (2.367)	0.337 (1.586)	-5.5472	-0.7299
R2	0.012	0.012	0.014	0.011
Observations	660	990	825	1254
Country	20	30	25	38

Note: Values indicate the regression coefficient for each variable (p-value in parentheses). Negative coefficients indicate negative effects on per capita GDP growth. Countries are grouped based on the World Bank's 2014 'gross national income' (GNI) classifications as: 'low-income' (LI), 'lower-middle-income' (LMI), 'upper-middle-income' (UMI), and 'high-income' (HI).

Significance levels: * 99.9%; ** 99%; * 95%; ' 90%**

Two characteristics that influence vulnerability to water-related risks

The effect of water availability and water-related hazards was significant in the global analysis, but some countries are clearly more water secure than others. What characteristics make a country more or less susceptible to water-related risks?

A panel regression analysis was conducted on subsets of countries, in order to investigate three factors that are potentially related to a country's sensitivity to water-related risks. These factors were (i) level of income; (ii) level of water stress; and (iii) dependence of the economy on agriculture. The results are shown in Table 1. The specifications for this model were identical to the fixed effects model described previously, in Box 3. In this case, however, the regressions were conducted for subsets of countries based on the three classifications given above. The analysis is not meant to be exhaustive, but rather a deeper investigation of selected factors that emerged in the preliminary analysis. The effects of water supply and sanitation-related hazards have not been assessed due to lack of available time series data, but they are also likely important.

The results showed that hydro-climatic effects on economic growth were stronger in agriculture-dependent countries, and in countries with high human water stress (an index reflecting per capita water resources) (see Table 1). The statistical significance of the effects of runoff and drought on economic growth was higher in water stressed and agricultural dependent countries. Also, for countries in the low-income group, the magnitude of the coefficients on the climate variables was higher for almost all variables, suggesting that the largest impacts of hydro-climatic conditions are in countries with lower incomes (see Table 2).

The results show that the countries most economically vulnerable to hydro-climatic effects are those that are poor, water stressed, and/or dependent on agriculture. Box 6 shows the countries falling into these categories: Africa, the Middle East and South Asia stand out. The economic growth of nations with high human water stress[27] is more sensitive to the availability of water, so any reductions of water availability due to climate variability are felt severely. Nations with lower levels of water stress show no such effects and are only sensitive to temperature (squared) of the variables considered. Similarly, the economic growth of nations with a relatively high contribution of agriculture to GDP (in excess of 20 percent) are more sensitive to runoff, and are negatively affected by drought. Nations with less dependence on agriculture (below 20 percent) still show dependence on runoff, albeit at a much lower magnitude, but no effect of drought.

For countries with high water stress, the effect of runoff was significantly higher than in other countries. This suggests that investments substituting for runoff (e.g., efficiency improvements) are more important for growth within countries that are currently water stressed (i.e., South Africa, Pakistan, Ethiopia, Mexico) than within countries that do not suffer from water stress (i.e., Canada).

This result also suggests that as water resources become increasingly stressed globally, the importance of managing water will become significantly more important for sustaining economic growth. Indeed, the OECD's baseline projections indicate that by 2050, 3.9 billion people will be subject to severe water stress. Three-quarters of these people will live in the BRIICS (Brazil, Russia, India, Indonesia, China and South Africa).[28]

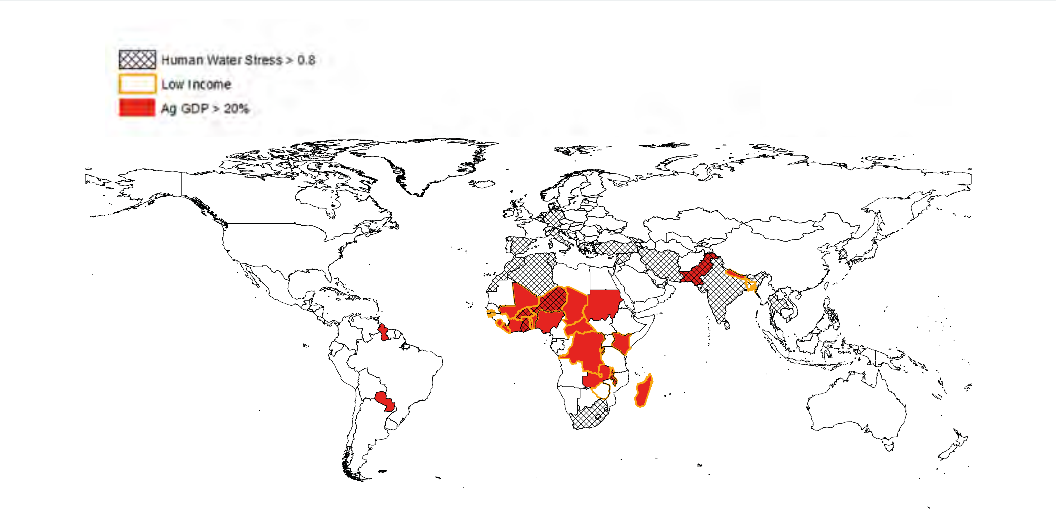
For agriculture-dependent countries, dependence on runoff and the effect of drought were significantly greater than they were in countries with less dependence on agriculture. For these countries, the results imply that a major drought (e.g., affecting half a country's

27 *The human water stress index is described in Table 1.*

28 *OECD (2012).*

Countries most economically vulnerable to hydro-climatic effects *(Box 6)*

This map shows the countries with: high human water stress (greater than 0.8; hatched); low income (World Bank designation; yellow outline); and high agricultural dependence (greater than 20%; red); all of which are factors associated with larger effects of water, and related hazards, on economic growth. Variables are explained in the note accompanying Table 2.



area) may reduce economic growth in that year by more than a percentage point in the span of a year. For example, based on these numbers, Brazil has lost an average of approximately a quarter of a percent of economic growth every year, for each of the last 30 years, to drought.

... the countries most vulnerable to the effects of hydro-climatic variables are those that are poor, water stressed, and/or dependent on agriculture, ... growth in these countries is significantly more vulnerable to hydro-climatic conditions.

In countries without water stress (< 0.8) or dependence on agriculture, the drought effect is not statistically significant. However, runoff remains a statistically significant factor even in those countries. This likely indicates the aggregate effects of variability and water availability, not only on agriculture, but also on energy production (e.g., hydropower generation, and cooling of thermo-electric power plants). Generally, economic growth is higher in years with more water available.

The overall results of this econometric analysis on subsets of countries show that the countries most vulnerable to the effects of hydro-climatic variables are those that are poor, water stressed, and/or dependent on agriculture, and that growth in these countries is significantly more vulnerable to hydro-climatic conditions.

2.5 Summary

The empirical and theoretical analysis demonstrates the importance of investment in water security for development, and the importance of development for investment in water security.

Our theoretical analysis of the economics of water security, risk, and growth, shows that when an economy is exposed to water-related risks, there is a benefit attached to early investment in assets that mitigate those risks. Countries that can make such investments protect their growth prospects from water-related threats, and can therefore better harness the productive benefits of water-related investments. By contrast, in situations where hydrological hazards cause losses that affect other sectors of the economy, the economy can experience a significant water-related drag.

Nonetheless, we find that the trajectories of changing national wealth over time are strongly context-dependent; they rely on a specific suite of policy choices and investment decisions, made at a specific point in time. Where a country is heavily exposed to hydro-climatic losses (for example, where agriculture dominates), the likelihood of substantial feedbacks between water-related losses on the one hand, and national wealth on the other, is strong. In such circumstances, a poverty trap is possible.

In contrasting situations, where the economy is more effectively disconnected from water-related losses – either through economic diversification, or via water-related policies, practices, and infrastructure that limit vulnerabilities – there is a much lower chance of experiencing water-related limits to growth. In particular, our findings reveal that even in an interacting hydro-economic system, the route from poverty to wealth cannot be found through water-related investments alone. The fastest improvements in economic growth arise through investments in water-related assets, combined with measures to create broad-based growth across multiple sectors of the economy.

The empirical findings of this report provide new evidence confirming that economic growth is vulnerable to negative hydro-climatic effects. Water, and water-related hazards, have a statistically significant effect on economic growth that historically has been at least as important – and likely more important – than temperature effects.[29] These results have significant implications for economists assessing the potential economic costs of climate change. They emphasize that water-related impacts should be considered; and that studies that neglect water may underestimate the economic consequences of climate change, especially in the most sensitive countries.

Water availability, and protection against drought and flood, are shown to be at the heart of the challenge to improve water security. Runoff, which can be thought of as fluctuating annual water availability, is shown to have a statistically significant effect on annual economic growth. Drought and flood are also shown to have statistically significant negative impacts on growth. Together, these factors reflect the multiple ways in which water, and water hazards, effect economic growth.

The effects of hydro-climatic variables on growth are strongest in poor countries as well as countries with high human water stress, high dependence on agriculture, or both. Such countries tend to be concentrated in Sub-Saharan Africa and South Asia, with few countries in South America and Europe.

For countries with high human water stress, the effect of runoff on per capita GDP growth is significantly higher than for other countries.

29 *The effects of changes in both water and temperature may prove to be highly non-linear. Our empirical results estimate relationships within historical temperature ranges, and find that water-related variables are likely to be more important than temperature variables. But climate change will move outside these historical ranges. If temperature increases have highly non-linear effects on crop yields, the economic consequences may be larger than the water-related effects we see in the historical data.*

This suggests that investment in water management is more important for growth in water stressed countries; and that, as water stress increases worldwide, the importance of managing water will become significantly more important for sustaining global economic growth. These findings concerning the importance of water resource endowments reinforce the insights of the theoretical model presented in this chapter.

In agriculture-dependent economies the drought effect and the dependence of growth on runoff were significantly stronger than in countries with less dependence on agriculture. Interestingly, in countries that are generally not water stressed, nor dependent on agriculture, the drought effect is not significant. However, runoff remained a statistically significant factor even in those countries. This likely reflects the aggregate effects of variable water availability; not only on agriculture, but also on energy production and other productive uses of water across the economy.

There are many ways to address the climate effects on growth highlighted in this paper. Our analysis suggests that managing the risks associated with agriculture-dependent economies, and low levels of mean water availability, is a priority. The empirical analysis reveals key investments to evaluate for de-linking the hydro-climate from economic growth. These include: making better use of available water in agriculture (in particular irrigation, drought management, and related natural and man-made water storage); managing financial risks associated with periods of shortage and natural disasters (e.g., risk sharing instruments); promoting transition to less agriculturally-dependent economies (e.g., through investment in economic diversification); and persevering in the provision of water supply and sanitation. Econometric analysis shows that these are key factors in economies' vulnerability to water-related drags, at a global level. Our theoretical model supports the need for a blend of water-related and unrelated investments to promote economic diversification and to sustain growth.

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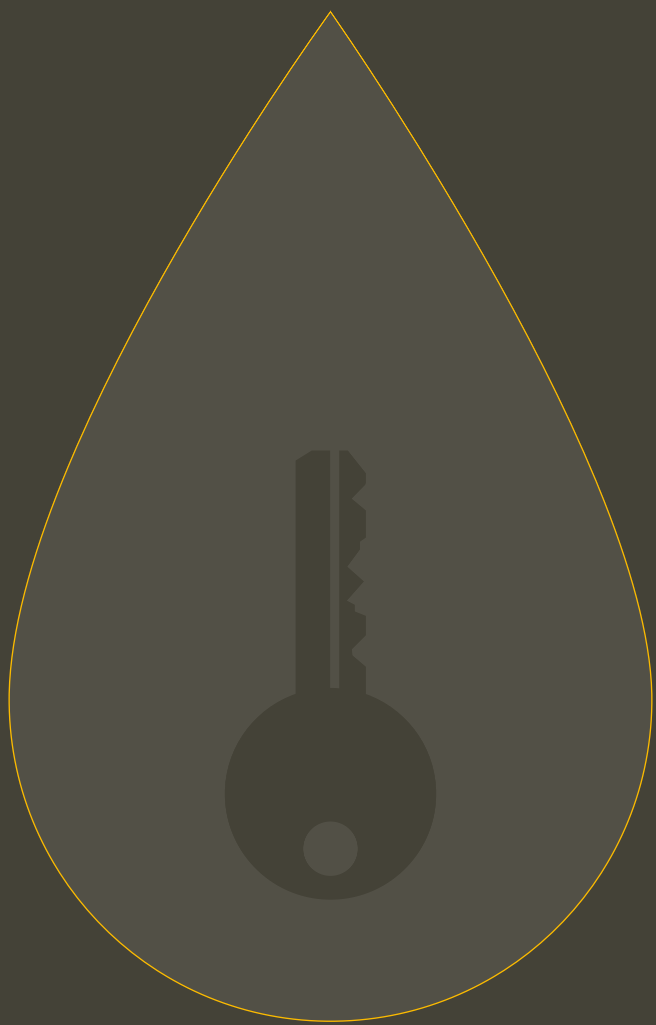


Chapter 3: The global status of water security

The economic impacts of water insecurity materialize through a wide range of different mechanisms for people, households, businesses, and communities. These impacts aggregate and spill over national boundaries.

The nature of these risks and opportunities varies both between and within countries. Indeed, global water insecurity is very unevenly distributed. The uneven distribution of risks and opportunities is not simply associated with developing economies.

We shall see that many of the world's most advanced and diversified economies are also subject to severe and growing water-related risks. Nonetheless, the poorest economies worldwide tend to bear the greatest relative burden of water insecurity: partly because of their hydrological endowment; and because of historic under-investment in infrastructure and institutions that would help to reduce, and manage, water insecurity. We use global-scale analysis to build a picture of the distribution of water-related risks and opportunities.

There are now more data to quantify risks on a global scale than has hitherto been the case. These datasets are providing new opportunities for analysis, but the coverage and accuracy of these datasets is still inevitably limited. In some locations, there are relatively precise datasets, so we take the opportunity to incorporate more local information and knowledge in the analysis of case studies in Chapter 4. Notwithstanding these inevitable data limitations, a global perspective on water security provides an opportunity to compare the nature and scale of risks between different countries. The analyses provide decision makers in different contexts with evidence of the scale of the water security threats and opportunities that they face.

The case for investment in institutions and infrastructure requires information – at the appropriate scale – about the potential benefits (in terms of risk reduction, and economic opportunities) and the costs of improving water security. The present value of risks over some future time-frame provides an upper bound on the amount it would be worthwhile to invest to eliminate the risk. In practice, it is never possible – nor even desirable – to reduce risk to zero: so, the benefit of risk reduction is the discounted value of the risk in the case that no investment is made, less the present value of the residual risk that remains after investment. Whether investment is economically attractive needs to be analyzed on a case-by-case basis, but national assessments have begun to demonstrate the economic case for investment in water security: for example, the UK Environment Agency's analysis of the optimal level of investment in flood protection.[1] Thus, understanding the scale of water-related risk, and the potential for risk reduction, is only the starting point on the pathway to water security. Subsequently in this Report, we will demonstrate the importance of the design and sequencing of investment in infrastructure and institutions.

The present value of risks over some future time-frame provides an upper bound on the amount it would be worthwhile to invest to eliminate the risk.

1 *Environment Agency (2014).*

3.1 Four headline risks

Water security emerges from complex interactions between human and natural phenomena. As we have seen in Chapter 2, these interactions yield opportunities and risks. Here, we apply the logic of risk to develop a set of indicators of water security, focused upon four headline risks.

1. Water scarcity

Our analysis of water scarcity combines water availability (in surface and groundwater sources) and water use. In contrast to metrics that deal with average availability per capita, our focus is upon the dynamics of supply and water use: how they vary from month to month and year to year. The manifestation of water scarcity is shortage of water for people or the environment, on a range of different timescales. Because of the effects of hydrological variability, the shortages can be acute, and may have multiple impacts. These events may be referred to as 'droughts', but in the absence of human vulnerability, droughts do not necessarily constitute a risk – although, in some circumstances, they produce negative impacts on aquatic ecosystems. Scarcity is the harmful state that is experienced by humans and the environment.

2. Floods

Floods impact households and industry at a range of scales, causing direct damage and broader indirect disruption to households, businesses, and trade. The economic and political consequences may be far-reaching. Floods are a natural phenomenon, and river ecosystems depend on such hydrological variability – but when people put themselves in the paths of floods, loss of life and damage to property can occur. We consider coastal and estuarial floods alongside river flooding, given the large and growing vulnerability of coastal regions (including megacities) to flood risk.

3. Inadequate water supply and sanitation

The largest human health/mortality risk from water is from inadequate water supply and sanitation. The risks are a consequence of inadequate institutions and infrastructure – unable to provide potable water supplies, or to separate humans from direct or indirect contact with human faeces. This third category of risk is effectively a man-made hazard, and a consequence of inaction or inability to reduce that risk.

4. Ecosystem degradation and pollution

Human interventions can have harmful side effects on land and water ecosystems. These impacts on the environment may be deliberate (e.g., draining wetlands for agricultural purposes) or inadvertent (e.g., diffuse pollution). As well as being harmful to habitats and species, these risks undermine the ecosystem services that the aquatic environment supplies to humankind.

We note that the first two categories of risk (scarcity and floods) are manifestations of hydrological variability. These two categories can overlap, particularly – but not only – in the poorest parts of the world; with cycles of damaging floods and droughts, interspersed with 'normal' seasons or years, as a consequence of unmitigated hydrological variability. The other two categories (harmful water supply and sanitation, and ecosystem degradation and pollution) are consequences of human (in)action. All four of these risks interact, so the risks associated with inadequate water supply and sanitation can be exacerbated by the interplay between hydrological variability and human vulnerability. For example, flooding can magnify the risks of poor sanitation practices by spreading faeces widely through a community. Ecosystem degradation and pollution can exacerbate the risks of droughts and floods.

We recognize broader indirect concerns about water insecurity: especially relating to production, services, trade, migration, and conflict. These insecurities, which materialize in response to the four direct risks we have identified, pose greater challenges in terms of quantification.

3.2 Risk-based indicators of water security

Risk is a contingent expectation of harmful outcomes, measured in the units of those outcomes (dollar losses, mortality, species declines etc.).

Risk is not an observable quantity. Risk is highly context-dependent, and depends on the perceptions and attitudes to risk of various stakeholders. Thus, any risk metric is bound to be a composite: incorporating elements of hazard, vulnerability, exposure, and perhaps also adaptive capacity – and doing so from a range of perspectives.[2]

The impacts of risks are observable, but these impacts occur – at least in part – in a random way; thus, observed impacts do not provide an effective way of monitoring risk, in particular for the most extreme events. In order to develop indicators of risk, we need to break risk down into its component parts. Conventionally, risk is thought of in terms of:

1. Hazard:
the phenomenon with the potential to cause harm

2. Exposure:
the people and assets in harm's way

3. Vulnerability:
the sensitivity of exposed people/assets i.e., their susceptibility to harm should a hazard materialize.

This suggests a structure for developing metrics of water security, based upon hazard, exposure, and vulnerability. At the same time, risk is thought of as a function of probability and consequences of harmful events: where the consequences are determined by exposure and vulnerability, while the probability characterizes the likelihood of the hazard.

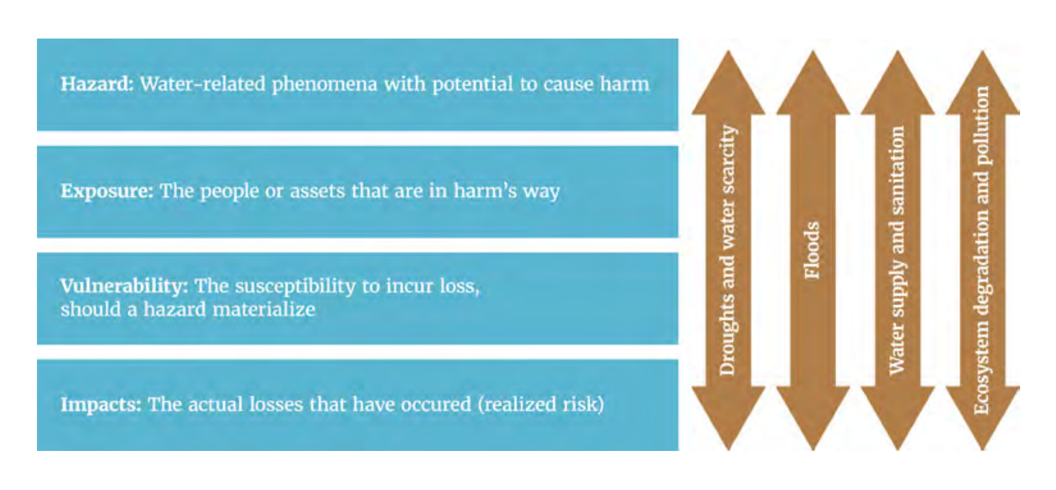
Vulnerability will be profoundly influenced by the actions humans have taken to reduce risk, e.g., the construction of flood protection. Adaptations may involve infrastructure, information, and institutions, typically in combination. While many adaptations are focused upon particular risks (e.g., water allocation), some institutional adaptations (e.g., effective river basin management institutions) may be cross-cutting. Adaptation actions may also modify exposure, e.g., via floodplain zoning or crop insurance.

In the long run, all other things being equal, we expect the realized impacts of risks to be roughly equal to the mathematical expectation of the risk. But 'all other things' are not equal: hazards are changing, for example due to climate change and catchment modification, and changing vulnerability is an inevitable consequence of economic development. Records of impact, as well as being inevitably limited by reporting gaps and errors, will also reflect these changes. Nonetheless, metrics of impact provide useful evidence to validate risk estimates and so they should be reported within a set of risk-based indicators.

Vulnerability will be profoundly influenced by the actions humans have taken to reduce risk …

2 *Hall and Borgomeo (2013); IPCC (2012).*

Overview of risk-based indicator framework *(Fig 4)*



Thus, our indicator framework has four main components (Figure 4):

A. Hazard
B. Exposure
C. Vulnerability
D. Realized impact.

A, B, and C – when integrated together – can provide an estimate of risk, against one or more dimensions of risk (e.g., financial loss, loss of life). D provides further evidence with which to compare, and to some extent validate, risk estimates. Each of these four dimensions can, in turn, be broken down into measurable contributing factors. As our objective has been to provide global indicators, the datasets at our disposal have been limited; but the risk-based indicator framework could be applied at small scales, which would enable more focused analysis.

Our emphasis in developing water security indicators is upon present day risks. Water insecurity threatens societies and economies now, often requiring urgent action. As we will see in Chapter 4, intolerable water-related risks have, in the past, triggered adaptation actions to manage those risks. Risks are dynamic: both changing through time, and interacting with economic growth trajectories. Looking to the future, we are particularly concerned about the factors that may increase the severity of water-related hazards (climate change, catchment alteration, pollution, etc.) or human exposure and vulnerability (e.g., population growth or floodplain development).
Where we have been able to do so, we report on the potential future impacts of climate change, population, and economic growth, based upon scenario studies.

Risks are dynamic: both changing through time, and interacting with economic growth trajectories.

3.3 Global analysis of water security: (1) water scarcity

In analysing the risk of water scarcity, we look beyond the standard calculations of average annual water availability per capita, instead focusing on shortages relative to existing water use in specific places, and the frequency and severity of those shortages.

We are concerned about the effects of hydrological drought (extreme low flows, soil moisture deficits, and low groundwater levels) and the interplay with human, economic, and environmental water uses. In times of shortage, supplies for municipal and industrial use will tend to be prioritized over agricultural uses and the environment – so, our analysis of shortage focuses upon agricultural use, and the trade-offs with the water required for a sustainable environment. We also explore evidence of the impacts of water scarcity for other economic activities, such as cooling of thermo-electric power plants.

Likelihood of water scarcity

In simple terms, analysis of water scarcity is a problem of calculating the 'water balance' in a given spatial unit of assessment, and identifying the frequency with which harmful deficits occur. This contrasts with metrics of average scarcity that compare the average sustainable water available with the average or desired water use. Metrics of average scarcity provide an overall picture of the likely pressure on the resource, but ignore the inherent variability in water availability. There may be ample water available on average, but if it materializes in a highly variable way (for example as occasional high flows, interspersed by longer periods of low/no flow) then there is a genuine and potentially harmful risk of scarcity.

Our concern is with the frequency and severity of harmful shortages, rather than with average scarcity.

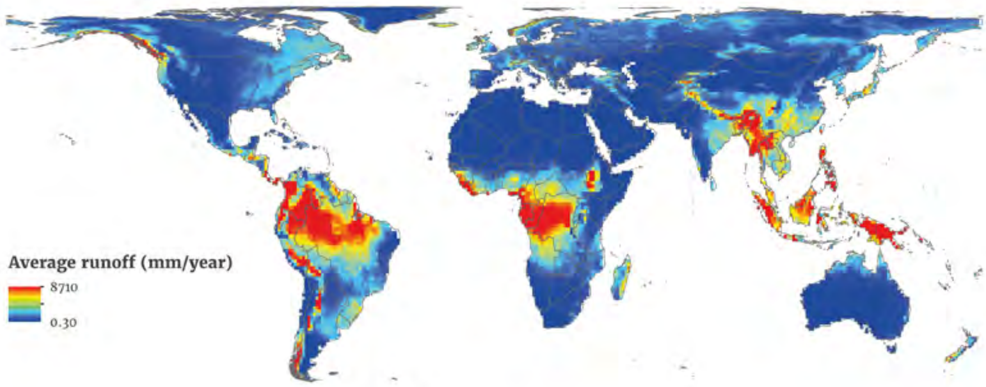
The analysis starts with global modelling of runoff, which Chapter 2 showed to be an important hydro-climatic variable, impacting economic growth per capita. The runoff data were simulated by the global hydrological model, MacPDM,[3] run at a 1-degree resolution. Daily runoff was calculated by summing the surface and subsurface flows, and aggregated to the river basin. MacPDM's performance in reproducing observed runoff compares well with other global hydrological models, where differences in inter-annual variations in runoff between models were demonstrated to be fairly small in the Water Model Inter-comparison Project.[4] MacPDM was driven by climate variables from the reanalysis data set ERA-Interim[5] for 1979 to 2012 inclusive. Daily precipitation, temperature, wind speed, surface solar radiation, surface thermal radiation, and dew point temperature were interpolated onto the 1-degree grid. Reanalysis data sets are produced using climate models, and incorporate historical observations. They offer spatially complete, consistent, and coherent records of climate – unlike observations alone.

3 *Arnell (1999).*

4 *Haddeland et al. (2011).*

5 *ECMWF (2014).*

Mean and variation of runoff: (a) mean annual runoff (b) coefficient of variation (CV) of monthly runoff *(Fig 5)*



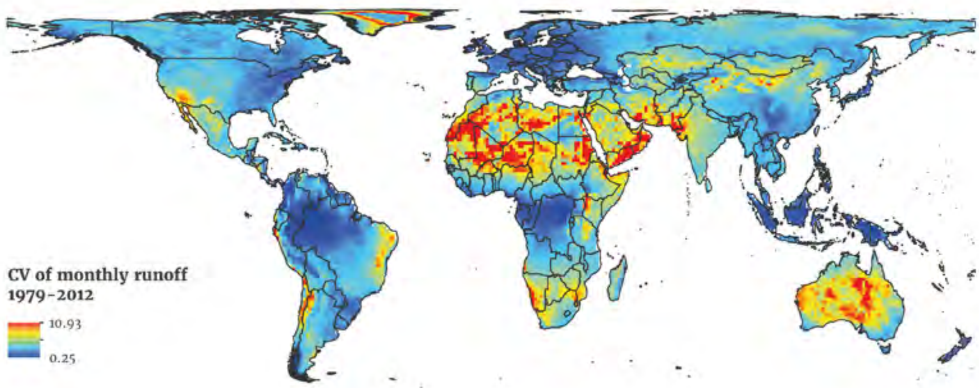
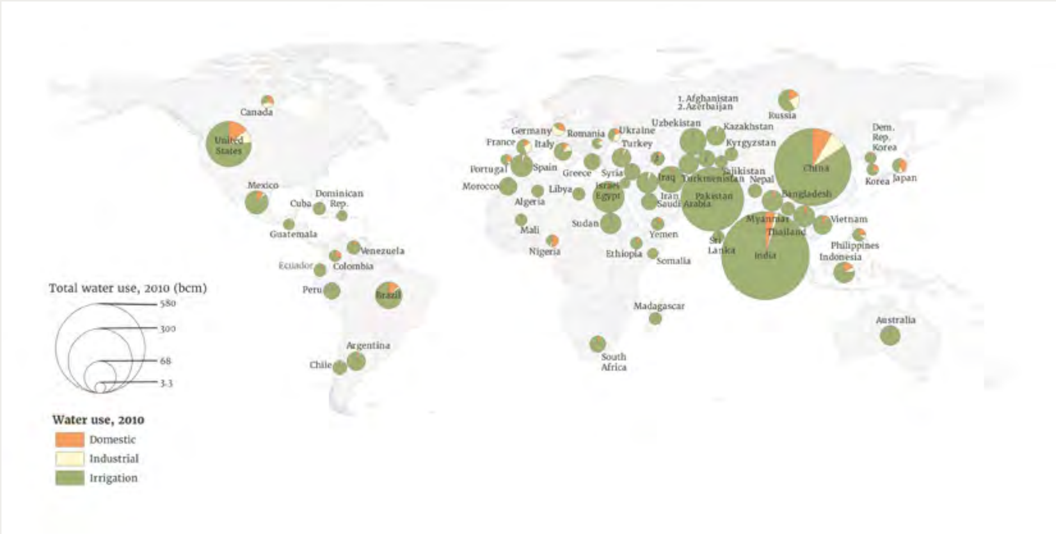


Figure 5a illustrates the mean annual runoff; and Figure 5b shows the coefficient of variation of monthly runoff, calculated as the standard deviation of all months in the series (1979–2012), divided by the mean of all months in the series. This coefficient of variation captures both intra-and inter-annual variability.

Strong seasonal variability, which is experienced in monsoonal and tropical climates, limits the productive portion of the year.
In parts of India, 50 percent of the precipitation falls in just 15 days, and over 90 percent of river flows are concentrated in only four months of the year.[6]

6 *Briscoe and Malik (2006).*

Water use *(Fig 6)*



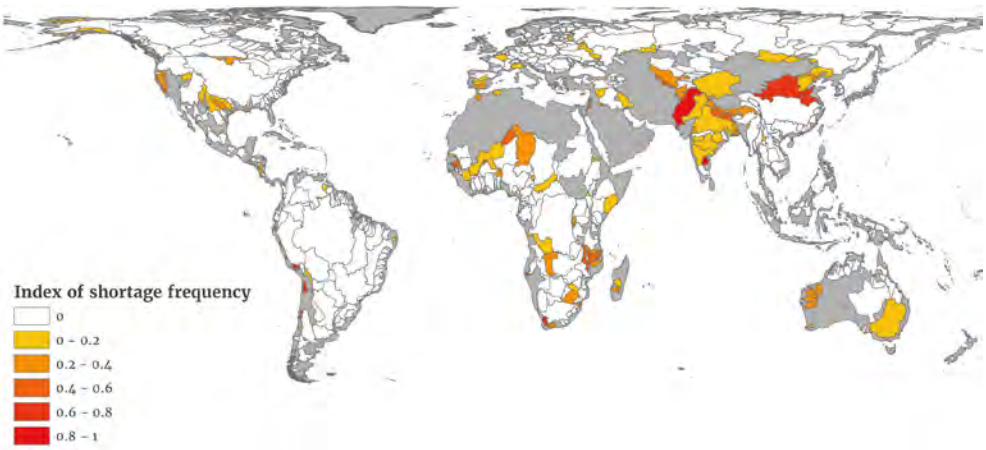
Water storage capacity *(Fig 7)*

The arid regions of the world, like the south-western United States, Australia, Middle East, North Africa, and Central Asia, are characterized by strong inter-annual variability, with the possibility of multi-year droughts, and intense rainfall that far exceeds the average and can lead to catastrophic flash flooding.

For each river basin, we have calculated the monthly balance of water availability (from runoff and groundwater abstractions) and water use for irrigated agricultural, domestic, and industrial purposes.[7] These estimates of water use can be seen in Figure 6.

7 *Rosegrant et al. (2012).*

Index of frequency of shortages of water available for use *(Fig 8)*



Our analysis of the frequency of shortages of water available for use (Figure 8) is calculated for Basin-Country Units (BCUs), based on all of the world's large river basins, sub-divided where national boundaries cross the basin. For transboundary rivers, flows are routed from one BCU to the next. In each BCU we have aggregated the total amount of storage available using the Global Reservoirs and Dams Database (GRanD) records data for 6,862 reservoirs, excluding natural lakes such as the Great Lakes.[8, 9] Figure 7 shows this aggregate storage capacity. We have accounted for evaporation losses from these reservoirs. The analysis tracked on a monthly basis whether there is enough water available from rivers, groundwater, or reservoirs to satisfy existing water use patterns.

Our risk metric is an indicator of how frequently reservoir levels are predicted to fall below 20 percent of the total storage – which we take as being the storage level at which, on average, restrictions on water use may be applied (Figure 8). The results show how scarcity emerges as a combination of hydrological variability (Figure 5b) and high human use of water (Figure 6), which may in part be mitigated by storage infrastructure (Figure 7). We observe that this class of water insecurity is most severe in South Asia and Northern China, but that signicant risks of water shortage exist in all continents. Note that this metric will not identify water insecurity to rainfed agriculture. Furthermore, being based upon river basins, the analysis does not address the most arid parts of the world through which no rivers flow (for example in much of North Africa and the Arabian peninsula).

The impacts of water scarcity are of particular security concern when water-scarce nations are highly dependent on transboundary flows.

8 *Lehner et al. (2011).*

9 *We observe anomalies with the GRanD database, for example: the 185bcm storage of (artificial) Lake Kariba appears to be allocated to Zambia and none to Zimbabwe, which co-owns the Kariba dam; and the 204.8bcm regulated storage of (natural) Lake Victoria appears to be allocated to Uganda.*

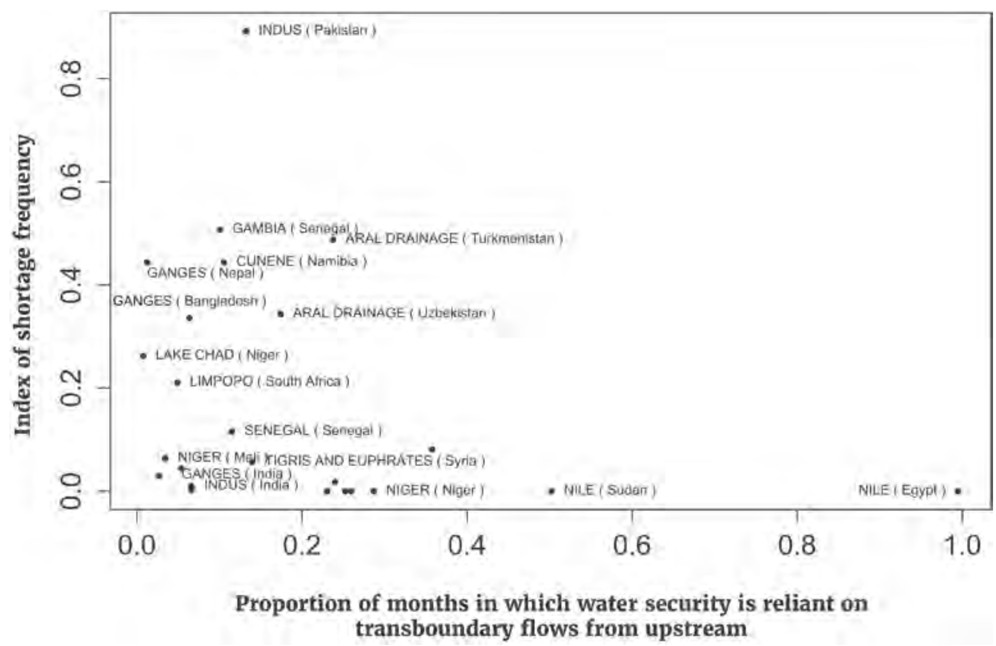
Analysis of transboundary water security *(Box 7)*

Figure 9 was derived using the results of our model of shortage of water availability for use. This index is plotted on the y-axis, and is defined as the proportion of months in our simulated period (1979–2012) when storage ≤ 20 percent full.

The proportion of months in which water security is reliant on transboundary flows from upstream (x-axis) was calculated as follows: Naturalized flows (no storage is included) were used to examine the frequency of water scarcity in all BCUs (occasions when the total water demand could not be met). Then, transboundary flows were excluded, which meant that downstream BCUs had less water supply, and water scarcity was examined again to find the number of months in which demand exceeded supply. The difference of water-scarce months between these two scenarios was calculated and divided by 408, which is the highest possible difference of months. The calculation was thus (shortage frequency without transboundary flows minus shortage frequencies with transboundary flows)/all months. In that way, the difference of water-scarce months was given more importance than the overall water scarcity (92 to 90 water-scarce months have the same importance as 6 to 4 water-scarce months).

Limitations: This is a water balance model that does not include dam operation rules, or political aspects such as water treaties. Results have to be interpreted accordingly.

Transboundary water dependence: which water-scarce countries are highly dependent on transboundary flows *(Fig 9)*



Total national food crop production *(Fig 10)*

'Other crops' = all cereals other than rice, wheat, and maize, plus soybeans

In Figure 9, we examined water-scarce BCUs using the same index of shortage frequency as used in Figure 8, but have also identified the proportion of water use that is supplied by transboundary flows. Egypt has the highest transboundary water dependence, but, because of the large storage capacity in Lake Nasser, Egypt has reasonable reliability of water available for use. The Indus and Aral basins stand out as having unreliable water supplies that are also highly dependent on transboundary flows (see Box 7 for further discussion).

Consequence of surface and groundwater water scarcity

The analysis in Chapter 2 has highlighted how water insecurity can impact the economies of agriculture-dependent countries. In our analysis of water scarcity we have therefore focused upon the impacts on agricultural production, and the consequences of reduced crop yields, increased agricultural commodity prices, and their child malnutrition impacts.

The consequences of hydrological variability for food production have been modelled with the IMPACT model.[10] The IMPACT model is a partial equilibrium agricultural sector model linked with a global hydrology model, a global water supply and demand model, and a gridded global crop simulation model. Unlike previous analyses, the effects of variability in precipitation and runoff on crop yields have been analysed, to give better insight into the effect of unmitigated variability on fluctuations in agricultural production and the value of the agricultural sector to national economies. The model has been calibrated to reproduce production averaged over the years 2004-2006. Figure 10 shows the global

10 *Rosegrant et al. (2012).*

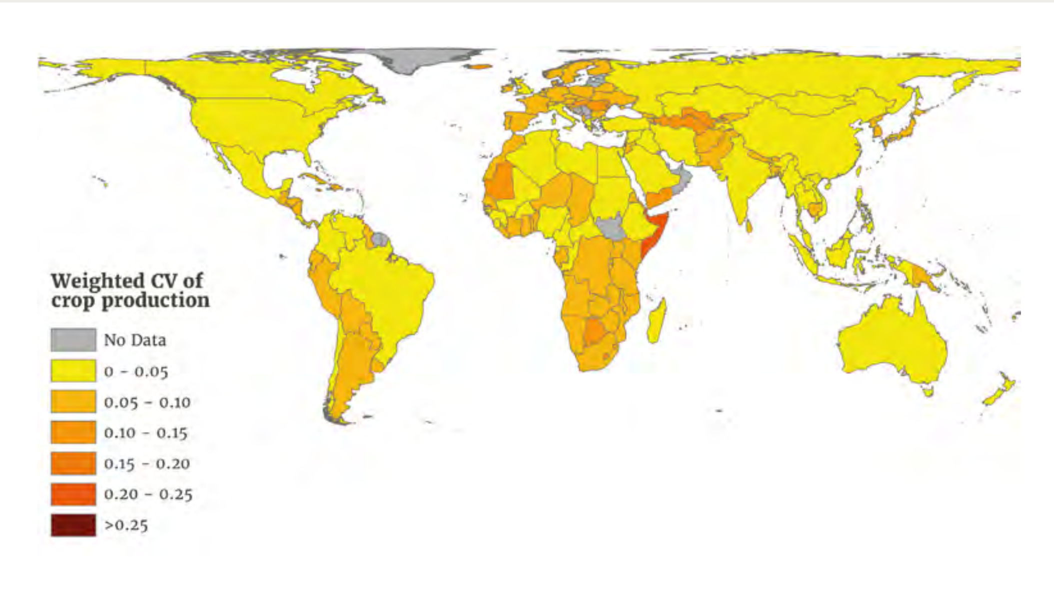
distribution of the production of food crops in 2010, with three staple crops (rice, wheat, and maize) shown explicitly.

Analysis of the variation of crop yields demonstrates that some locations are more susceptible to hydrological variability than others. Africa stands out as having the greatest variability in agricultural yields, while South America, Central Asia, and parts of Europe show significant variability as well. (See Figure 11.)

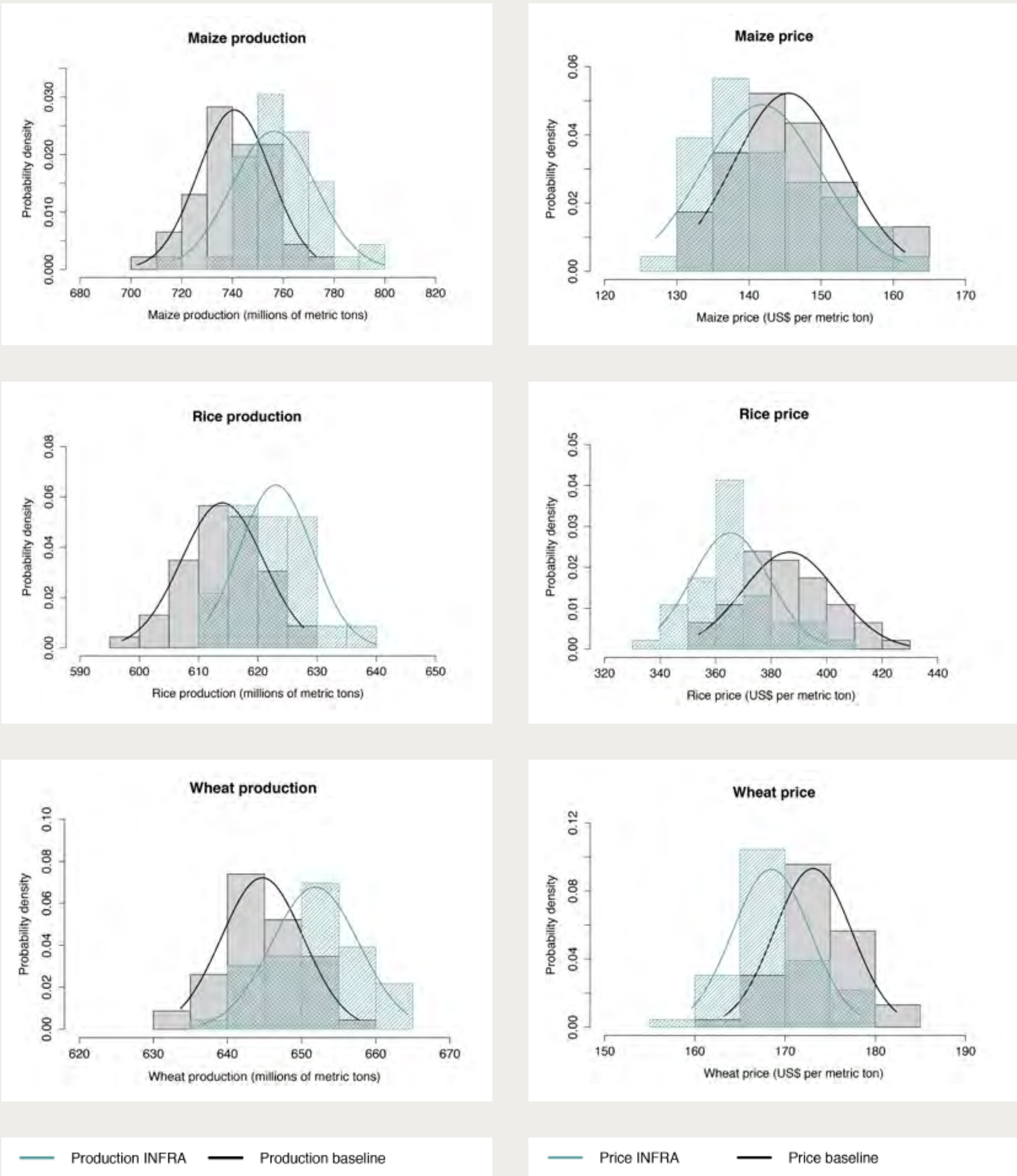
We can analyze the economic significance of hydrological variability on food crop production by using the IMPACT model to simulate a situation in which variability is effectively suppressed by assuming that water storage and delivery capacity is able to maximize the use of all available water. In this scenario, reservoir storage capacity and surface water withdrawal capacity constraints in the IMPACT model are relaxed so that surface water supply is not limited by the regulation capacity of surface reservoirs and the withdrawal capacity of diversion and conveyance infrastructure. Irrigation area is fixed and groundwater withdrawal capacity is retained to control depletion. Rain-fed agriculture is not directly affected by this scenario, although may be indirectly affected through price effects. This counterfactual still respects the constraints on water availability, but supposes that the available water can be stored and delivered efficiently to existing users to enable agricultural production.

This scenario, which makes more water available to irrigated agriculture, increases global production and also reduces the variability in production of some food commodities (notably rice) and prices (see upper graphs of Figure 12). Investing to enhance water security reduces the probability of food production being at the low end of the ranges shown in Figure 12. For example, the probability of global wheat production falling below 650 million tons per year is reduced from 83 percent to 38 percent. The IMPACT model has been used to estimate the corresponding variation in the prices of food commodities (Figure 12). The effect is greatest for rice, which is the most irrigation-dependent of the three crops. The effect of suppressing water insecurity not only reduces the mean rice price, but also has a noticeable effect on the variance in the price. The probability that the price of rice could exceed US$400 per ton is reduced from 21 percent to 0.7 percent, in the market conditions simulated in the model.

Coefficient of variation (CV) of annual food crop production *(Fig 11)*



Variability in food crop production and commodity prices, plotted as probability density functions *(Fig 12)*



There would be winners and losers in the scenario described above. The drop in prices would diminish the incomes of some farmers. Other farmers, who are currently water insecure (and likely more poor and vulnerable), would be able to increase production significantly and increase their incomes despite the drop in prices.

All consumers would benefit from lower food prices, which would be particularly important for low-income households.

To measure the welfare implications of this scenario, IFPRI's IMPACT model was used to estimate aggregate welfare benefits. On the consumer side, demand curves with regional demand elasticities adjusted from the United States Department of Agriculture were used to calculate the consumer surplus. On the producer side, supply curves come from price-sensitive area and yield functions by land type (irrigated and rain-fed) at the sub-regional level and were used to calculate producer surplus. Because IMPACT is a partial equilibrium model, it directly captures changes in producer and consumer surplus only in agriculture, but not any welfare gains from spillover effects from agriculture to the rest of the economy. We provide an estimated measure of this spillover effect at the national level that must be viewed as an approximation since we do not have information about supply and demand curves in the non-agricultural sectors.

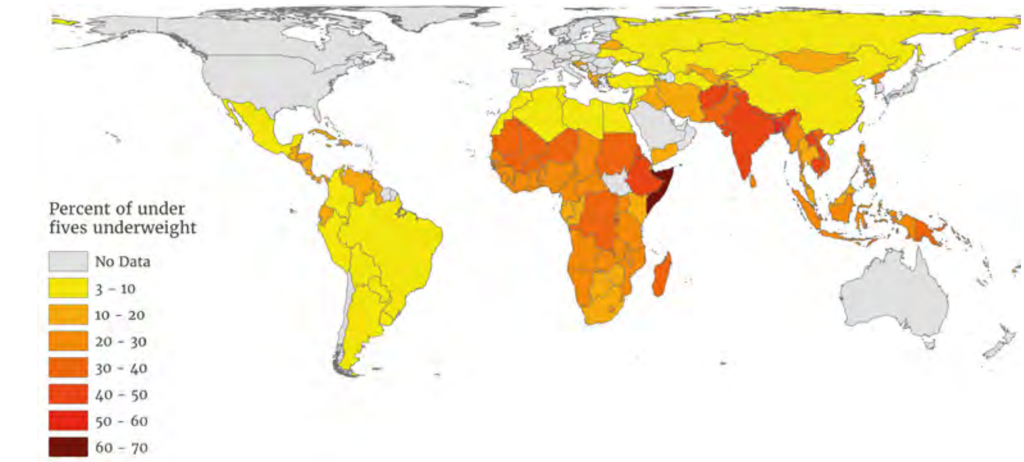
Using this analysis, the total welfare gains of improving water security to existing irrigators was estimated to be US$94 billion globally for 2010, of which about half comes from standard measures of producer and consumer surplus (for producers from increased water security and for consumers from reduced food prices) and half from spillover effects to the non-agricultural sectors. These welfare changes are plotted in Figure 12.

While the aggregate welfare benefits are very significant, they represent a rather narrow interpretation of the potential benefits of water security for agriculture, because the analysis relates only to irrigated agriculture, not to rain-fed agriculture. Moreover, the opportunity that water security might provide to expand irrigated areas is not included.

To test the potential economic benefits of increasing irrigation, we have modelled a scenario in which the area of irrigated agriculture is increased by 3.8 percent. The global welfare benefit of this increased area of irrigation, accompanied by secure water supplies, is calculated to be US$246 billion per year.

Welfare gains and losses in a scenario in which there is more water available for irrigation, helping to suppress the effects of hydrological variability *(Fig 13)*

Child malnutrition (2010) *(Fig 14)*



Furthermore, there are also opportunities for other water-related innovations, often at a farm and field scale, to improve productivity; such investments might be made as a consequence of enhanced water security. The results of this welfare analysis should therefore be taken as a lower bound.

Variable agricultural production directly impacts nutrition of subsistence farmers. Low yields during periods of water scarcity, and the consequent increase in prices, impacts all low-income households that spend a large share of their household income on food.

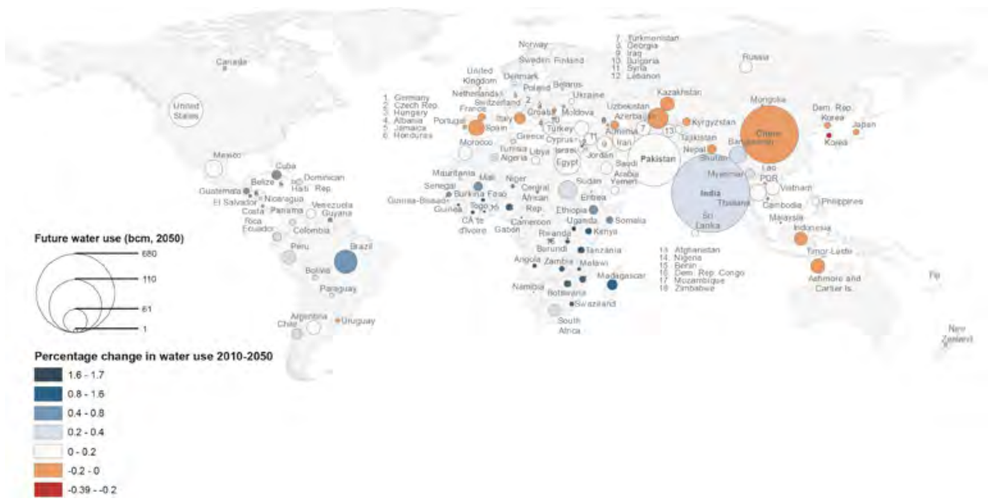
The IMPACT analysis of malnutrition (Figure 14) estimates that 150 million children are currently undernourished, with the impacts greatest in South and Southeast Asia and widely distributed across Africa.

Projecting future agricultural risks and opportunities

Increasing global populations and increasing diversity of demand for food associated with increasing wealth will intensify pressure on water resources.

Figure 15 shows the scale of these potential increases in demand for irrigation water. Whether these increases can be sustainably achieved, depends in part, on the scale of climate change. To estimate future agricultural production and water use, we have combined a scenario of population growth and socio-economic change, based on the SSP2 scenario

Future irrigation water use *(Fig 15)*



Future food crop production *(Fig 16)*

of the Shared Socio-Economic Pathways[11] with a corresponding set of climate projections from the HadGEM climate model run with an RCP8.5 forcing. The results show that population growth and increasing wealth will drive demand for food commodities, in the context of a more variable climate. By 2050, food production will increase in all regions, the greatest proportional increase being projected in South America (Figure 16).

Consequences of water insecurity for energy security

Thermo-electric power plants (coal, gas, nuclear) depend directly on the availability and temperature of water resources for cooling.

During recent warm, dry summers several thermoelectric power plants in Europe and the south eastern United States were forced to reduce production owing to cooling-water scarcity.[12] Vulnerability to the risks of water shortage on cooling water supplies depends on the power plant location and cooling technology. We have analyzed this vulnerability making use of the index of shortage frequency shown in Figure 8. We have multiplied this index by the cooling water demand of the power plants located in each river basin. Figure 17 therefore shows where power plants are located in river basins that we have calculated to have potentially unreliable water availability. India and northern China stand out as having the highest water security risks to electricity production. South Asia and the southern United States also have noteworthy risks. We have not been able to disaggregate power plants by cooling type, which is an important determinant of their vulnerability.

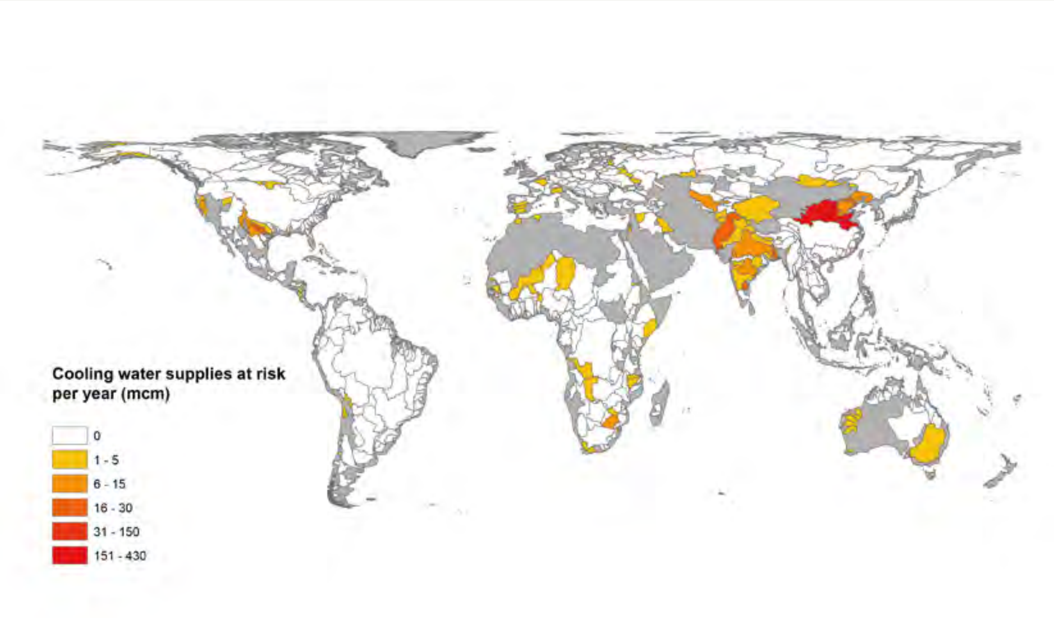
For countries that are highly dependent on hydropower, reductions in flow can mean shifting demand to more expensive and polluting thermal plants. Brazil relies on hydropower for 75 percent of its electricity supply, but a severe drought has forced production to shift to thermo-electric plants, with consequential price increases and a surge in imports of Liquefied Natural Gas.

Where water resources are secure and abundant, hydropower represents an opportunity for renewable energy production. However, the distribution of hydropower exploitation worldwide is uneven. Using data from the International Hydropower Association, in Figure 18 we illustrate the proportion of hydropower potential that has been exploited in different countries worldwide, noting that this reflects physical potential but not necessarily economic or financial feasibility, or environmental desirability.

11 *Kriegler et al. (2014).*

12 *van Vliet et al. (2012).*

Vulnerability of thermal power plants to unreliable cooling water availability *(Fig 17)*



Hydropower generation capacity and potential[13] *(Fig 18)*

13 International Hydropower Association.

3.4 Global analysis of water security: (2) floods

The societal and economic impacts of river and coastal flooding are large, and the economic losses associated with flooding are increasing rapidly because more property is at risk in floodplains. For example, Kundzewicz et al.[14] estimate that fluvial flood losses at the global level have increased from US$7 billion per year during the 1980s, to US$24 billion per year during 2001-2011 (inflation-corrected). These floods affected the livelihoods of millions of people. The economic impacts of flooding can negatively affect the long-term economic performance of countries[15] as well as directly affect the well-being of people.[16]

While records of flood losses provide some indication of impacts from flooding, they do not fully reflect the scale and extent of risk. Global flood risk assessment that incorporates quantification of hazards, vulnerability, and exposure can help to provide a more complete picture.

The analysis conducted here combines results from two global flood models (Box 8):

1. The GLOFRIS model[17] has been used to assess risks from river flooding.

2. The DIVA model[18] has been used to assess flood risk in coastal and estuarine areas.

By combining GLOFRIS and DIVA, we have for the first time been able to assess the combined risks of fluvial and coastal flooding. In both cases, as Box 8 shows, the economic risks of flooding have been estimated by quantifying the damage to assets located in (fluvial or coastal) floodplains for floods of different severity, where that severity is measured in terms of return period (the average time between arrival of flood of that severity). The population at risk has been estimated using gridded global population datasets.

The economic risk of flooding is spread across countries at all income levels (Figure 19). Our analysis suggests that the United States, China, and India all have expected annual damages (EAD) in excess of US$10 billion. As a share of GDP, the losses are greatest in South and Southeast Asia, Sub-Saharan Africa and parts of South America (Figure 20). These economic losses are expectations and do not materialize every year. They occur as extreme events at a range of severities (Figure 21). Large countries will incur some floods - of at least low severity - each year; however, the expected annual damages also incorporate the risk of occasional extreme events that will greatly exceed the EAD. For example, floods in Thailand in 2011 resulted in economic losses of US$46 billion.[19] Because of the differing standards of flood protection, the risk in high-income countries materializes from less frequent - but more severe - events overwhelming flood protection. At return periods greater than 100 years, the damage potential in North America exceeds that in Asia.

14 *Kundzewicz et al. (2014).*

15 *Brown et al. (2013).*

16 *Luechinger and Raschky (2009).*

17 *Ward et al. (2013); Winsemius et al. (2013).*

18 *Hinkel and Klein (2009); Hinkel et al. (2014).*

19 *World Bank (2012).*

GLOFRIS and DIVA *(Box 8)*

GLOFRIS is a cascade of models for estimating flood risk at the global scale.[20] GLOFRIS calculates flood risk at a resolution of 30x30 arc-seconds (c. 1 km x 1 km at the equator). The cascade of models in GLOFRIS essentially involves five steps: (a) hydrological and hydraulic modelling to develop daily time-series of flood volumes; (b) extreme value statistics to estimate flood volumes for different return periods; (c) inundation modelling for different return periods; (d) impact modelling; and (e) estimating impacts under flood protection and calculating annual expected impacts.

The Dynamic Interactive Vulnerability model (DIVA) currently offers the most detailed global scale representation of the coastal zone and relevant processes at a global scale.[21] DIVA assesses biophysical and socio-economic consequences of sea-level rise and socio-economic development. It incorporates coastal erosion (both direct and indirect), coastal flooding (including rivers), wetland change, and salinity intrusion into deltas and estuaries. DIVA is also able to account for adaptation in terms of raising dikes and nourishing shores and beaches.

To estimate economic flood risk, we have made assumptions about the standard of flood protection in different locations. Estimates of actual protection standards have been used for the world's largest 140 port cities.[22]

	Fluvial		Coastal	
	Urban	**Rural**	**Urban**	**Rural**
Low income	*1:10*	*None*	*1:10*	*None*
Lower-middle income	*1:25*	*None*	*1:25*	*None*
Upper-middle income	*1:50*	*1:10*	*1:100*	*1:20*
High income	*1:100*	*1:50*	*1:200*	*1:50*
Netherlands	*1:1000*	*1:1000*	*1:10000*	*1:10000*

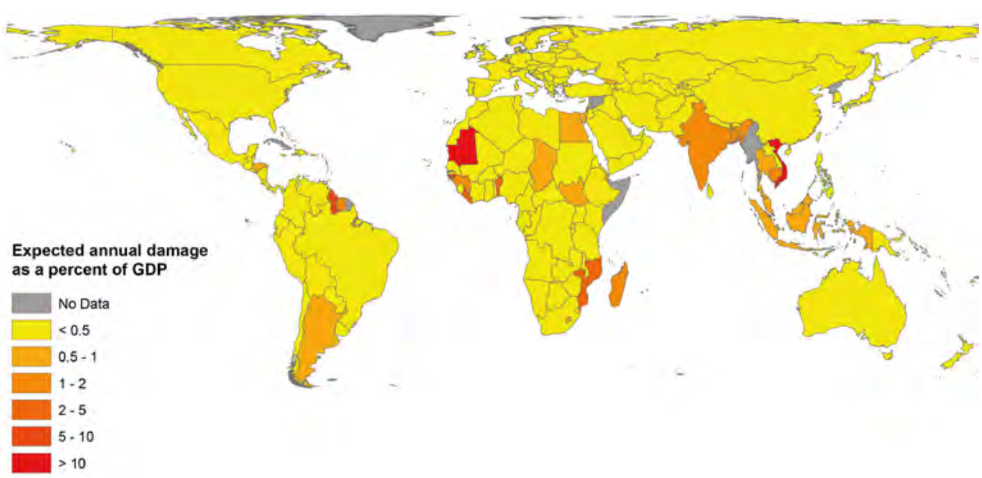
20 *Ward et al. (2013); Winsemius et al. (2013).*

21 *Hinkel and Klein (2009); Hinkel et al. (2014).*

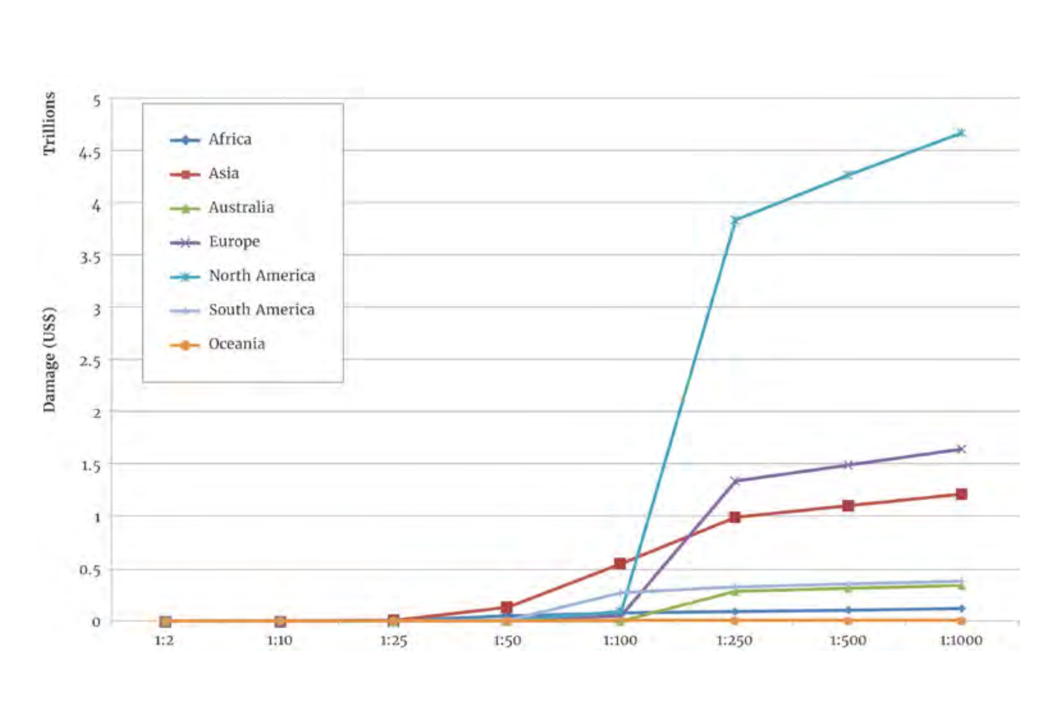
22 *Hallegatte et al. (2013).*

Expected annual damage due to fluvial and coastal flooding *(Fig 19)*

Expected annual damage due to fluvial and coastal flooding as a share of GDP *(Fig 20)*



Damage due to floods at different return periods *(Fig 21)*



Our expected annual damage estimates are larger than previous estimates[23] and empirical estimates based on reported losses. We have included coastal flood risk. Moreover, the length of time over which reported losses are available is limited, and we suspect that 'reported' losses do not report all losses, in particular losses from smaller but more frequent floods.

Modelling of flood damage at a global scale is in its infancy, and there are significant limitations. The results are sensitive to the assumed protection levels. For countries with a high standard of protection and dense floodplain development, a small underestimate in the standard of protection can greatly increase the flood damage estimate, introducing a bias into the analysis. The protection standards assumed in this study (Box 8) are relatively crude estimates, so cannot accurately represent all protection standards globally. For example the River Rhine, which has an assumed protection standard of 1:100 years in this study, is known to have an average protection standard of about 1:750 years (higher in some places, lower in others). The risk calculation itself uses best practice for broad scale studies, but there are inevitable approximations in the assumed water levels during floods, both in rivers and in floodplains. Finally, the data used for constructing damage functions in poorer parts of the world is very limited, meaning that flood damages may be under- or overestimated.

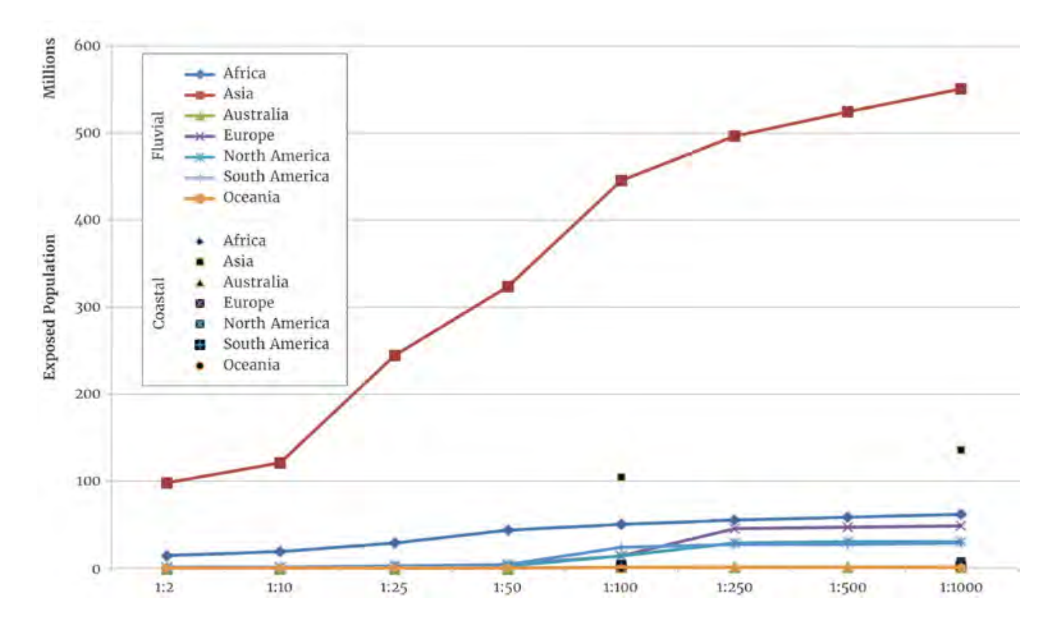
The damages estimated in our analysis include only direct financial losses to built assets in the floodplain. The risk estimate does not include the effects of business interruptions, human health and life losses, employment disruptions, or potential economic spill-overs, which during the Thailand floods of 2011, for example, had disruptive impacts on global manufacturing supply chains.

23 *Kundzewicz et al. (2014).*

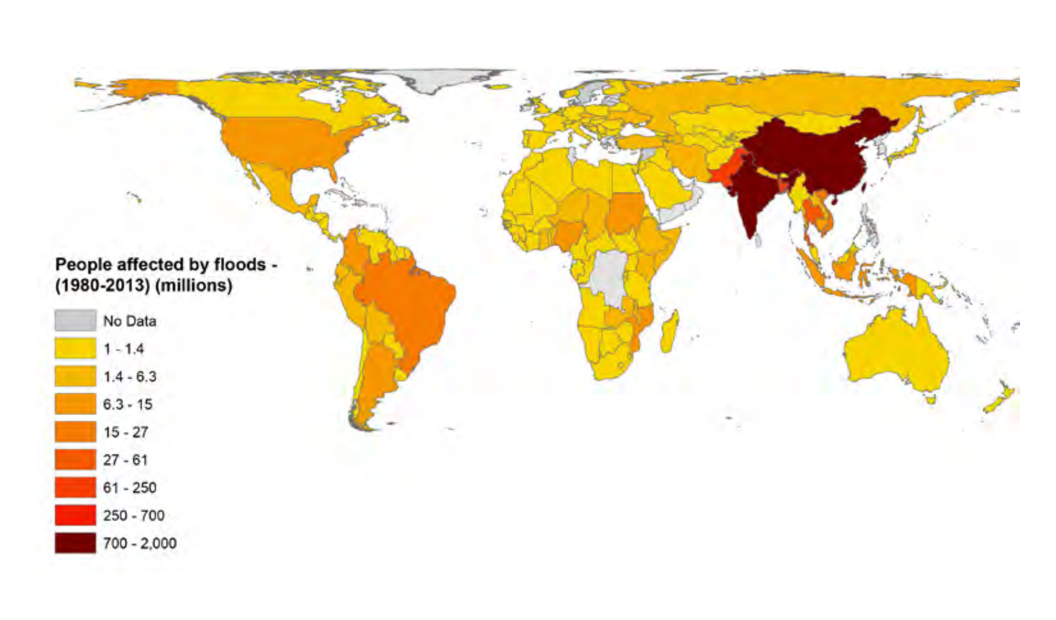
Flood risk to people *(Fig 22)*

Floods not only cause property losses, they also put people's lives and health at risk. While the financial risks of flooding are distributed across the continents, the greatest flood risk for human lives and health (measured in Figure 24 in terms of the expected number of people at risk from flooding) is concentrated in Asia, in particular in South and Southeast Asia and China (Figure 22). The exposed population increases steadily with return period (Figure 23) and Asian population dominates throughout. While we have not been able to calculate the population exposed to coastal flood risk at all return periods, for 1:100 and 1:1000 year events the coastal exposure is roughly a quarter of the fluvial exposure. The reported flood impacts on people (Figure 24) broadly reflect our risk analysis.

Expected number of people exposed to flooding at different flood return periods *(Fig 23)*



People affected by floods (1980–2013)[24] *(Fig 24)*



24 *EM-DAT (2014).*

Projecting future risks

Flood risk will increase as a consequence of increasing population exposure, and the value of financial assets at risk. In coastal locations, sea-level rise, along with subsidence in many densely populated deltas,[25] will increase flood hazard. The effects of climate change on fluvial flood risk are more difficult to predict: a recent model inter-comparison study[26] found that the return level of a 1:30 year flood decreases in magnitude and frequency at roughly one-third (20–45 percent) of the global land grid points, particularly in areas where the hydrograph is dominated by snowmelt flood peak in spring. In most model experiments, however, an increase in flooding frequency was found in more than half of the grid points.

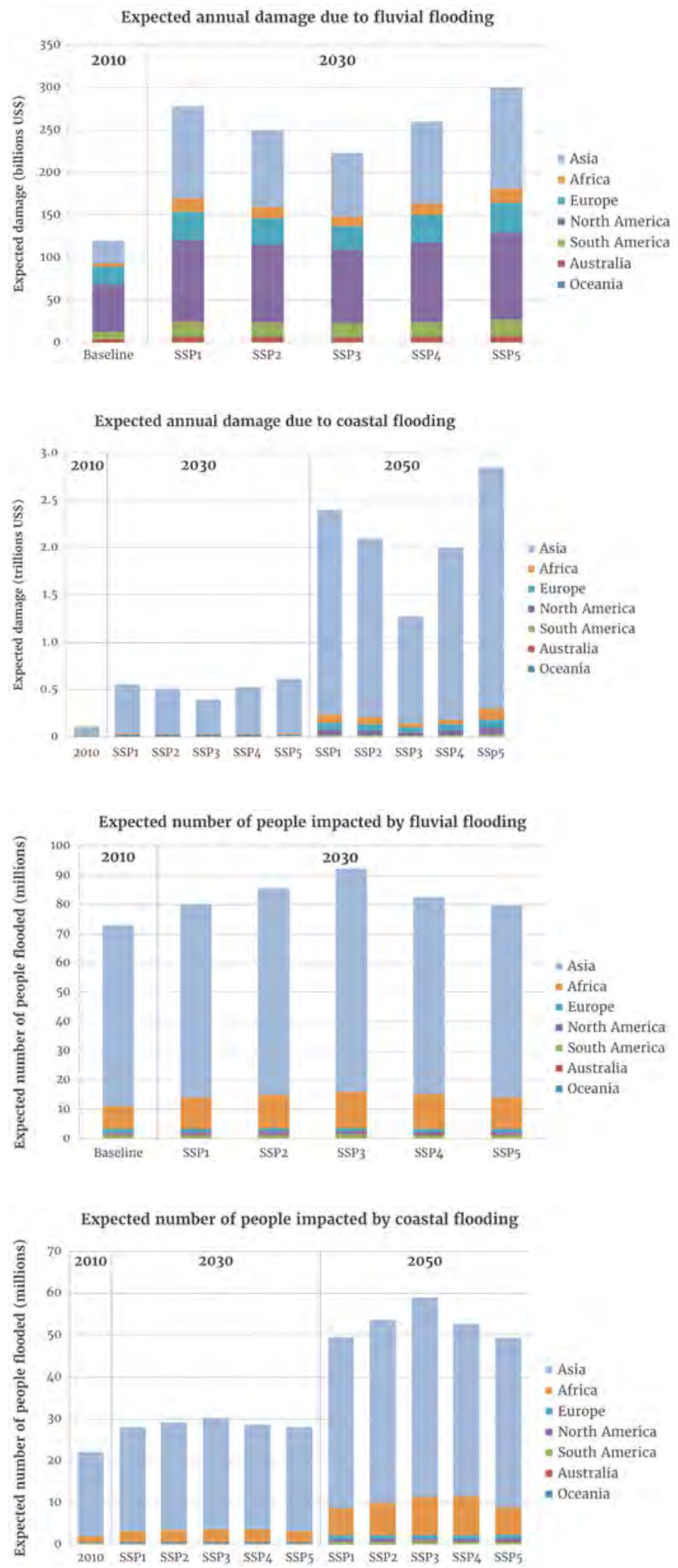
We have used selected scenarios from model analyses of future flood risk to explore the challenge that this aspect of water security poses in the future (2030s and 2050s, Figure 25). As with the agricultural projections, the analysis is based upon the Shared Socio-economic Pathways (SSPs).[27] The coastal scenarios contain the projected effect of sea-level rise on flood risk while the fluvial analysis does not include the effect of climate change on fluvial flood risk, given the uncertainties in the direction of future change. In all cases, the scenarios do not include additional investment in flood protection. The most striking effect on the financial risk of flooding is the projected increase in coastal flood risk in Asia, driven by the combined factors of coastal urbanization and rising sea levels. By the 2030s, in the absence of adaptation, the coastal flood risk is projected to increase by a factor of four while the fluvial flood risk could more than double. Thus, flood risk is already a major contributor to water insecurity and is set to increase in future.

25 *Syvitski et al. (2009).*

26 *Dankers et al. (2014).*

27 *Kriegler et al. (2014).*

Scenario analysis of future flood risk *(Fig 25)*



3.5 Global analysis of water security: (3) inadequate water supply and sanitation

The economic benefits of improving inadequate water supply and sanitation do not just include improved health outcomes. Bringing piped water services to households saves time spent collecting water from outside the home (especially of women), and results in important quality of life benefits. Improved sanitation services can also result in time-savings where households are walking away from their homes to defecate in the open, as well as improved human dignity and reduced vulnerability to personal assault (again, especially for women).

While major steps have been taken to address the risks of inadequate water supply and sanitation, this continues to be the largest global water security risk in terms of annual numbers of fatalities (Figure 26). The data on access to water supply and sanitation, which come from the WHO/UNESCO Joint Monitoring Programme (Box 9) data for 2012, demonstrate that the risks are concentrated in South Asia and Africa, which reflects the size of the population without access to improved water supplies (Figures 27 and 28) and sanitation (Figures 29 and 30). Improvements in access to water supply and sanitation have kept pace with global population growth (Figures 28 and 30), but the risk persists, and is increasing in Africa.[28]

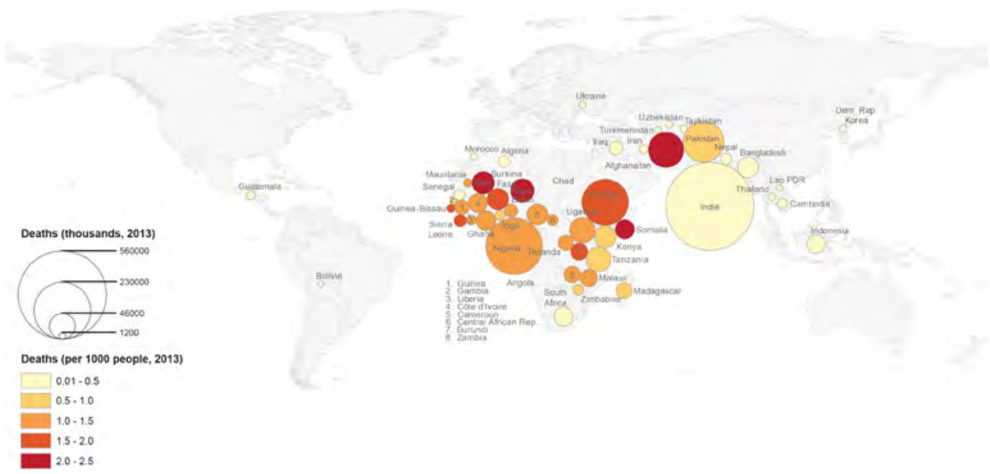
The World Health Organization (WHO) has estimated economic losses associated with inadequate water supply and sanitation (WSS) (Figure 31).[29] The value of time-savings that result from using a water source or latrine closer to home than existing facilities accounts for a large share of total economic losses. The estimated economic losses also include healthcare costs, lost productive time due to being sick, and premature mortality. WHO estimates the total global economic losses associated with inadequate water supply and sanitation to be US$260 billion annually in 2010, or 1.5 percent of GDP of the countries included in this study.[30] In Niger, Democratic Republic of Congo, and Somalia, the economic losses from inadequate WSS is estimated to be equal to more than 10 percent of GDP (2010 estimates). The largest absolute economic losses are incurred in China and India, which together account for US$120 billion in economic losses annually, though in China these losses now only amount to 1.6% of GDP.

28 *Jeuland et al. (2013).*

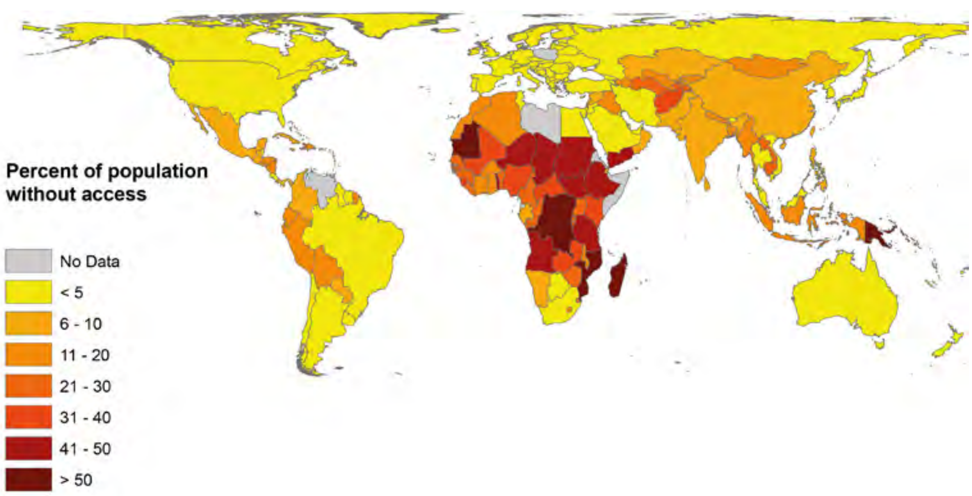
29 *Hutton (2013); WHO (2012).*

30 *Ibid.*

Deaths from water supply and sanitation related diseases[31] *(Fig 26)*



Percentage of population without access to improved water supply[32] *(Fig 27)*



31 *WHO UNICEF (2012).*

32 *Ibid.*

Definitions of water supply and sanitation from the WHO/UNICEF Joint Monitoring Programme (JMP) *(Box 9)*

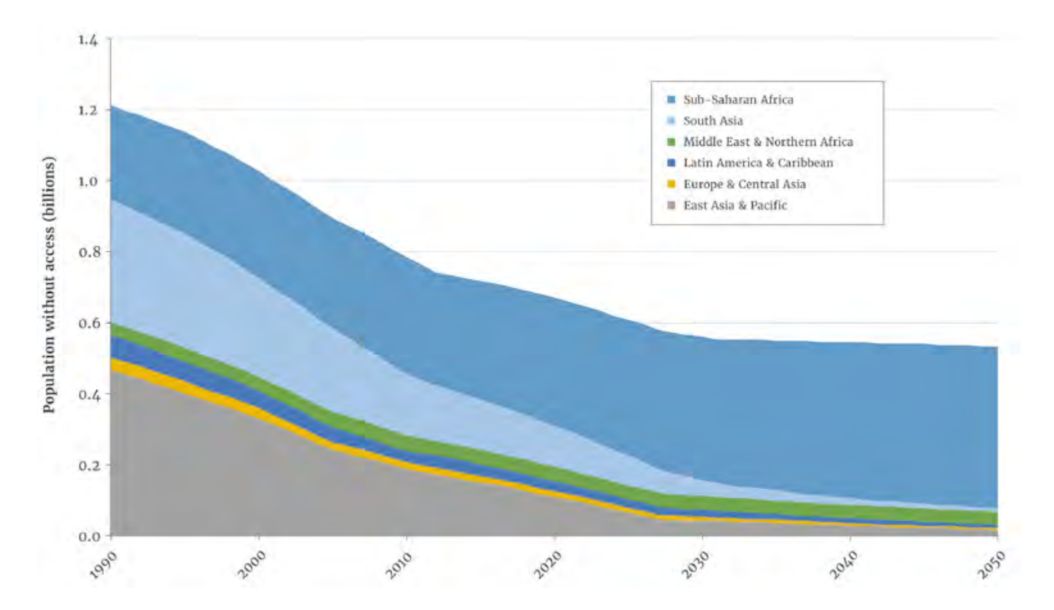
The Joint Monitoring Programme (JMP) publishes coverage statistics for two definitions of improved water services. The first is the simplest and most straightforward: ‘a piped water connection on the premises’. This definition includes both yard taps (outdoor plumbing), and piped water delivered inside the house (indoor plumbing). The second statistic measures: ‘an improved water source that by the nature of its construction, adequately protects the source from outside contamination in particular with faecal matter’. The JMP classifies all of the following as improved sources: (1) piped into dwelling, plot, or yard; (2) public tap/standpipe; (3) tube well/borehole; (4) protected dug well; (5) protected spring; and (6) rainwater collection. ‘Piped into dwelling, plot, or yard’ (item 1, above) is one of the six types of improved sources, therefore the first definition is a subset of the second definition, i.e., reported coverage using the second definition will always be higher than reported coverage using the first definition.

Both indicators of coverage can be misleading. First, a piped water connection on the premises is counted as an improved source in both JMP definitions, but there is no assurance that the quality of water delivered to the household is potable. A piped connection that delivered unreliable, poor-quality water is still counted as an ‘improved source’. Similarly, for the second definition, water from the other types of improved sources may be contaminated – yet the household will still be counted as having an ‘improved source’.

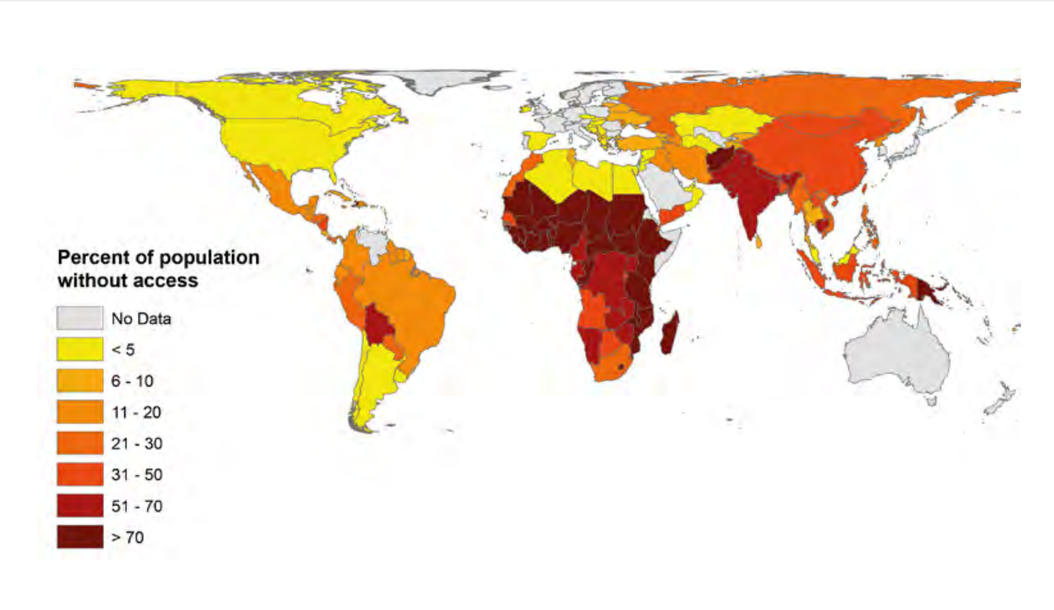
Second, water sources considered by the JMP to be ‘unimproved’ may, in fact, provide a household with potable water. For example, water vendors (both tanker trucks and distributing vendors) and bottled water are counted as ‘unimproved sources’, even though both may reliably supply a household with sufficient quantities of safe (i.e., high-quality) water.

Third, both indicators of coverage implicitly assume that a household only uses one source for its drinking water. This is often untrue. Households may collect drinking water from both improved and unimproved sources, even if their ‘improved’ water source is a piped water connection on the premises. Despite these limitations, the JMP data on improved water coverage are the best available, and we rely upon them for our analysis.

Changes in population without access to improved water supply[33] *(Fig 28)*



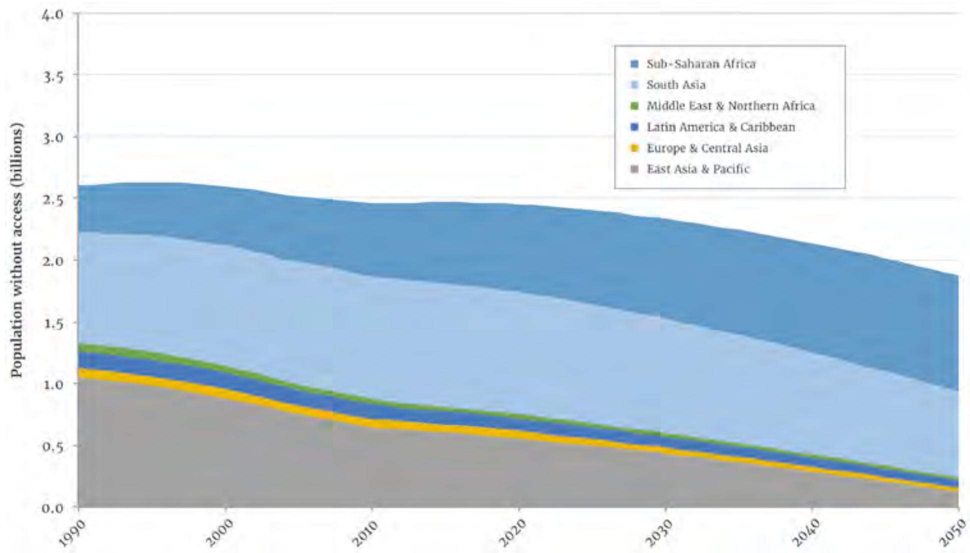
Percentage of population without access to improved sanitation[34] *(Fig 29)*



33 *Jeuland et al. (2013).*

34 *WHO UNICEF (2012).*

Change in access to improved sanitation[35] *(Fig 30)*



Economic losses from inadequate water supply and sanitation[36] *(Fig 31)*

35 *Jeuland et al. (2013).*

36 *Hutton (2013); WHO (2012).*

3.6 Global analysis of water security: (4) ecosystem degradation and pollution

Water-related threats to the natural environment arise from human action for a number of reasons including: pollution, over-abstraction, modification of the natural variability of flow regimes and of river, wetland, and coastal morphology.

Many of these impacts are a consequence of humans adapting to water-related risks that have already been described, notably:

- water abstraction as a response to water scarcity
- interruption of river connectivity and natural flow regimes due to reservoir construction, for water supply, irrigation, hydropower, or flood control
- river training, dredging, and separation from floodplains, to enable urban expansion or in order to reduce flood risks
- urban wastewater discharges resulting from piped sewer networks without wastewater treatment facilities.

Other threats arise from industrial activities, including waterway modification for navigation, point and diffuse pollution from industry and agriculture, over-fishing, and temperature modifications from cooling water. The presence of invasive species is, in part, a broader consequence of globalization.

The threats are therefore multiple and interacting. The scale of the risk depends upon the sensitivity of the natural environment to these hazards, acting individually and in combination. Analysis of the nature of water-related risks to the natural environment at a global scale is in its infancy, and in particular, there is very limited analysis of the relationship between environmental threat and observed impacts (for example in terms of species distributions or extinction).

Here we rely extensively on the work of Vörösmarty and colleagues who analyzed threats to river biodiversity on a global scale.[37] We supplement that analysis with evidence of actual impacts on aquatic species (from the IUCN Red List) and our own analysis of the locations where environmental water requirements are threatened and/or not met.

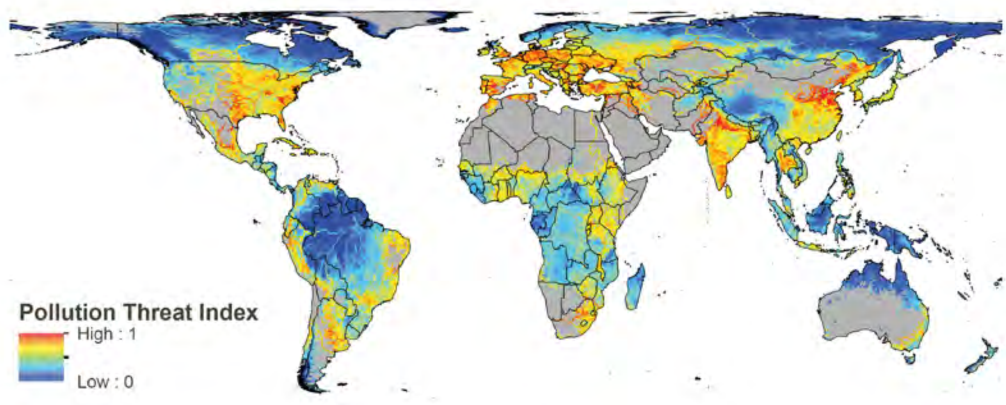
Figure 32 illustrates the global distribution of pollution threat, which includes the effects of nitrogen loading, phosphorous loading, mercury deposition, pesticide loading, organic loading, salinization, acidification, and sediment loading. The index reflects the impacts that intensive agriculture, industries, and over-abstraction have on water quality.

We have estimated the frequency of over-abstraction relative to environmental water requirements through consideration of proposed environmental flow requirements (EFR), which here are defined as a percentage of the monthly flow.[38] In the analysis of water scarcity, we estimated residual flows after human abstractions and the effect of reservoirs. We have calculated the average residual flow, as a percentage of the EFR for every month of the year. In Figure 33, we show the fraction of months in which the flow is less than the EFR. This illustrates where the environment's requirement for water is most impacted by water use.

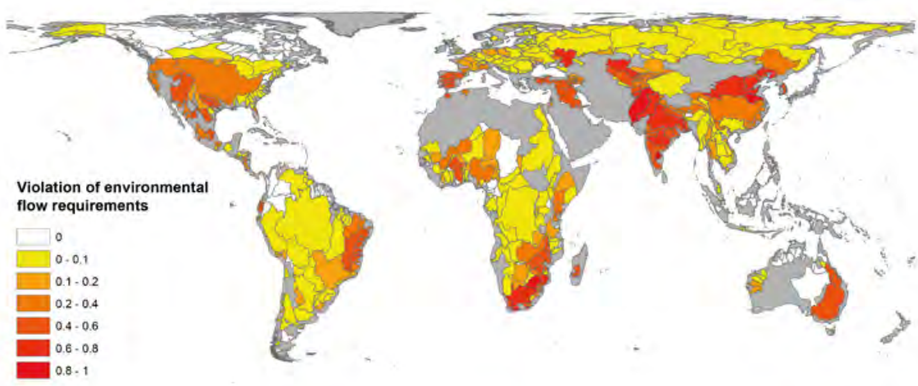
37 *Vörösmarty et al. (2010).*

38 *Pastor et al. (2014).*

Aggregated pollution hazard[39] *(Fig 32)*

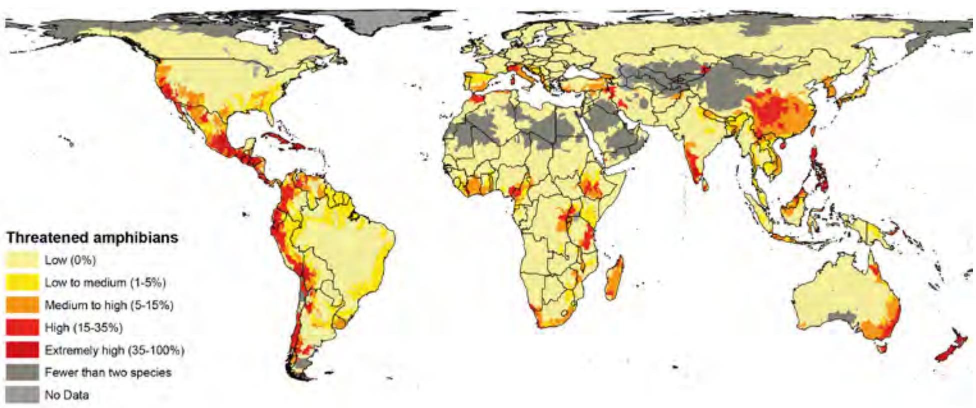


Fraction of months in which flows are less than environmental flow requirements *(Fig 33)*



39 *Vörösmarty et al. (2010).*

Threatened amphibians[40] *(Fig 34)*



Evidence of harmful impacts of water-related risks to ecosystems is scarce. The most extensive relevant dataset are IUCN Red List records for amphibians (the data for freshwater fish are even less complete) (Figure 34). The data are limited by incomplete coverage and to some extent reflect the native extent of amphibian species. Nonetheless, alongside the composite biodiversity map and analysis of environmental flows, Figure 34 helps to build up a picture of the environmental dimension of water insecurity.

The various environmental metrics we have developed are not directly comparable. However, by evaluating the metrics in combination, we can begin to develop an overview of water-related threats to the natural environment.

Table 3 ranks countries according to each of these metrics and shows the top ten countries where the risks to the aquatic environment are greatest according to these metrics.

40 *Adapted by WRI from IUCN.*

Top ten countries for risks to the aquatic environment *(Table 3)*

Rank	Pollution Index	Environmental Flow Violation Index	Biodiversity Index	Percent Threatened Amphibians
1	Tunisia	Pakistan	Czech Republic	Haiti
2	Israel	South Africa	Luxembourg	Jamaica
3	Moldova	India	Kuwait	Dominican Republic
4	Syria	Spain	Belgium	New Zealand
5	Hungary	Nepal	Tunisia	Cuba
6	Macedonia	Afghanistan	Germany	Honduras
7	Germany	Korea	Moldova	El Salvador
8	Netherlands	Bangladesh	Syria	Guatemala
9	Czech Republic	Madagascar	Slovak Republic	Philippines
10	Algeria	Iraq	Spain	Ecuador

Colour scale is GDP per capita income classification:

Low income	Lower-middle income	Higher-middle income	High income

3.7 Aggregating water security risks

From the analysis presented in this chapter, we observe that different parts of the world are subject to different versions of water insecurity. The risks of water scarcity are concentrated in locations with highly variable hydrology and over-exploitation of relatively scarce resources. The risks to people from flooding are greatest in Asia. The economic risks from flooding are increasing in all locations worldwide, due to increasing economic vulnerability, and Asia is set to overtake North America and Europe as having the greatest economic concentration of flood risk. The burden of inadequate water supply and sanitation is greatest for Sub-Saharan Africa, but significant economic impacts are still felt in Asia. Hazards to the aquatic environment have tended to materialize as a consequence of industrialization.

Each of these four categories has major economic implications:

1. As we saw in Chapter 2 of this Report, the economic consequences of droughts and **water scarcity** are most pronounced in agriculture-dependent economies. Runoff variability affects all economies, however, reflecting non-agricultural impacts such as instances of water scarcity impacting hydropower production (as in Brazil) and cooling water availability. While water scarcity can also hit urban water supplies, urban water demands tend to be prioritized in times of scarcity, so the earliest impacts are felt in agricultural production. We have therefore based our economic metric on the estimates of the economic value of water-related constraints on agricultural production as being the primary economic metric of water scarcity (Figure 13).

2. Our analysis of **flood** risk was computed directly in terms of expected annual damages (expressed in financial terms) (Figure 19). These calculations are for damage to property and do not include agricultural losses, but these tend to be less than urban damage. Nor does the analysis incorporate the economic impacts of business interruption and spillover effects.

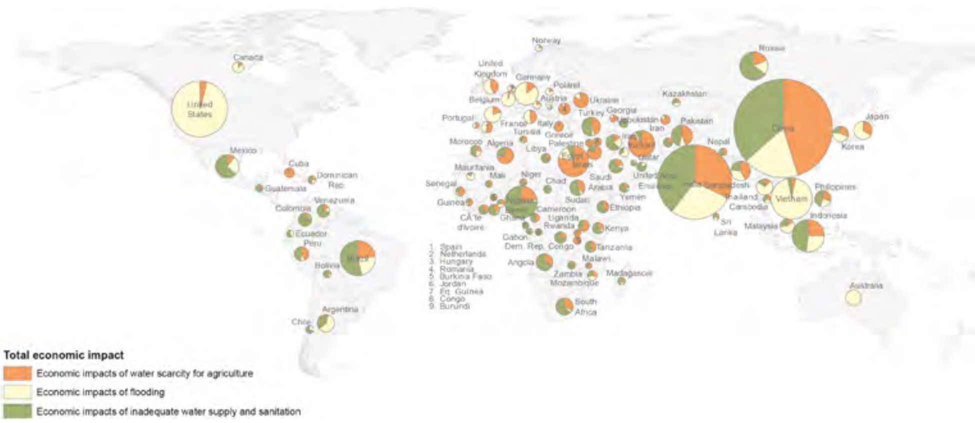
3. The economic impacts of inadequate water **supply and sanitation** are based on WHO estimates of the benefits of universal access (Figure 31). Most of these impacts are associated with unproductive use of time due to inadequate WSS, along with healthcare costs and loss of life.

4. Degradation of the aquatic **environment** is reflected in the lost value of the ecosystem services that those environments supply. While the value of freshwater ecosystem services has been estimated,[41] the value by which those services have been reduced due to degradation in the aquatic environment has not been estimated. We are therefore not able to incorporate an environmental dimension in our calculation of the economic scale of these water-related risks.

Given very different economic assumptions used to estimate (1) the welfare impacts of water scarcity for agriculture; (2) the expected direct damages due to flooding; and (3) the economic impacts of inadequate water supply and sanitation, these economic values are not directly comparable. To show how the burden of risk is distributed between countries and across risks, we have standardized the three categories of economic impact to have equal total impact globally. Figure 35 shows this relative burden of economic risk.

41 *Wilson and Carpenter (1999).*

Relative economic impacts of water insecurity *(Fig 35)*



Relative economic impacts of water insecurity, per capita *(Fig 36)*

China and India stand out carrying the greatest total economic burden of water insecurity, and are subject to all three risk categories. In Africa the economic impact from inadequate water supply and sanitation is greatest, whereas in most advanced economies flooding makes the greatest contribution to economic risk. In Figure 36 this economic burden has been divided by the national population. On a per capita basis, Africa and the Middle East stand out as having the greatest economic impacts from water insecurity.

In Africa the economic impact from inadequate water supply and sanitation is greatest, whereas in most advanced economies flooding makes the greatest contribution to economic risk.

The risks of water insecurity impact people directly in terms of health, livelihoods, and wider well-being. These diverse impacts are not necessarily comparable with one-another, but we can endeavour to quantify which populations are most heavily burdened by water insecurity (Table 4). We have ranked countries according to:

1. the number of people exposed to shortages of different severity
2. the number of people at risk of flooding
3. the number of people without access to improved sanitation.[42]

The impacts on people are for the most part concentrated in lower-middle income countries. India and China stand out as the most water insecure nations according to all three of the risks to people. Pakistan and Bangladesh also rank highly in all three rankings for risks to people.

Table 5 shows the top ten countries that have the greatest percentage of population exposed to the three major risks to people listed above. All of the countries with the highest percentages at risk of flooding or without access to improved sanitation are low or lower-middle income countries. Vietnam, Myanmar, and Bangladesh are global hotspots for flood risk in absolute and per capita terms. Some of the poorest countries of the world have the lowest levels of access to improved sanitation.

42 *To avoid double counting within this category, the number of people without access to improved water supply has not been included.*

Top ten countries for people at risk of water insecurity *(Table 4)*

Rank	Shortage Index: Total population at risk of frequent water shortages	Flood Index: Expected population flooded	Water and Sanitation Index: Total population lacking sanitation
1	China	India	India
2	Pakistan	China	China
3	India	Vietnam	Nigeria
4	Bangladesh	Bangladesh	Indonesia
5	Nepal	Myanmar	Pakistan
6	Algeria	Indonesia	Ethiopia
7	Saudi Arabia	Pakistan	Bangladesh
8	Uzbekistan	Egypt, Arab Rep.	Congo, Dem. Rep.
9	United States	Thailand	Russian Federation
10	Afghanistan	Nigeria	Tanzania

Colour scale is GDP per capita income classification:

Low income | Lower-middle income | Higher-middle income | High income

Top ten countries (with population greater than 1 million) for proportion of population at risk of water insecurity *(Table 5)*

Rank	Shortage Index: % of 2010 population at risk of frequent water shortages	Flood Index: % of 2010 population expected to be flooded	Water and Sanitation Index: % of 2010 population lacking sanitation
1	Israel	Vietnam	South Sudan
2	Pakistan	Mauritania	Niger
3	Jordan	Myanmar	Malawi
4	Turkmenistan	Bangladesh	Chad
5	Malawi	Guinea-Bissau	Togo
6	Nepal	Lao PDR	Tanzania
7	Guatemala	Cambodia	Madagascar
8	Guinea-Bissau	Mozambique	Benin
9	Saudi Arabia	Korea, Dem. Rep.	Sierra Leone
10	Lebanon	Somalia	Congo, Dem. Rep.

Colour scale is GDP per capita income classification:

Low income | Lower-middle income | Higher-middle income | High income

3.8 Toward common metrics of water security

The analysis described in this chapter has sought to develop quantified metrics of the impacts of water security. We have focused upon risks of water insecurity to people and the environment, and also sought to quantify some of the economic benefits that water security could yield.

Quantified metrics of risk and opportunity provide a logical and consistent approach to measuring water security. The approach is attractive in that it focuses on outcomes that people value: economic and human well-being, and health of the environment. Calculation of these metrics has been based on a consistent methodology of risk, aimed at understanding water-related hazards and their consequences. This risk-based approach provides a consistent logic, which avoids arbitrariness in the specification of water security metrics. The quantification of risk provides a starting point for estimating the value of investing in order to reduce risk. Thus, there is a direct link from our analysis to the process of building an economic case for reduction of water insecurity.

The analysis has involved large quantities of data. These data have been aggregated to develop headline indicators of four key water-related risks:

1. The economic and human impacts of water scarcity

We have concentrated upon agriculture and malnutrition, but even from this rather focused perspective, the analysis has raised challenges of defining a reasonable counterfactual of water security for farmers. We expect future studies to also quantify the economic impacts of water scarcity for the energy sector, other industries, and municipal water supplies.

2. The economic and human impacts of flooding

We have focused upon direct impacts of fluvial and coastal flooding on urban assets, and the associated populations at risk. We expect future studies to quantify potential for loss-of-life and health impacts, and to explore the indirect economic impacts to business and supply chain interruption.

3. The economic and human impacts of inadequate water supply and sanitation (WSS)

We have been able to draw upon the JMP's monitoring efforts of the Millennium Development Goal for WSS, and in-depth economic analysis from the WHO, to present estimates of economic damages of, and populations at risk from, inadequate water supply and sanitation.

4. The impacts of water insecurity on the natural environment

We have inevitably used a multi-attribute approach, drawing upon indicators of pollution, flow disruption, and environmental impact. We expect that future studies will seek to quantify the economic value of water security threats to ecosystems services.

Each of the economic metrics is based upon somewhat different methodological approaches. We expect future studies to explore more general and transferable approaches and datasets for quantification of the economics of water security. A focus upon monetization also

... the analysis reported here has put in place frameworks and methodology for the quantification of water security.

risks overlooking important impacts that are harder to monetize: most notably, the impacts upon the natural environment, and the social and cultural values associated with sustainable water resources management. Even with further progress in monetization, water security will continue to be a multi-attribute construct.

The methods we have used to calculate risk can doubtless be improved upon, so we expect that future assessments will generate better estimates. Nonetheless, we believe that the analysis reported here has put in place frameworks and methodology for the quantification of water security.

3.9 Summary

Water insecurity has harmful impacts on people, economies, and the natural environment. Those risks influence people directly: for example, via the health impacts of inadequate water supply and sanitation; through reduced yields to farmers because of water scarcity; or through damage to people's health and homes because of floods. Water-related risks also influence people's economic opportunities: for example, through the time required to collect water, which could be used for other productive activities. Water-related risks have impacts on production, notably in the agriculture and energy sectors. They can impact the natural environment as well, in ways that are less amenable to quantification in economic terms.

In this chapter, we have sought to quantify, as far as global datasets have allowed, the most important direct water-related risks to the economy, society, and the environment. The focus of these metrics reflects the findings of the global econometric analysis developed in Chapter 2. That analysis pointed to runoff variability (in particular scarcity and flood), and to investments in water supply and sanitation (WSS) as important factors in water security. We have demonstrated the scale of water-related risks using global-scale analysis, providing a basis for comparison between risks, and between countries. It has not been possible to monetize all of the impacts of water security; a multi-attribute approach has allowed us to incorporate dimensions (most notably, of risks to the natural environment) that are more problematic to monetize. The analysis has demonstrated the following:

- Inadequate WSS has been estimated to be the largest water-related risk globally, in terms of economic and human impact. This is a chronic risk, materializing on a daily basis in countries without adequate water supply and sanitation infrastructure and services. Improvements in access to sanitation have kept pace with global population growth, but the risk persists – and is increasing in Africa.
- Floods are a major and growing economic risk in all societies, and we project a growing proportion of flood risk in coastal megacities. Asia stands out in this regard, because of large human exposure to flood risk. While Europe and North America have invested heavily to reduce the human and economic impacts of floods, they still face the greatest economic risks, and their exposure to the most extreme events continues to grow. By the 2030s, in the absence of adaptation, coastal flood risk worldwide is projected to increase by a factor of four, while fluvial flood risk could more than double.
- Our analysis has demonstrated the complex effects of water insecurity on agricultural production, food prices, and the health of malnourished children. Water insecurity leads to higher and more-variable food prices (in particular, for rice) than would be expected in a more water-secure world. Investment in water security could boost production, and reduce food prices and food price volatility for the world's poorest consumers.
- The impacts of water insecurity on the natural environment are multiple and interacting. Ecosystem services in the regulation of runoff, assimilation of waste, and provision of fisheries, all underpin water security. We have demonstrated the extent of major risks to the aquatic environment, which need to be managed on the pathway to water security.

The analysis of risks has focused upon known physical mechanisms by which water-related risks harm people and the environment. These impacts aggregate, and have broader impacts on the economy and society. We have demonstrated how the market can compensate for local impacts to some extent – for example, through food-trade and price adjustments – but markets are also a mechanism for propagating risks globally. Perceptions of risk can modify investment choices: from those of individual farmers, to major foreign direct investment decisions. Extreme events – be they droughts, floods, disease outbreaks, or pollution incidents – have particularly broad-ranging economic and political consequences. These impacts interact with other contextual factors within society, and so become increasingly difficult to isolate and quantify. The risk analysis methodology adopted here ensures that analysis of risk is grounded in known observable mechanisms, but it inevitably overlooks these broader scale impacts.

The analysis has drawn extensively on global datasets that are now becoming available, thereby providing exciting opportunities for the quantification of water security impacts. While addressing most of the dimensions of water security already considered by previous studies (and in several instances, the same datasets), our approach is novel in its consistent focus upon hazards and impacts within a risk-based framework. We have sought to avoid commonplace 'fragmented' approaches to water, by addressing diverse aspects of water-related risk within this common framework. The geographical aspect of our approach has helped to identify the spatial co-location of risks. The risk-based approach has also led to a focus upon the effects of hydrological variability. We have looked specifically at the effects of variability on agricultural production and prices. We have developed a metric of water scarcity that accounts for runoff and demand variability, the mitigating effect of storage, and the seasonal variability in the environment's requirement for water.

Analysis and quantification of risk provides the starting point for action to tackle water insecurity. It helps to prioritize action, target it geographically, and indicate the scale of an appropriate response. However, investment decision-making requires analysis of costs, impacts, and residual risks, on a case-by-case basis. Not all water security investments will be cost-beneficial. The sequencing of investment in infrastructure, institutions, and information is essential – as we shall see in the next chapter. Nonetheless, our analysis has demonstrated that the risks of water insecurity are both globally significant, and unevenly distributed – providing a strong case for targeted action.

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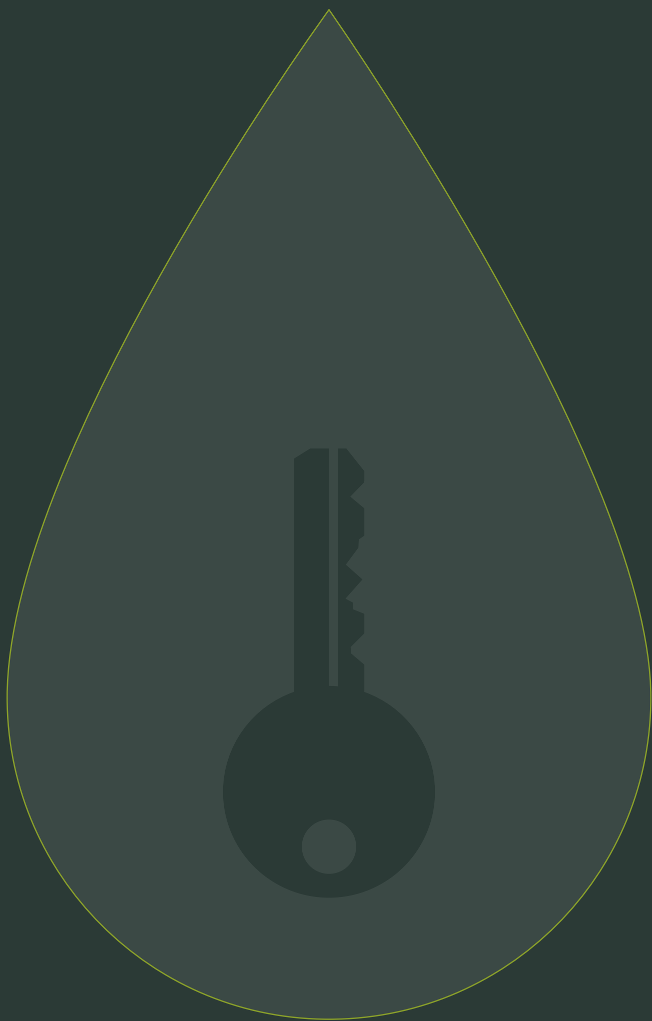


Chapter 4: Pathways to water security

‘For every hundred studies of what might or should be done with a river system, there is hardly one that deals with the results … [T]here are only the roughest gauges of the effects of river works upon economic growth and community stability or change. Little basis exists for comparing the effectiveness of one multiple-purpose plan with another for the same basin or with an alternate method of fostering social change.’

White (1957)

‘Most of the available documents and sources on the long-term development of water services and utilities are of a descriptive nature, often based on a deterministic conception of technological development and concentrating on technical evolution of the systems rather than bifurcation points, alternative development paths and path dependencies … In the early establishment phase of the WSS (Water Supply and Sanitation) systems, several alternatives were debated and discussed often for several decades, if not a century. After the systems were established, the focus was on continuous expansion of the systems together with urban population growth, while less attention was paid to alternatives.’

Juuti and Katko (2005)

4.1 Introduction

In previous chapters, we have shown how water insecurity can act as a drag on growth. We have examined the scale and distribution of water-related risks on a global level – establishing that even the wealthiest economies face risks from hydrological variability and deteriorating water quality. Yet for all its value, this broad-scale analysis struggles to deal with the complexity and context of water security. It cannot tell us why risks and economic impacts come into being, and change with time. It cannot tell us why an investment brings greater water security in one circumstance – and failure in another. Gilbert White's observations, from nearly 60 years ago, about river basin development still capture the fundamental challenge today of identifying and evaluating alternative pathways to water security.

This chapter draws on an examination of 32 cases, including the eight selected for presentation in this chapter. We reconstruct, analyze and compare historical water development paths at three scales: river basins, cities, and aquifers. We use multiple sources of evidence – including interviews with local and international experts, and policy and academic literature. Together, these data underpin a comparative analysis, allowing us to learn from historic pathways to water security, examine setbacks – and understand successes.

In the sections that follow, we define pathways to water security, and identify their main elements. These elements include investments in the three key areas of information, institutions, and infrastructure, typically designed, combined, and sequenced in response to water-related risks and opportunities, as well as broader social, economic, and environmental drivers. We develop and compare case studies, to generate a mixture of context-specific insights and crosscutting lessons. Our historical analysis compares patterns of investment, and lays foundations for informed decisions and investments in years to come.

4.2 Pathways to water security

'Investments, projects, and regulations can move societies along different trajectories toward a water-secure future.'[1]

Pathways

The idea of a 'pathway' has long been used to describe the sequence of decisions and investments aimed at achieving complex goals, ranging from poverty reduction to resilience or adaptive capacity.[2]

Evidence about pathways has emerged from many different fields, including dynamic models of economic growth, social-technological transitions theory, and the management of the commons.[3] All of these perspectives share a focus on the interactions and interdependency of institutions, information, and infrastructure. They also emphasize the potential for alternative paths to a given outcome, the importance of 'triggers' in prompting human action, and the long-lasting effects of historic decisions and technologies. Pathways to water security are, therefore, 'path-dependent' – past choices open some options, and foreclose others.[4] Framing the dynamics of water security in terms of adaptive pathways helps to achieve two key goals: first, understanding the historical development paths that shape water security today; and second, gaining insight that helps navigate paths to future water security.

Here we define 'pathway to water security' as a sequenced portfolio of investments in institutions and infrastructure, underpinned by investments in information. And, as we see time and again, information, institution, and infrastructure are interdependent. We use the word 'portfolio' to denote a set of different investments ideally chosen to complement one another. We may measure different portfolios' success by different baskets of metrics – but all portfolio investments are intended to achieve more collectively, than they can alone.

Historic pathways are relevant for decisions today because past choices influence future options. The evidence from historic pathways is descriptive, cataloguing events and decisions in a development path and identifying critical interactions and consequences, including unanticipated impacts.

Developing and implementing pathways is difficult due to the technical complexity and the political considerations involved. Historically, many investments were chosen through one incremental decision after another, with varying levels of coordination across projects. Dynamic, adaptive pathways and planning approaches are increasingly being developed to guide decision-making under uncertainty as part of multi-stage planning processes – processes with identified contingency options and opportunities for learning and adjustment. Executing long-term, multi-step plans is difficult, however, within almost any dynamic, political context.

1 *Whittington et al. (2013).*

2 *Haasnoot et al. (2013).*

3 *Anderies and Janssen (2013); Geels and Schot (2007); Haasnoot et al. (2013).*

4 *Heinmiller (2009).*

Portfolios

Pathways are characterized by sequenced portfolios of policies and water security-related investments in institutions, information, and infrastructure implemented in response to triggers – both risks and opportunities. Pathways are shaped by historical, geographic, political, and economic factors.

Institutions

Institutions are the 'rules of the game' shaping how people, technology, and the environment interact.[5] In the broadest sense, they include formal laws, policies, regulations, and administrative organizations as well as informal networks and coalitions. Formal and informal institutions create a system of water governance – a set of rules, incentives and processes for decision-making and accountability across multiple values and scales.

Institutions contribute to water security in multiple ways and are needed, for example, to:

- plan, finance, construct, operate, and manage water information and infrastructure systems
- deliver water and sanitation (including waste-water treatment services) and irrigation services
- allocate water resources, including permitting, property rights, pricing, and other incentives
- regulate water quality in drinking water supplies, river/coastal waters, and the environment
- regulate floodplain development
- establish building codes relating to water efficiency, wastewater, and flood resilience
- insure against losses from water-related hazards
- ensure monitoring, enforcement, conflict resolution, and public participation in relation to all of the above.

National and international laws and plans can act as an overarching institutional framework, but governance arrangements and capacity exist at all levels from the individual, community, district, and service area to the national, transboundary, and international levels. The result is a 'poly-centric' and multi-level governance system that has been described as an 'institutional tripod' involving water users, states and markets.[6] Without the rule of law, transparency, and security of property rights, water institutions are unlikely to succeed.[7] In transboundary rivers, international agreements can define rights and responsibilities among riparian countries, and stimulate investment by reducing risks of disputes and clarifying costs and benefits of national and transboundary actions in the basin.[8]

Information

Information provides the foundation needed to enable sound decision-making for water development and management. When designing and implementing pathways to water security, information challenges are created through water resource variability and uncertainty, changing water supply and demand patterns, and the need for trade-offs across multiple sectors and values.

Information used for policy-making, investment decisions and operations is gathered from diverse sources, including:

- local knowledge, participatory governance, and stakeholder involvement
- long-term and continuous observations of hydrological and meteorological parameters at an appropriate-scale, including monitoring networks and metering systems
- development studies and options analyses (e.g., cost-benefit and cost-effectiveness studies, and risk assessments)

5 *North (1990).*

6 *Meinzen-Dick (2007).*

7 *Pahl-Wostl et al. (2012).*

8 *Leb (2013).*

- modelling tools that assess investments and engage stakeholders (e.g., systems optimisation, decision support systems, dynamic adaptive planning)
- communication tools that forecast, monitor, and communicate hazards to decision makers in government, civil society and business, and to vulnerable communities.

Good institutions and infrastructure are founded on good information, about risks, opportunities, and values for example, each of which will evolve with economic development, population growth, and climate change. In this context, information is a shared knowledge asset that underpins the design and operation of any water infrastructure or institution, the re-operation of existing systems to respond to evolving water security challenges, and the monitoring and appraisal of investments. Diverse forms of knowledge and institutional learning shape how information feeds into decisions made under uncertainty. A pathway to water security is guided by technical capacity, public participation, and accountability, underscoring the essential role of information.

Infrastructure

Water infrastructure refers to the structures that modify the course, flow, quality, storage, and distribution of water. This includes, for example:

- delivery systems for urban, rural, industrial, and irrigation users
- treatment facilities for potable water and for wastewater
- storage structures such as reservoirs, lakes, aquifers, floodplains, and wetlands
- development of alternative sources, for example rainwater harvesting, wastewater reuse, and desalination
- flood protection and flood control structures
- land and urban drainage, and water level management.

Related investments that can reduce costs and environmental impacts and, potentially, provide long-run economic gains, might include water conservation and efficiency, re-use of water supply and storm water for irrigation, pollution and wastewater bioremediation in natural or constructed wetlands, and watershed, wetland, and floodplain restoration and management

Infrastructure systems seek to reduce risks and capture water-related opportunities, although efforts to reduce some risks may exacerbate others. For example, water security for irrigation may lead to reductions in energy security and ecosystem health/quality.

Challenges and opportunities

Historically, management of water resources has involved cycles of development in response to human needs, cultural values and economic opportunities, interacting with chronic or acute stresses that impact upon human development in ways that require adaptation.[9] Adaptation is inherently dynamic: actions are taken in response to a changing and evolving context of risks and opportunities. A pathway to water security is a pursuit of a moving target with a recurring pattern of challenges and responses.

Triggers

The factors triggering social and technological transitions in pathways to water security will vary in their frequency, amplitude, speed, and scope. The triggers for action can come in different forms: gradual or chronic stress, variability, shocks, disruptions to a key external force, or 'avalanches' of major changes to multiple dimensions simultaneously.[10] Gradual and chronic stresses include inadequate water supply and sanitation. Variability and shocks include unpredictable seasonal and/or inter-annual runoff and extreme events such as droughts and floods.

9 *Briscoe (2014).*

10 *Geels and Schot (2007).*

Population growth is an example of a disruption (a trend in one dominant variable), while 'avalanches' may involve the combination of an external event, like a political change or financial crisis, along with a water-related hazard, such as a drought. A typology of triggers and disturbances is useful for diagnosing the governance and infrastructure needed for robustness and resilience.[11]

Path dependency and sequencing

Path dependency means that historical decisions and technologies open some pathways, while foreclosing others. Any discussion of pathways starts with a recognition of these constraints and the importance of selecting and sequencing investments to preserve flexibility. The sequencing of each pathway to water security involves a pattern of information, institutional development and infrastructure systems that shapes contemporary challenges and opportunities, influencing the costs and benefits, and the winners and losers, for alternative actions.

Economic decoupling

Economies depend on some access to water for almost all activities. Economies that are dependent on agriculture require a substantial and reliable supply of water, and are especially vulnerable to hydrological variability, unpredictability, and shocks. In Chapter 2, we see that unmitigated hydro-climatic variability is a drag on growth, especially where the contribution of agriculture to growth is high. Economic 'de-coupling' occurs when agriculture-dependent economies industrialize and diversify economic activity, reducing the proportion of the GDP and labour force in agriculture, and expanding the industrial and service sectors. Economic de-coupling from the monsoon in India is described by reports declaring that the growth surge due to manufacturing and services meant that growth was 'no longer a gamble on the monsoon'. However, the widespread move by farmers and industries from unreliable surface water to unregulated and unsustainable groundwater abstraction is leading to new economic threats, due to rapidly falling groundwater levels in some parts of India.[12] Pathways to water security cannot be separated from local and national economic planning.

Key institutional actors and policy leaders

Water cuts across many different economic sectors, administrative and political boundaries and institutional responsibilities. Water security is jeopardized when institutional arrangements are not in place at appropriate scales, or when there are substantial coordination gaps within and across governance or administrative levels.[13] The principle of subsidiarity suggests that decisions should be taken at the lowest level with authority and capacity to act. Subsidiarity implies local actions at the municipal or user level when possible, complemented by higher-level institutions, including national governments, river basin organizations, intergovernmental bodies, and special districts.[14] However, the entities with primary responsibility to lead on issues in the water sector will vary by context and starting points.

11 *Schoon and Cox (2012).*

12 *Briscoe and Malik (2006).*

13 *OECD (2011).*

14 *Marshall (2008).*

4.3 Approach

Case study selection

Political and economic histories have told the story of water development experiences as diverse as New York City's water supply, the ancient civilizations and modern infrastructure of the Colorado, Indus, and the Nile, and the relationship between groundwater and livelihoods in South Asia.[15] Each history tells a story of a challenging water development path, yet the scope for comparison is limited by the lack of a common language to guide the analysis and interpret the results.

We use case studies to illustrate different historic pathways and to identify different triggers and types and sequences of investment. Thirty-two cases were examined as background to our analysis, eight of which are presented in this chapter. The cases were selected at three intersecting scales: the river basin, city, and aquifer, including transboundary river basins and aquifers (Figure 37). The cases illustrate different hydroclimatic conditions (semi-arid, highly variable/monsoonal, temperate), levels of development, social and economic contexts, configurations of water-related risks, and patterns of investment in water security.[16]

Evidence of historic pathways is typically limited and dispersed within different disciplines – each using different terms to describe similar concepts and relationships. This chapter includes 'timelines', which take an initial step toward establishing consistent chronologies of risks, opportunities, and patterns of investment, drawing from two main sources: consultations with experts (interviews, surveys, verification of data from policy, and academic literature); and economic histories, development plans, and risk assessments.

The river basins we have examined include examples of highly-variable/monsoonal, arid and semi-arid, and temperate rivers with different levels of economic development. The highly variable/monsoonal rivers (e.g., Mekong) are mostly low to middle-income. The arid and semi-arid rivers include all levels of development from lower (e.g., Senegal, Aral drainage) to middle (e.g., Yellow) to higher income (e.g., Colorado and Murray-Darling). Temperate rivers (e.g., Rhine) are typically higher-income with substantial assets at risk from flooding and from water quality impacts of urban, agricultural, and industrial pollution. Some rivers may cross these climate zones, for example from upstream highly-variable/monsoonal, to downstream arid and semi-arid (e.g., Indus, Nile, São Francisco), or even vice-versa (e.g., Niger). While all pathways to water security reflect local context, this identifies rivers with similar hydro-climatic characteristics and levels of development for direct comparison, and allows the distinction between general lessons (all or most rivers) and context-specific insights (one or a few rivers).

The cities we have examined include major urban centres on each continent, given their role as critical nodes in the global economy. These cities are characterized by a range of growth rates, population densities, water service delivery systems, and risks from flooding and inadequate WASH services. The OECD has catalogued the recent development of typologies of global cities and identified the attributes important for distinguishing the innovation pathways to urban water security. The factors identified by the OECD include the profile of water-related risks, urban characteristics, and the institutional architecture of urban water services.[17]

15 *Molle and Wester (2009); Scarborough (2003); Shah (2010); Soll (2013).*

16 *Grey et al. (2013).*

17 *OECD (2015 forthcoming).*

The aquifers we have examined are principally major systems with different levels of exploitation, pollution, and economic development. Intensively exploited aquifers have experienced different patterns of development. Intensive groundwater-based irrigation is undertaken in wealthy economies (e.g, Guadiana, Spain; Ogallala, US) and in less wealthy economies (e.g., Ica Valley, Peru; Indus Plain). Some urban centres are underlain by major aquifers (e.g., North China Plain; Gnangara, Australia; Mexico City). Other major aquifers have varying levels of development across a wide area, where the effects of groundwater management and use (e.g., water level decline, pollution,) are felt locally (e.g., Guarani Aquifer System; Gangetic Plain; Nubian Sandstone). Our primary approach in this chapter is the development of case studies, guided by a common framework. This complements the econometric analysis in Chapter 2 and the risk mapping in Chapter 3, both of which used global data sets of information, with the case study analysis of water security and development in river basins, aquifers, and cities.

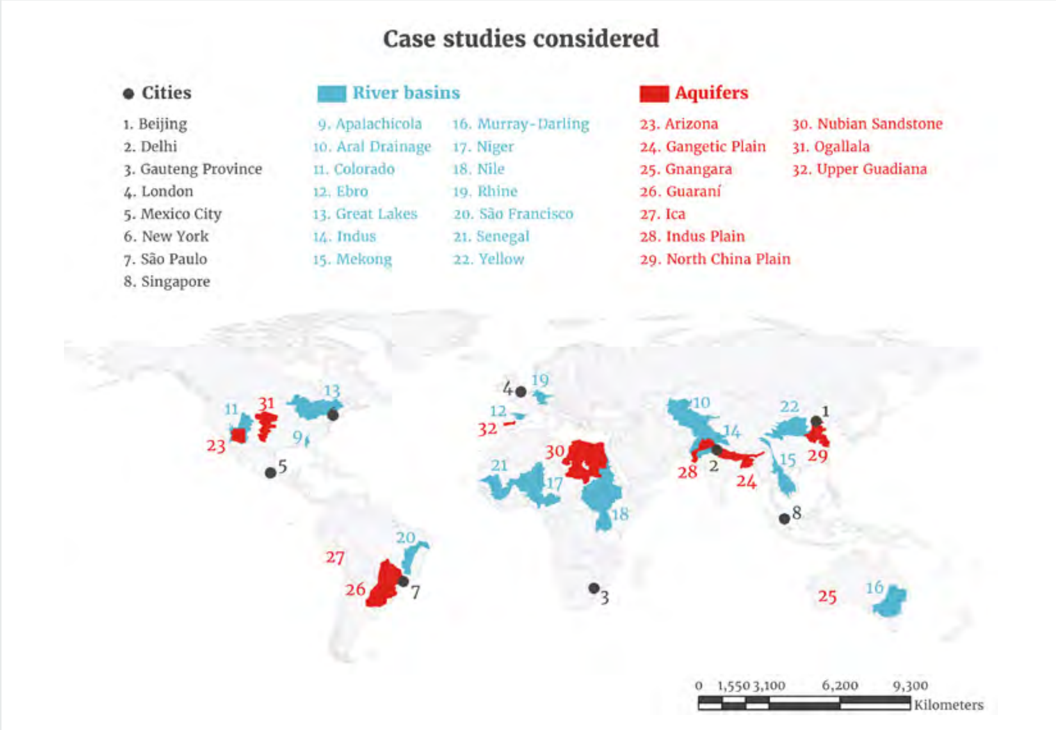
Each location experiences its own path to water security. The importance of taking context seriously – the cultural, environmental, political, and economic conditions – makes it difficult to generalize from local experiences at best, and dangerous at worst. Through analysis of the histories, investments, and system responses that have evolved through time, we can learn lessons about alternative pathways in different contexts.

Timelines

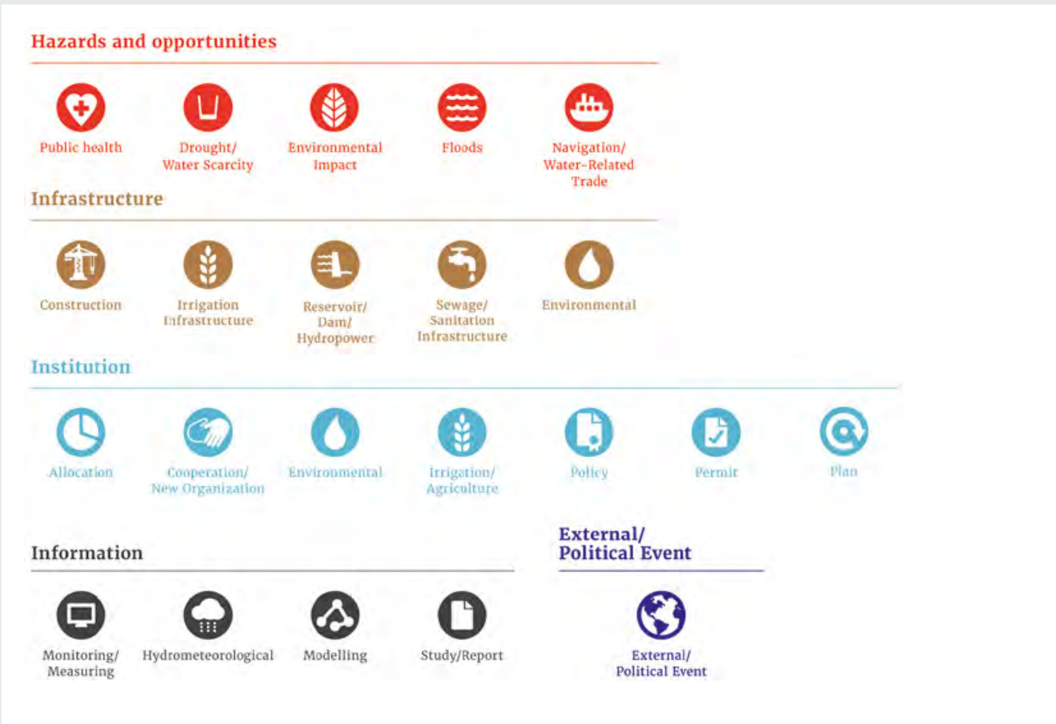
Timelines of selected case studies were created to illustrate specific pathways and patterns of risks, opportunities, and investments. The timelines include: (i) past political and economic events, water-related hazards and opportunities that may have acted as triggers for investment; and (ii) discrete past investments in information, institutions, and infrastructure (Figure 38).

Water-related hazards include the four headline risks examined in Chapter 3: drought and shortage, flooding, inadequate water supply and sanitation, and water pollution and ecosystem degradation. Water-related opportunities include a focus on irrigation and hydropower, and we also identified other investment purposes, including shipping and navigation, ecosystem restoration and tourism, and industry. Investments in information include: local knowledge and expertise studies or reports; hydrological, biophysical, socio-economic, and financial monitoring systems; and measurement technologies and modelling tools for river system planning and operations. Institutional investments include: water service institutions; irrigation user associations; institutional coordination bodies (e.g., river basin organizations); water planning and legislation (policy); allocation systems; financing mechanisms for infrastructure construction; and environmental regulations. Infrastructure investments include the construction and maintenance of reservoirs, dykes, and water and wastewater treatment networks. Economic development provides a backdrop for pathways to water security, which respond to driving forces that include urban, industrial, and irrigation development opportunities featured on the timelines. Each of the timelines will tell a context-specific story, with not all of the headline risks appearing, with different portfolios and sequences of investments, and with the detailed patterns of risks and responses selectively depicted. These timelines reflect the events captured in economic histories and reviewed by experts and should be viewed as indicative, not exhuastive.

Cities, aquifers, and river basins selected as case studies *(Fig 37)*



Common elements of case study timelines *(Fig 38)*



4.4 Case studies

River basins

In this section, we consider the case of three river basins, each providing different histories of investment in water security.

The Colorado River is an example of a pathway to water security in a semi-arid region, where climate variability and sustained drought have posed challenges for regional development and prompted transboundary cooperation and conflict resolution to harness, adapt and restore the river. The Rhine River illustrates the modification of the river in pursuit of economic development opportunities, together with evolving risks from environmental pollution and flooding. The São Francisco River faces similar challenges of variability to those of the Colorado; in this case, Brazil has invested in infrastructure and institutions to develop hydropower, irrigation and urban water supplies.

The Colorado River Basin: chasing water security in a difficult hydrology

The Colorado River (637,137 km^2) is an international river shared by two federal countries: Mexico and the US. It straddles seven US and two Mexican states, supporting 2.23 million hectares of irrigated agriculture and 40 million people concentrated in diverse cities and rural areas (from Los Angeles to Las Vegas and from Mexicali to the Navajo Nation).[18] The Basin's extensive multi-purpose reservoir system stores approximately four years of annual average runoff (approximately 18.5 billion m^3), provides 4200MW of hydropower capacity, and supports a range of recreational uses, including rafting and boating. However, upstream development of water resources has led to the decline of a once-vast delta ecosystem, which is now the focus of bi-national restoration efforts by the US and Mexico to secure water for baseflows and pulse flows.

Triggers and sequencing

The gold rush in the North American west in the mid to late ninteenth century triggered the modern pathway to water security in the Colorado River Basin. This period spurred the development of rules and technologies for diverting water in this semi-arid region, initially in the mining camps of California and Colorado. The boom-and-bust cycle of mining enterprises gave way to regional and national efforts to support irrigation development and to buffer agricultural production against the seasonal variability and multi-year droughts prevalent in the region.

Flooding in 1905 destroyed a private irrigation scheme in California's Imperial Valley, coinciding with a new federal commitment to land reclamation in the Western US. The interstate and federal responses to the flood, combined with efforts to rebuild and expand water infrastructure in the Basin, marked the end of laissez-faire development (Figure 39 traces this evolution and interplay of risks, opportunities, and investments). The farmers of the Imperial Valley in Southern California petitioned the US government to accelerate federal investments, stimulating the development of US interstate institutions to share the costs and benefits of river basin development for irrigation and hydropower.[19]

Elements of the pathway

The earliest European settlements in the Colorado River occurred in the late 1500s and early 1600s when Spanish missions were established in the Lower Colorado.[20] Today, the Colorado River Basin is governed by a complex mix of more than 100 laws, court decisions, operational guidelines, and technical rules known as the 'Law of the River'. The 1922 Colorado River Compact and the 1928 Boulder Canyon Project Act established a fixed water allocation for downstream states within the US. This legal framework for interstate

18 *US Bureau of Reclamation (2012).*

19 *National Research Council (2007).*

20 *Kenney (2009).*

apportionment was confirmed in the Supreme Court decision on *Arizona v. California* in 1963; it requires 'upper division' states (Wyoming, Colorado, Utah, and New Mexico) to deliver 92.5 billion m^3 to the 'lower division' states (Arizona, California, and Nevada) over a rolling 10-year period. It formally allocated an equivalent volume to the upper division states. Downstream delivery requirements from the upper division to lower division states are assessed on a rolling 10-year accounting period. In practice, the fixed allocation leaves the upper division states with residual flows and hence disproportionate exposure to hydroclimatic risks. Both divisions are responsible for Mexico's 1.85 billion m^3 annual allocation secured under a 1944 international treaty.

Early studies and institutional reforms enabled a period of intensive development from the early 1930s to the 1960s, bookended by the construction of the Hoover and Glen Canyon dams. The completion of the Central Arizona Project marked the end of this development era.

Contemporary and future water security challenges have required adaptation to a variable and changing climate; at the same time, intensified competition between farms, cities, energy, and ecosystems has reduced the margin for error when prolonged droughts occur. In 1999, long-term supply and demand intersected for the first time, coinciding with the beginning of an unprecedented 15-year sequence of dry years and increasing evidence from tree-rings of the potential for severe sustained drought. Despite over-allocation and a history of dispute, this period was marked by institutional innovations, including interstate cooperation and interim rules, as well as renewed investments in information and infrastructure. The states and other stakeholders in the Basin have undertaken inter-related investments in institutions, infrastructure, and information to address the consequences of climate variability and change, starting with the development of interim guidelines for sharing surplus water among the states in 2001, and six years later, for sharing shortage.

Key information investments include long-range, adaptive planning for water supply variability and climate change impacts – the 2010-12 Colorado River Basin Study – supported by a river system-modelling platform for engaging stakeholders and by a basin-wide research group, established to integrate climate science into basin planning and operations. Institutional adaptations include interstate and bi-national agreements for coordinated operations of reservoir storage, together with new rules for managing surpluses and shortages, incentives for system efficiency improvements, and commitments to ecosystem restoration.

Investments in infrastructure include the operation of desalination plants, conservation measures, and reservoir intakes. In the context of prolonged drought conditions, environmental flow requirements in the Delta have received additional attention, culminating in 2012 in 'Minute 319', an agreement made under the 1944 Treaty, coordinating US and Mexico's water storage and delivery options to enhance water supply reliability for Mexican water users and the Delta ecosystem. Looking forward, the annual average cost of reducing shortage risks is projected to approach up to US$6 billion in 2060, demonstrating that future pathways will require substantial investment to sustain water security and safeguard the economic activities, urban centres, and ecosystems that depend on the river in a changing climate. The historic pathway also demonstrates the importance of maintaining flexibility, enabling learning, and making trade-offs across competing demands in a closed and highly variable basin, particularly as heightened competition and the impacts of climate change have increased systemic risks and interdependencies across food, energy, and water security.

The Rhine River Basin: a dynamic, adaptive pathway

The Rhine is one of Europe's major river basins, with an area of 185,000 km^2 primarily in Switzerland, Germany, France, and the Netherlands. The Rhine originates in the high Alps and flows through lower mountain ranges where the largest tributaries, the Main and the Mosel, join and continue through the lowlands and into the North Sea. The Rhine has contributed to the economic development of the basin countries and continues to provide important services. It forms a major shipping route, connecting Rotterdam port with the hinterland of the industrial Ruhr and up to Basel in Switzerland. Hydropower is produced in the upstream stretches and river water is used by industry and power plants. Thirty million people depend on the Rhine for drinking water and many people use the river for recreation. It also provides an important habitat corridor for fauna and flora. However, human pressure on the river has also resulted in major risks, including flooding, pollution, and, historically, public health.

Triggers and sequencing

There have been many triggers in the Rhine basin, including floods and pollution, leading to significant transitions. Flood disasters, near-disasters, changing values, and new climate scenarios have triggered adaptive management and planning in the Rhine basin, together with substantial investment in flood protection infrastructure.

The 1986 Sandoz agrochemical storehouse fire in Switzerland was a shock and a stimulus for major changes. The fire led to contaminated water leaking into the river in Basel, killing almost all fish, and requiring prolonged closure of intakes for drinking water along the Rhine in Germany and the Netherlands. The profound impacts of Sandoz became the trigger for political commitment to action. Effective legislation in all Rhine riparian countries and systematic monitoring of the river's water quality were rapidly established after Sandoz. The large scale of the environmental impacts required the establishment of robust institutions – both nationally and internationally. Treaties and conventions resulted from cooperation within the International Commission for the Protection of the Rhine (ICPR), established in 1950 to analyse pollution, recommend water protection measures, harmonize monitoring and analysis methods, and exchange data. The Rhine Action Programme built upon these investments in information and institutions, coupled with major investments in infrastructure, including treatment plants to clean up industrial emissions and reduce pollution of the river.

Elements of the pathway

The pathway to water security in the Rhine can be traced back at least 1,200 years, with land reclamation of the Rhine-Meuse delta starting between 800-1100 AD. The reclaimed land was highly productive, population increased and cities developed. Around 1100, water management intensified with the reclamation of larger floodplain and peat areas converted to polders. The Duke of Holland established institutions in the thirteenth century, with the first official 'water board' established in 1323, having responsibility for water management and flood protection. By 1350, the lower Rhine branches were completely embanked. The industrial revolution in the nineteenth century and the subsequent period of intensive demographic and economic development led to new waves of development in the basin, accompanied by increased vulnerability to flooding. Industrial activities in the Ruhr area in Germany increased the need for transport and, as ships grew in size, long stretches of the Rhine were modified and even canalized, resulting in narrower and deeper channels. Hydropower was developed to power industry. Figure 40 traces this intensive development and increasing vulnerability.

The subsequent emergence of systemic risks increasingly required international cooperation. Water quality quickly became an issue in the wake of rapid industrial development in the Rhine basin after the Second World War. Algal blooms, bad odour, and foam-covered rivers and lakes helped rally public opinion against pollution. Nevertheless, regular monitoring of Rhine water quality started only in the late 1970s. After 'hard' flood protection measures were completed in the second half of the twentieth century, the focus shifted to the ecological and landscape values of the river. The severe floods of 1993 and 1995 and the very dry summer of 2003 resulted in both policy makers and the public realising that extreme events may be rare, but will come and with little warning. At the same time, awareness of the potential impacts of climate change on the river grew and has increasingly been accounted for in national and international policies and plans. A new approach has been developed in the Netherlands, using vulnerability to define Adaptation Tipping Points (ATP) to indicate whether current water management strategies will continue to be effective under different climate change scenarios. Unexpected events and shocks are recognized as triggers for adaptation, with societal change and learning, which focus both on a future endpoint and on the pathway to get there. The ATP approach and the exploration of 'dynamic adaptation pathways' have together enabled adaptive management, with changing environmental values and recognition of climate-related risks.

The São Francisco: in transition to water security for people, irrigation, and energy

The São Francisco River Basin (640,000 km^2, 15 million inhabitants) covers five Brazilian states and represents nearly 8 percent of Brazil's territory. Most of its flow results from precipitation in the upstream part of the basin, with the discharge decreasing from 15 l/sec/km^2 upstream to 5 l/sec/km^2 downstream.

The river provides development opportunities that range from hydropower generation to mining and urban water uses, and from irrigated agriculture to freight transportation. Rainfall variability is high, groundwater resources are limited, and recurrent droughts periodically affect water uses in the basin. Water quality concerns include pollution from untreated wastewater, agrochemicals, and heavy metals from industry and mining as well as soil erosion.

Triggers and sequencing

Historically, the need for agriculture and energy development within the basin triggered early investment by the Federal Government in irrigation projects and large hydropower plants in the basin (Figure 41 traces these efforts and the interplay of risks, opportunities and investments).[21] Infrastructure investments have since resulted in nine storage reservoirs with a capacity of 45 billion m^3, 50 percent of the mean annual flow, and hydropower plants with a total installed capacity of 10.3 GW (about 11 percent of national hydropower generation). The plants are connected to the high-voltage grid that serves most of the Brazilian population. Between the 1950s and 1990s, more than 28 irrigation projects have been promoted and funded by the Government, which developed the irrigation, transportation, and energy infrastructure and reserved about 50 percent of the irrigated land for local, small-scale farmers. The establishment of capable institutions within the basin to address key issues, such as issuing water rights, managing conflicts among competing uses, and cost recovery of infrastructure operation and maintenance, has lagged behind the development of infrastructure.

The development of the São Francisco is also entwined with the water needs of the semi-arid Northeast States beyond the basin, which have always seen the resources of the basin as a solution to their severe water security and poverty challenges, with 10 percent of the national population and by far the lowest per capita income. Political pressures triggered a decision to move water from the São Francisco to enable firm supply to the cities and, if possible, to high-value irrigated agriculture in Northeast Brazil. After a fierce technical and political dispute between those in favour and those against, an ambitious inter-basin transfer project (the Transposition Project) to divert water from the São Francisco to the Northeast was approved in 2005 by the National Water Resources Council. The project is presently under construction, at an estimated cost of US$4 billion. The inter-basin transfer scheme will only use the infrastructure at full capacity during wet years, when part of the flow will be

21 *Lee et al. (2014).*

diverted into storage reservoirs in the recipient area. It will be some time before there will be evidence that the poverty alleviation objective is being met.

Elements of the pathway

The Federal Government has had a long-standing objective of developing irrigated agriculture in the semi-arid, downstream section of the basin. Some public irrigation districts have been very successful in the cultivation of fruits and in progressively taking responsibility for infrastructure operation and maintenance. Other irrigation districts have not performed as well, due to the lack of local capacity to produce market-oriented crops and the absence of agribusiness moving local production into national and international markets. The Federal Government is now considering moving from State-supported agriculture to public-private partnerships, with agribusiness companies playing a greater role in the management of infrastructure and the commercialization of agricultural production of both large and small farms. Private entrepreneurs have been attracted to the region and there are currently about 500,000 hectares of irrigated land in the semi-arid zone (140,000 and 360,000 in public and private properties, respectively).

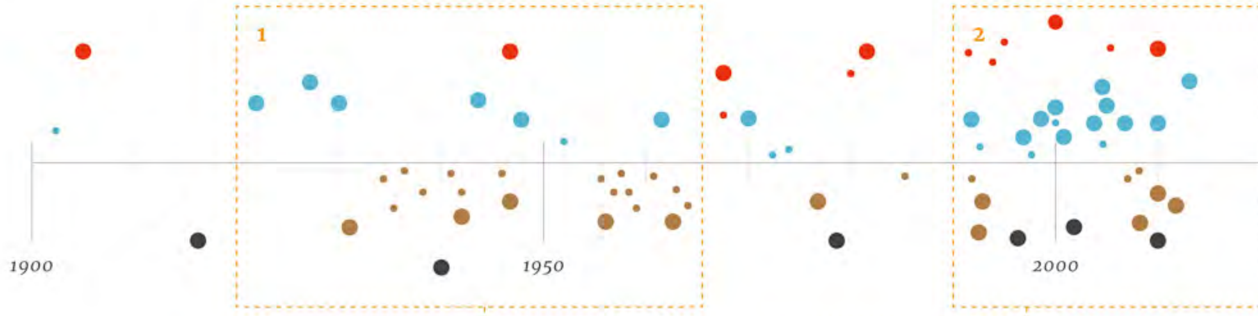
Most of the irrigation infrastructure is privately owned and there is now significant agricultural research underway by Embrapa (a government agency that specializes in tropical agriculture), boosting productivity of agribusiness. Hydropower production is partially decreasing due to water withdrawals resulting from the expansion of agribusiness and the siltation of reservoirs diminishing their capacity, but the complex revenue system of the Brazilian power system creates little incentive for companies to engage in an open debate with the agricultural sector over water rights. New water right applications need careful evaluation to ensure that new uses do not jeopardize existing ones, especially during droughts.

Institutional investments are now being given priority. During the latter part of the twentieth century, Government recognized that little progress would be achieved without capable water institutions. In 2001 the Brazilian Water Agency (ANA) was created within the legal framework of the 1997 Water Resource Law and several states have made substantial progress in developing modern water resource management agencies. The most pressing challenges in the São Francisco river basin are related to the need to create a favourable institutional environment to ensure sustainable economic growth within the basin and to develop the potential of the Transposition Project. While the hydropower potential of the river is almost fully employed, water use for irrigation, transport, and other industry can still be significantly increased. Developing this new potential, however, requires optimising water allocation to different uses, stimulating competitive, self-sustained irrigated agriculture, and addressing water quality issues. The institutional challenges of the Transposition Project include allocating water among receiving states, ensuring recovery of operational costs, and designing an effective management regime.

Colorado *(Fig 39)*

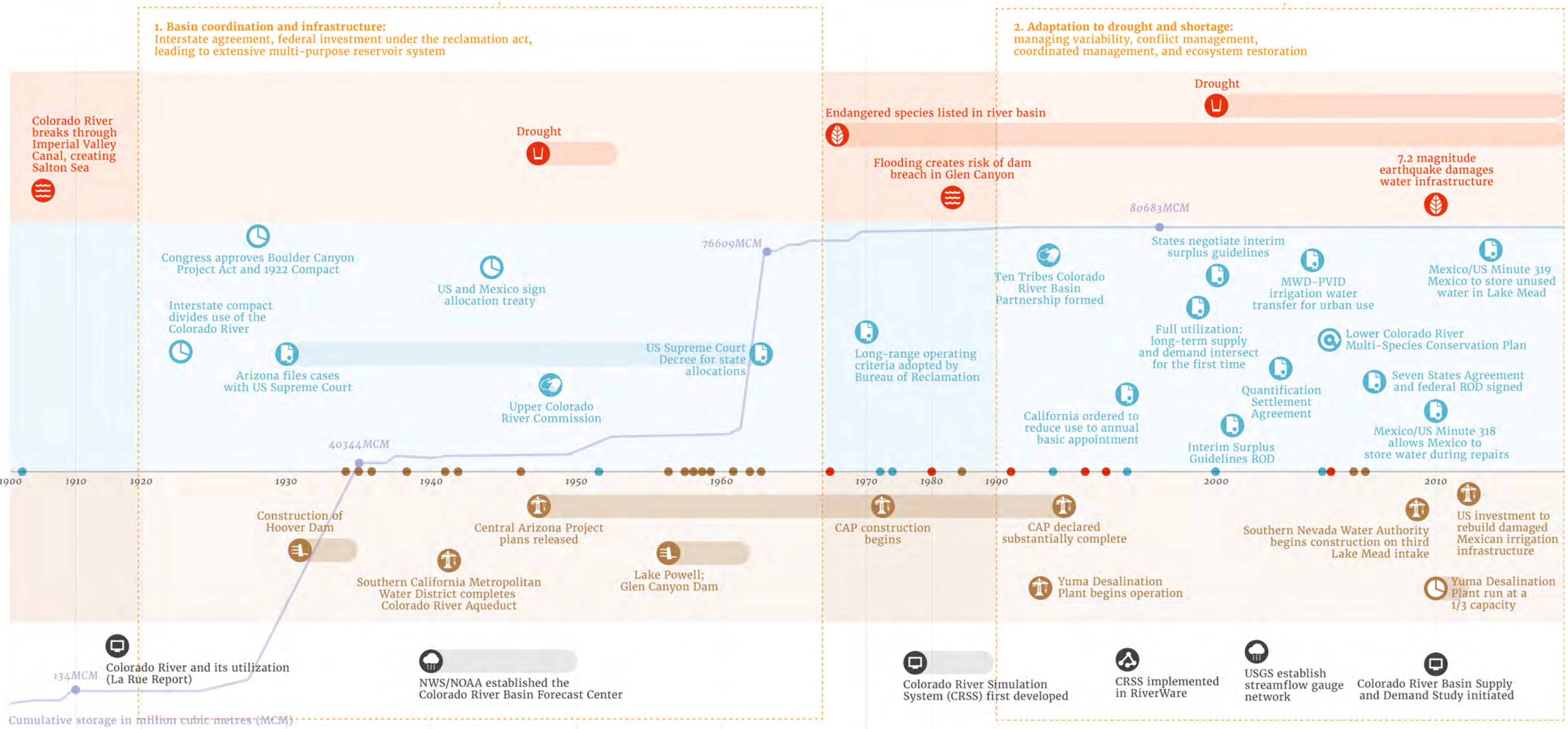
The Colorado (637,137 km²) is an international river shared by two federal countries: Mexico and the US. It straddles seven US and two Mexican states, supporting 2.23 million hectares of irrigated agriculture and 40 million people concentrated in diverse cities and rural areas (from Los Angeles to Las Vegas and from Mexicali to the Navajo Nation). The Basin's extensive multi-purpose reservoir system stores approximately four years of annual average runoff (approximately 18.5 billion m³), to buffer against freshwater variability. The river system has 4,200MW of hydropower capacity and supports a range of recreational uses including rafting and boating. However, upstream development of water resources has led to the decline of a once-vast delta ecosystem, which is now the focus of bi-national restoration efforts by the US and Mexico to secure water for baseflows and pulse flows.

*Each timeline is indicative, and not exhaustive. Major elements have been selected based on expert consultations to depict broad patterns of water-related risks, opportunities and investments. The schematic below features additional elements essential to the pathway, conveying a cycle of challenges and responses unique to **the Colorado River Basin.***



← 1800s laissez faire development, common law and self-organization in mining camps

Future: competition, environmental restoration, and climate change projected 4 billion M³ annual average shortage



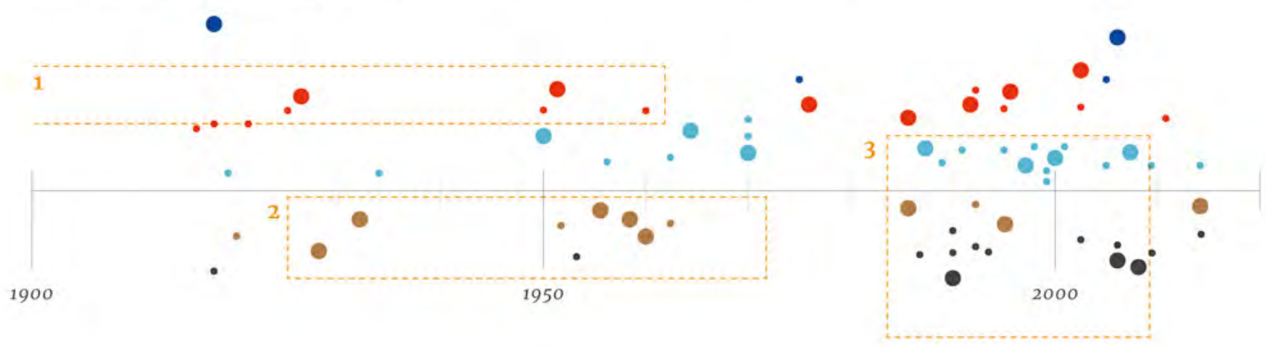
Source: Global Reservoir and Dams Database (GRAND)

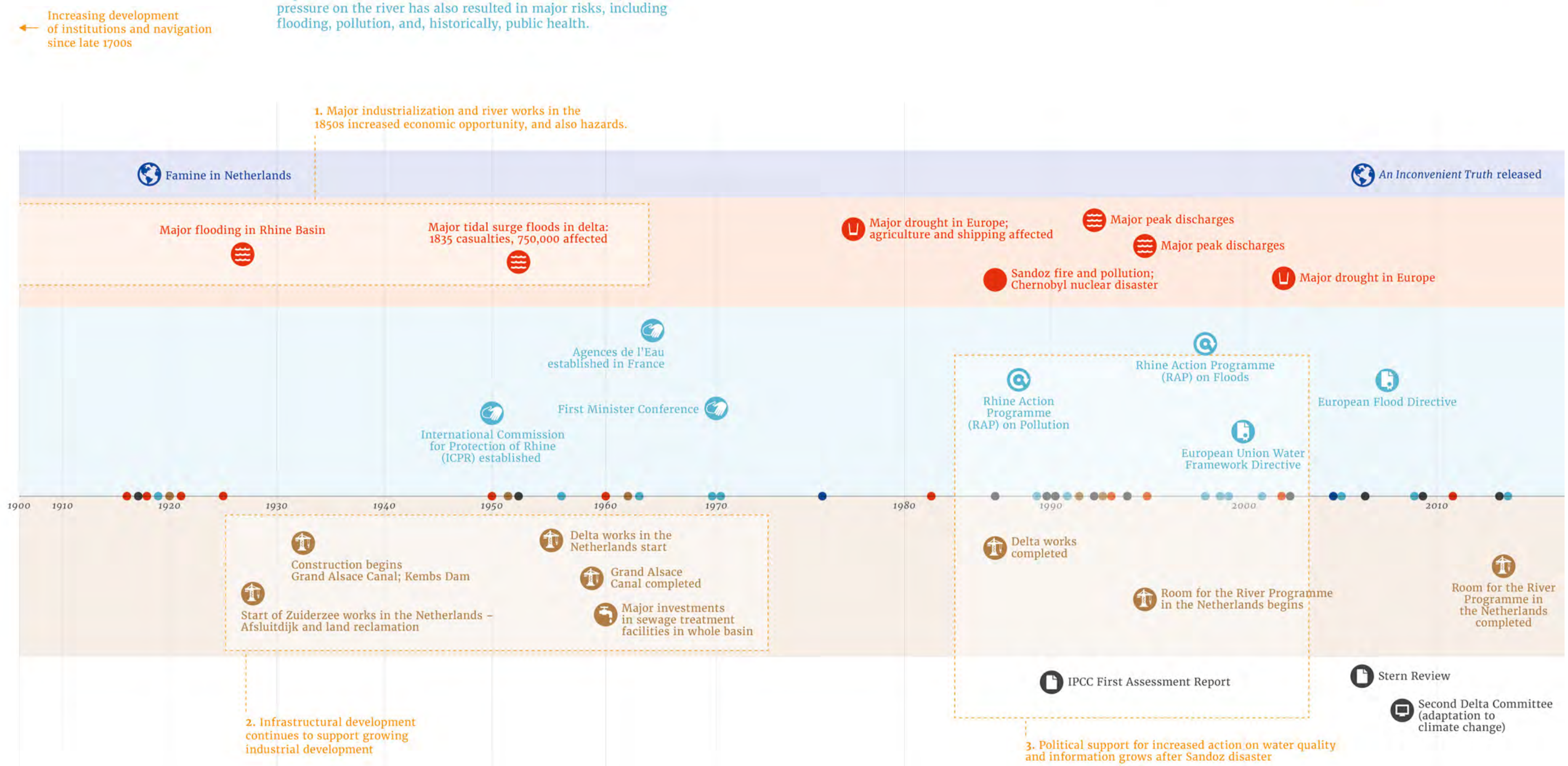
ROD (Record of Decision); PVID (Palo Verde Irrigation District); MWD (Metropolitan Water District); NWS (National Weather Service); NOAA (National Oceanic and Atmospheric Administration); USGS (United States Geological Survey).

Rhine *(Fig 40)*

The Rhine is one of Europe's major river basins, with an area of 185,000 km² primarily in Switzerland, Germany, France, and the Netherlands. The Rhine originates in the high Alps and flows through lower mountain ranges where the largest tributaries, the Main and the Mosel, join and continue through the lowlands and into the North Sea. The Rhine has contributed to the economic development of the basin countries and continues to provide important services. It forms a major shipping route, connecting Rotterdam port with the hinterland of the industrial Ruhr and up to Basel in Switzerland. Hydropower is produced in the upstream stretches and river water is used by industry and power plants. Thirty million people depend on the Rhine for drinking water and many people use the river for recreation. It also provides an important habitat corridor for fauna and flora. However, human pressure on the river has also resulted in major risks, including flooding, pollution, and, historically, public health.

Each timeline is indicative, and not exhaustive. Major elements have been selected based on expert consultations to depict broad patterns of water-related risks, opportunities and investments. The schematic below features additional elements essential to the pathway, conveying a cycle of challenges and responses unique to ***the Rhine River Basin.***



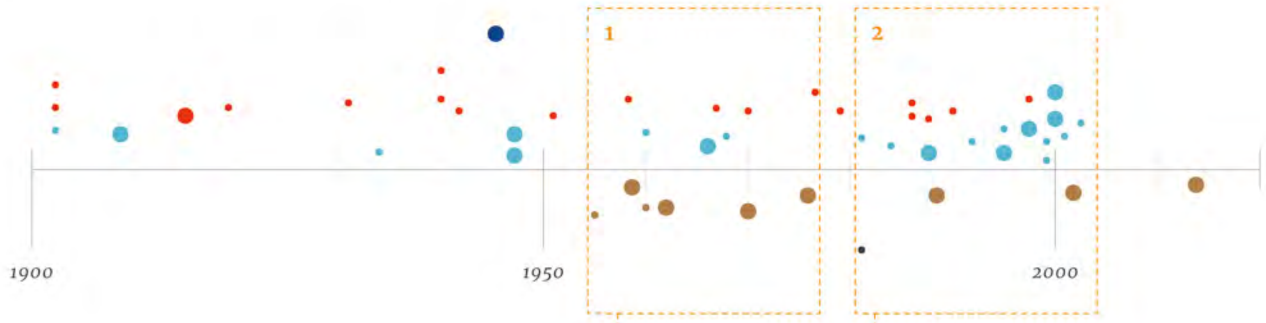


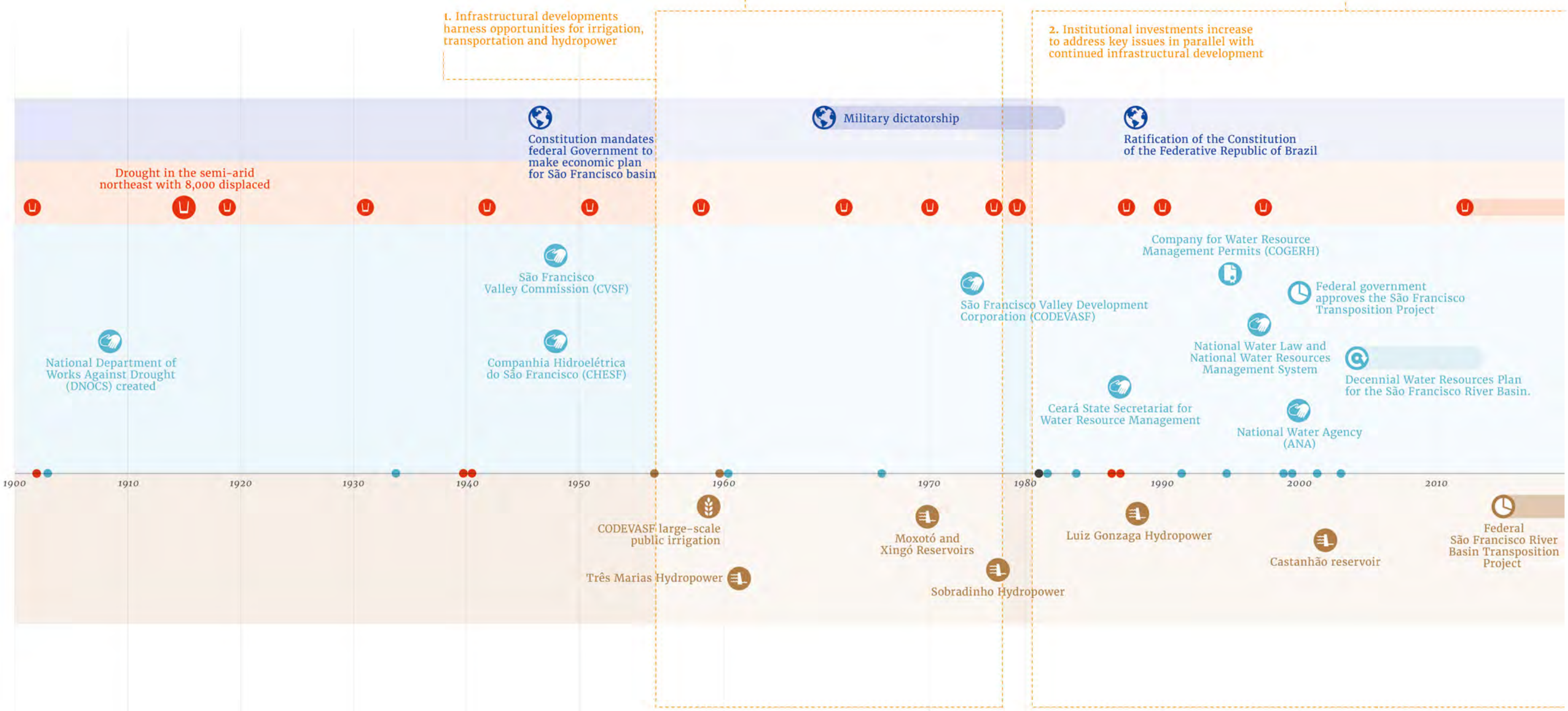
IPCC (Intergovernmental Panel on Climate Change)

São Francisco *(Fig 41)*

The São Francisco river basin (640,000 km², 15 million inhabitants) covers five Brazilian states and represents nearly 8 percent of Brazil's territory. Most of its flow results from precipitation in the upstream part of the basin, with the discharge decreasing from 15 l/sec/km² upstream to 5 l/sec/km² downstream. The river provides development opportunities that range from hydropower generation to mining and urban water uses, and from irrigated agriculture to freight transportation. Rainfall variability is high, groundwater resources are limited, and recurrent droughts affect water uses in the basin. Water quality concerns include pollution from untreated wastewater, agrochemicals, and heavy metals from industry and mining as well as soil erosion.

*Each timeline is indicative, and not exhaustive. Major elements have been selected based on expert consultations to depict broad patterns of water-related risks, opportunities and investments. The schematic below features additional elements essential to the pathway, conveying a cycle of challenges and responses unique to **the São Francisco River Basin.***





Cities

Even if they share common features, each of the large cities in this study has followed a distinct pathway. Singapore, Mexico City, and Gauteng Province in South Africa (which comprises Johannesburg and Pretoria) illustrate contrasting pathways in three rapidly developing regions.

Singapore exemplifies a sustained and strategic effort to develop domestic water sources, increase water use efficiency, and reduce dependence on imported water supplies. The Gauteng Province of South Africa lacks local water supplies, which has prompted a century-long water resource development effort to deliver sustainable water services for the conurbation – first in response to gold mining opportunities and now to address inequality of access in the post-Apartheid era. Mexico City is one of the largest groundwater-dependent cities in the world; it illustrates a combination of chronic impacts and shocks, creating windows for institutional reform and capital investment. Each pathway illustrates major features of the triggers, types, and sequences of investments.

Singapore: a sophisticated approach to achieving water security

Singapore is a highly urbanized city-state with an area of 18.3 km^2 and the third highest population density in the world. Although Singapore's annual rainfall of 2,400mm is well above the global average of 1,050mm, it is not sufficient to provide water to a population of 5.4 million people and industry, commercial, and landscaping sectors that require 55 percent of a mixture of potable water, NEWater (high-grade recycled wastewater), and industrial water. Established in 1963 under the Prime Minister's Office, the Public Utilities Board (PUB) was initially responsible for electricity, water, and piped gas. It was established as the National Water Authority in 2001, relinquishing its other utility responsibilities and taking over those of sewerage and drainage.

Triggers and Sequencing

Prior to independence from Malaysia in 1965, when it had a much smaller population, Singapore supplied its water through three reservoirs in its own territory and transfers via pipeline from Malaysia. The 1961 transfer agreement with Malaysia expired in 2011, and the 1962 agreement will expire in 2061 (Figure 42 traces the interplay of risks, opportunities and investments). Singapore's limited capacity to capture and store rainwater and its historical dependence on transboundary water transfers triggered a major, long-term strategy to explore the options for self-sufficiency, while retaining the option for continuing to import water, if necessary, at a reasonable price.

Although water self-sufficiency may be technically achievable, there will be trade-offs between self sufficiency and affordability, even in a prosperous state. Singapore's long-term strategy for achieving affordable water security has meant developing an integrated portfolio of approaches that focuses on long-term planning, promoting policy, management, and technology innovation and retaining flexibility for the future.[22] The starting points are maximizing the use of rainfall on the island, managing per capita demand, and developing infrastructure and unconventional sources of water. Runoff from two-thirds of the island's area is captured, and the PUB hopes to extend this to 90 percent of the island's area by 2060. This work has been accompanied by vigorous source protection, for example, by implementing strict regulations to limit contamination in urban areas and from industry. Leakage from the supply system averages 4.5 percent, which is exceptionally low for an urban water supply. Meanwhile, per capita demand has been managed through a combination of pricing, water efficiency measures, and public education, with an increasing block tariff structure penalising excessive domestic use. These policies have led to a drop in domestic demand from 176 l/cap/day in 1994 to 151 l/cap/day in 2014.

22 *Tortajada et al. (2013).*

Elements of the pathway

Singapore has taken a long-term and integrated approach to water resources management. The strategic direction was set at independence and has been implemented through sustained investment in water institutions, infrastructure, and information.

The PUB has overall responsibility for the water resources system, and use of sustainable water resources has been embedded in land-use legislation and building regulations. The infrastructure system has been developed with staged investments and progressively integrated to enable efficient management of the resources. The PUB has promoted policy and management (e.g., catchment management), institutional (e.g., tariff structure), technological (e.g., NEWater and desalination), and institutional (e.g., tariff structure) innovations. The first desalination plant was constructed at Tuas in 2005, and a second, larger plant opened in 2013 in the same location; yet, desalination is more costly than wastewater treatment and reuse, in which Singapore has become a pioneer globally. Re-used water, which is known as NEWater in Singapore, has been controversial worldwide, and suffers from the risk of public unacceptability. Singapore managed this risk by developing the technology over a period of decades and progressively raising public awareness. The first experimental reuse plant was closed in 1975 because it proved to be uneconomical and unreliable. A new plant was completed in 2000, and water quality was monitored over a period of two years, when an expert panel approved the water for use in the public supply. At present, NEWater is able to cover up to 30 percent of the water demand of the city-state.

Looking forward, population, urbanization, industrial growth, and overall development continue to challenge Singapore's water security objectives. In the face of uncertainties regarding energy prices, societal expectations and attitudes, climate change, and international relations, Singapore has adopted a diversified approach. Although a least-cost approach would suggest an emphasis on surface water and NEWater, Singapore has preserved the option to adopt new technologies that may become more cost-effective in the future, such as low-energy desalination by freezing (using liquefied natural gas regasification as a heat sink), energy recovery from brine streams, increasing energy and water recovery from NEWater, and exploring groundwater sources. Singapore has diversified its approach while managing public concerns about the safety of recycled water for human consumption. This has also involved a long-term strategic approach that links investment in information (knowledge and public communications), institutions, and infrastructure. Facing a future that is uncertain in significant respects, Singapore's strategic approach includes the sophisticated analysis of uncertainties and options for managing future risks.

Mexico City: urban water security in a groundwater-dependent city – a national priority

The Mexico City Metropolitan Area (MCMA) is located in the Valley of Mexico (almost 10,000 km^2) where the pathway to water security can be traced prior to the Aztec period and the use of chinampa farming techniques (artificial islands on shallow lakebeds) to support a growing urban population. Today, the MCMA is home to over 21 million people and it generates about 30 percent of Mexico's GDP[23] – making it of great national and regional economic importance. The modern pathway to water security depends heavily on groundwater development, which accounts for about 68 percent of the valley's water supply. Groundwater withdrawals exceed recharge rates with an annual deficit of 713 Mm^3/yr, and the resulting land subsidence damages municipal infrastructure and increases losses and leakages.

Urban water security within the MCMA also requires infrastructure and organizational capacity to deliver water supply and sanitation services to a growing metro area, which has rapidly expanded by about 500 percent in both area and population between 1950 and 2000. Access to potable water and sanitation has improved but coverage remains incomplete at about 92 and 94 percent respectively. Water-

23 *In this case it is Mexico's 'producto interno bruto manufacturero del país' or GDP of the manufacturing sector.*

related hazards include climate variability, with urban flooding and the drought impacts on surface water sources. The economic costs of deficiencies in water services have been estimated at almost US$2 billion annually, approximately 1 percent of GDP in the Valley.[24]

Triggers and sequencing

In the face of these chronic pressures, the combination of natural hazards, rapid population growth, and political changes have produced policy and planning windows for reform (Figure 43 traces these reforms and the interplay of risks, opportunities and investments). Drought in the 1960s, major flooding in 1967, an earthquake in the 1980s, political changes associated with the Salinas presidency in 1988, and economic crises, have all been triggers for investment and influences on the water security pathway. Major crises appear to have recurred on a 20- to 25-year cycle, which has led to an opportunity: plan with purpose, be ready for a crisis, and then act. The MCMA has adopted proactive planning to reduce the impacts of crises; and to seize the opportunities during crises, to coordinate investments in water security in line with national and regional development priorities.

Elements of the pathway

After the Mexican Revolution in the early twentieth century, the problem of food security prompted institutional development with the creation of the national commission for irrigation, which gave way to the Ministry of Water in 1946. Initial plans were adopted for importing water supply to the MCMA from two interbasin transfers from the Lerma and Cutzamala systems of 151 and 464 Mm^3/yr, respectively. In 1976, the Ministry of Agriculture annexed the Water Ministry, fragmenting authority over water. However, the national government initiated a water-planning programme in 1972, which laid the foundation for a comprehensive programme that took effect when the Salinas administration took office in 1988. During this political transition, water services were at the top of the political agenda due to problems of reliability, equality of access, conflicts, and scarcity.

24 *CONAGUA and World Bank (2013).*

Planning conducted from the early 1970s identified the need for a comprehensive approach to water development, which culminated in the creation of the national water agency (CONAGUA) in 1989. The 1992 National Water Law and 2004 amendments have promoted decentralization, resulting in the building of local capacity, and private sector participation in water services. As part of these efforts, the groundwater challenges have been addressed by the National Water Commission of Mexico, with participation of River Basin Councils and their auxiliary bodies, such as the Technical Groundwater Committee (COTAS), which promotes participation of watershed stakeholders. River basin councils and their auxiliary bodies are still work in progress.

Water supply and sanitation services are a municipal responsibility governed by 23 municipal operators in the Valley of Mexico, and the Mexico City Water System (Sistema de Aguas de la Ciudad México 'SACM' within the federal district portion of the MCMA). Few of these operators perform well. Initially, local governments were opposed to private participation and water tariff reviews. Efforts to improve services have now included private participation in water provision in several Mexican cities, with success stories in Aguascalientes, Cancún, and Saltillo, despite the mixed success in the MCMA.

The modern pathway to water security in the MCMA highlights the need to consider the water security of cities as part of the national development agenda, with the fate of Mexico City directly linked to that of the country, due to the major infrastructure and economic linkages between the MCMA and the surrounding region. Urban water security, delivering water supply and sanitation services, remains a major challenge. Groundwater dependence has enabled urban growth, but also poses risks from subsidence and unreliable or costly extraction.

In a context of chronic stresses and periodic crises, the MCMA has sought to plan with purpose so as to be ready to act, rather than wait for crises. This allows the steady development of ideas and the opportunity to promote these ideas before policy, planning, and investment windows open. The case study highlights that people are at the heart of both problems and solutions. People who have experience and institutional knowledge must build new capacity; regulations are not a substitute for the experience that ensures that information, institutions, and infrastructure will be coordinated to deliver urban water security.

Gauteng Province: water resource security underpins sustainable water services

First colonized at the beginning of the nineteenth century, South Africa's Gauteng Province, including the cities of Johannesburg and Pretoria, is the highly urbanized core of a larger economic zone encompassing the rich goldfields that attracted settlement and economic development to the region in the nineteenth century.

Gauteng is the smallest of South Africa's nine provinces, yet the most populous and wealthy – accounting for 60 percent of national GDP. Although situated on the Witwatersrand, the watershed between two major river systems, Gauteng's achievement of water security shows how centres of economic growth can interact effectively with their surrounding urban and rural regions, even across multiple river basins and national borders, to manage and develop water resources for sustainable water services.

Triggers and sequencing

The region was transformed by the discovery, in 1884, of large gold reserves, triggering a gold 'rush' and the need for water supplies for mining and an expanding population. The aggregation of economic activity and the location of the administrative capital (Pretoria) of the newly established Union of South Africa in 1910 has seen Gauteng grow into a global city-region with a population approaching 13 million, dependent on a high degree of water security for its sustainability. Water supply to the region, initially derived from a few private springs serving a few thousand people in temporary mining communities, progressed through the development of the Vaal (a tributary of the Orange-Sengu River) to today's 'Vaal system' that inter-links the resources of four major river systems (the Orange, Limpopo, Thukela and Inco Maputo), three of which are international.

Climate variability and water demand have necessitated extensive storage and transmission infrastructure, designed and operated to achieve reliability levels of 99.5 percent for power, and 98 percent for urban water supplies. Ninety-seven percent of the Province's population has access to a safe water supply although human settlement and industry affect water quality, with old mines adding 15-20 percent to the salt loads in the Vaal River. The post-Apartheid period has created the political imperative for investment in water services for black communities and informal settlements to enhance equity of access (Figure 44 traces the interplay of risks, opportunities, and investments).

Elements of the pathway

The Vaal system includes major investments in infrastructure, with large storage and inter-basin transfers, including energy-saving diversions from neighbouring Lesotho, and now integrates wastewater streams that support neighbouring areas. While local works were built by the Rand Water Board (a regional utility, established in 1903), the infrastructure of the wider system was built and managed by the national government department responsible for water matters.[25] Today, Rand Water draws 'raw' water from the system, which it treats and distributes to the region's municipalities and industries both inside and beyond the province.

Much of the infrastructure created by the national government and Rand Water was funded by charges levied on major users, with recent infrastructure developments, such as the Lesotho Highlands Water Project (LHWP), entirely paid for by user charges. For the past four decades, the Vaal system has been extensively modelled, with annual reviews of performance, resource availability, and demand trends, which are used to schedule investments – an exercise conducted collaboratively with major water users. The last major augmentation in supply, LHWP Phase 1B, was completed in 2003 in accordance with a 1986 Treaty between Lesotho and South Africa; Phase 2 is currently a

25 *Tempelhoff (2003).*

few years behind schedule, putting the system's reliability targets at risk if a drought greater than 1-in-50-years severity occurs before 2024.

The keys to the region's sustained water security include (1) effective monitoring and management of growing demand, (2) timely planning, implementation and operation of infrastructure investments, with involvement of and funding by the users and (3) improvement of water quality through effective monitoring and management. These investments in information, institutions and infrastructure have underpinned the region's water security, enabling provision of basic water services as well as sustained economic growth.[26]

A further contribution to this water security is that water resources and their management are under the control of national government.[27] This has enabled timely investments across a wide geographic area without prolonged negotiations between different administrations, a challenge that has typically undermined water security in other metropolitan areas. The focus on the needs of user sectors rather than on river basin or sub-national jurisdictions has also been critical for success, allowing the system's boundaries to be expanded to meet the needs of expanding populations and economic activities. The availability of adequate public and private investment at an early stage has been critical to the establishment of the infrastructural base. The economic activity supported now allows new infrastructure to be financed by users, through utility structures that can access market finance.

Future water security will require an intensification of water management, strengthening of management institutions and continued engagement with key water users. The expansion of the inter-connected system will pose complex risks, and water quality management will increase in importance. Having a very interconnected system reduces risk in a variable climate and may improve the climate resilience of the system, since there is no dependence on just one catchment. The availability of human resources to undertake these tasks is perhaps the major medium-term risk facing the region.

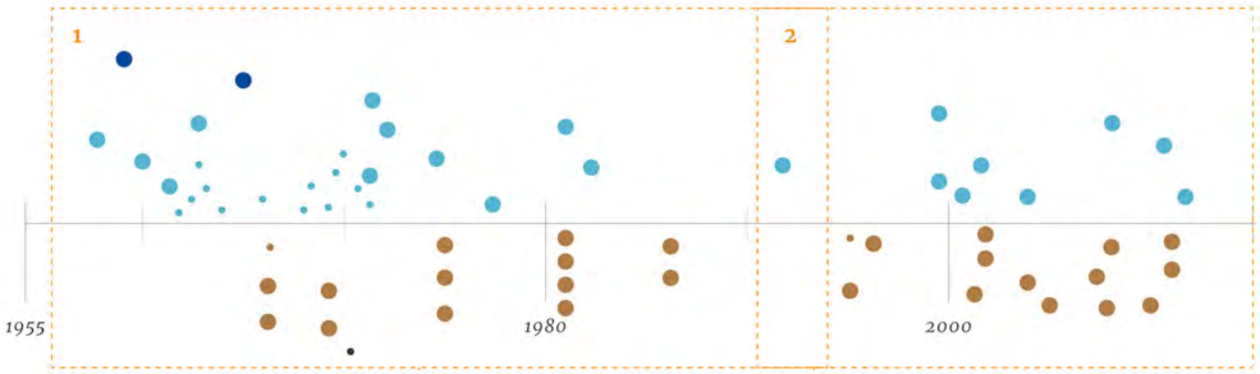
26 *Eales and Schreiner (2008).*

27 *Muller (2012).*

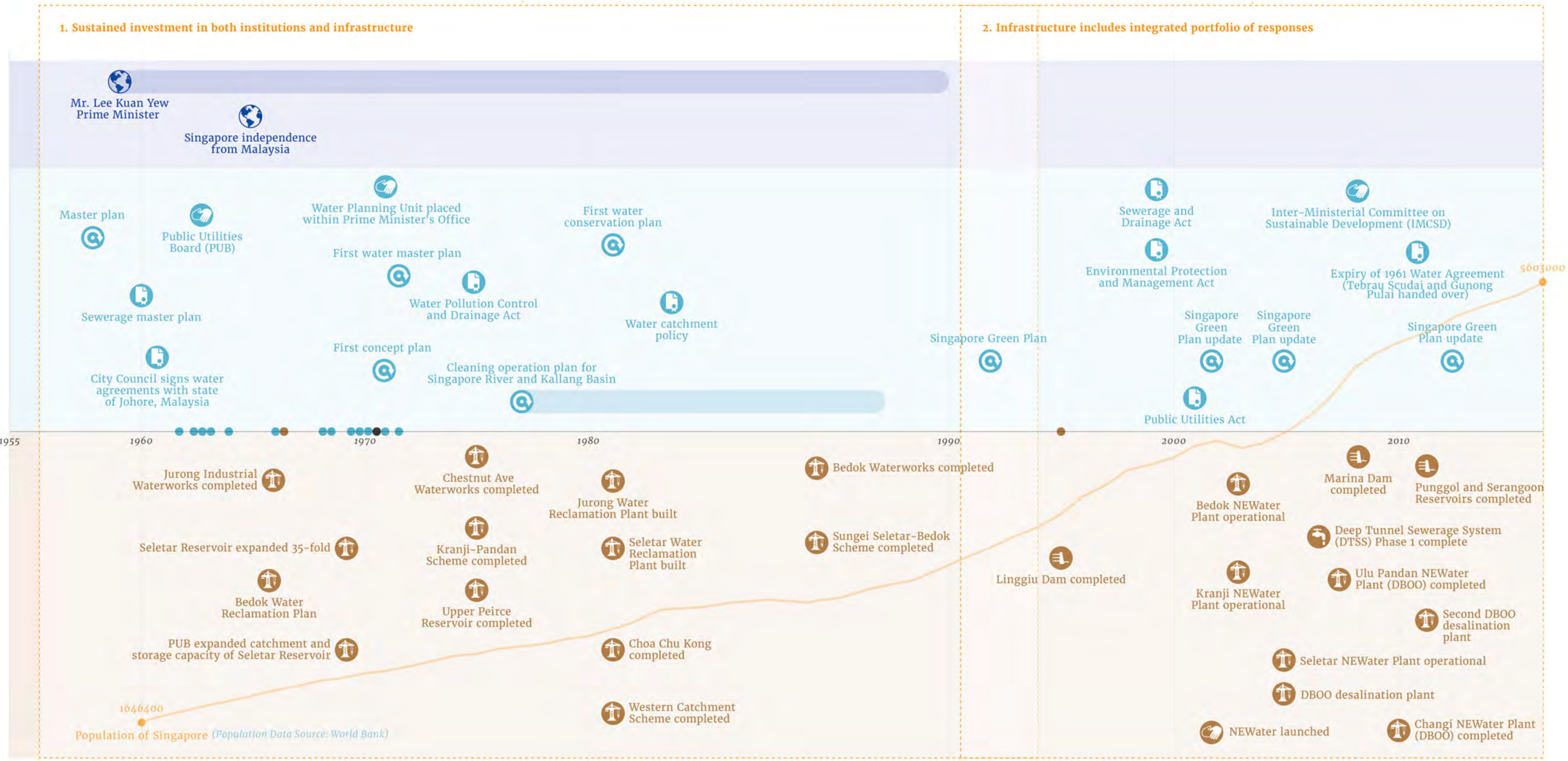
Singapore *(Fig 42)*

Singapore is a highly urbanized city-state with an area of 718.3 km² and the third highest population density in the world. Although Singapore's annual rainfall of 2,400mm is well above the global average of 1,050mm, it is not sufficient to provide water to a population of 5.4 million people and industry, commercial and landscaping sectors that require 55 percent of a mixture of potable water, NEWater (high-grade recycled wastewater) and industrial water. Established in 1963 under the Prime Minister's office, the Public Utilities Board (PUB) was initially responsible for electricity, water, and piped gas. It was established as the National Water Authority in 2001, relinquishing its other utility responsibilities and taking over those of sewerage and drainage.

*Each timeline is indicative, and not exhaustive. Major elements have been selected based on expert consultations to depict broad patterns of water-related risks, opportunities and investments. The schematic below features additional elements essential to the pathway, conveying a cycle of challenges and responses unique to **Singapore**.*



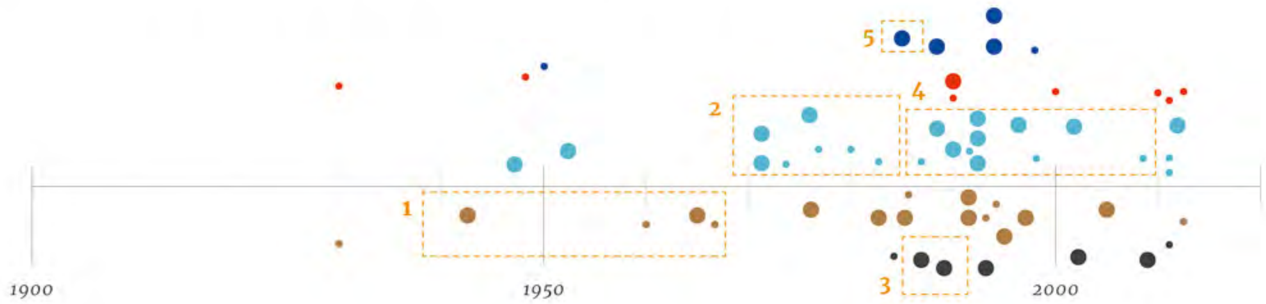
← Before 1950 MacRitchie, Seletar, Peirce reservoirs built on ad hoc basis

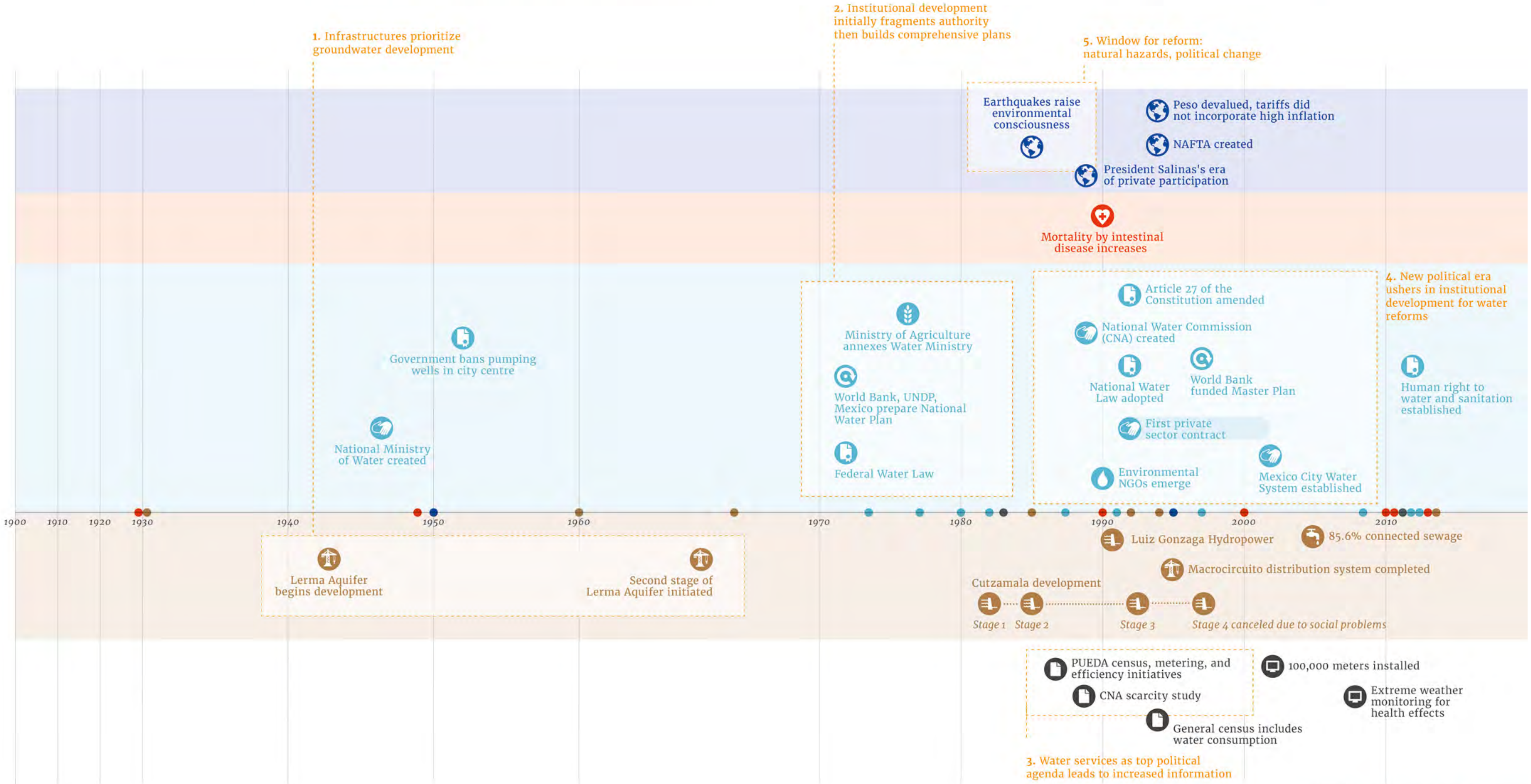


Mexico City *(Fig 43)*

The Mexico City Metropolitan Area (MCMA) is located in the Valley of Mexico (almost ten thousand km²) where the pathway to water security can be traced prior to the Aztec period and the use of chinampa farming techniques (artificial islands on shallow lakebeds) to support a growing urban population. Today, the MCMA is home to over 21 million people and it generates about 30 percent of Mexico's GDP – making it of great national and regional economic importance. The modern pathway to water security depends heavily on groundwater development, which accounts for about 68 percent of the valley's water supply. Groundwater withdrawals exceed recharge rates with an annual deficit of 713 Mm³/yr, and the resulting land subsidence damages municipal infrastructure and increases losses and leakages.

Each timeline is indicative, and not exhaustive. Major elements have been selected based on expert consultations to depict broad patterns of water-related risks, opportunities and investments. The schematic below features additional elements essential to the pathway, conveying a cycle of challenges and responses unique to ***Mexico City.***



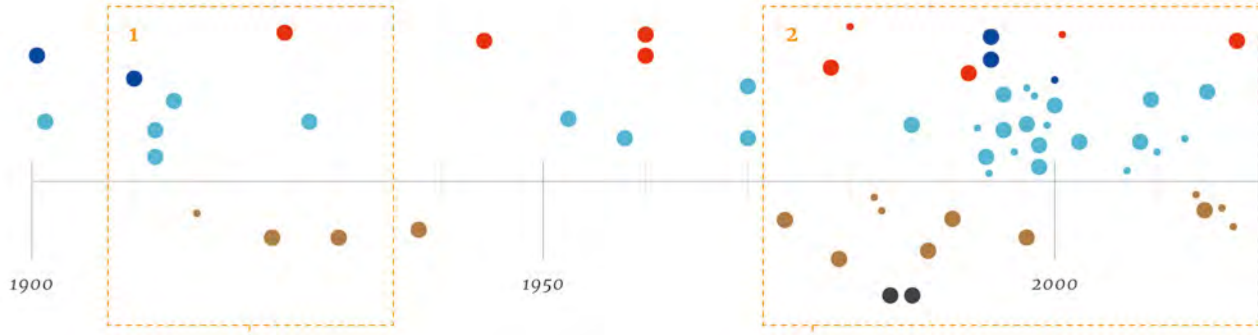


NAFTA (North American Free Trade Agreement)

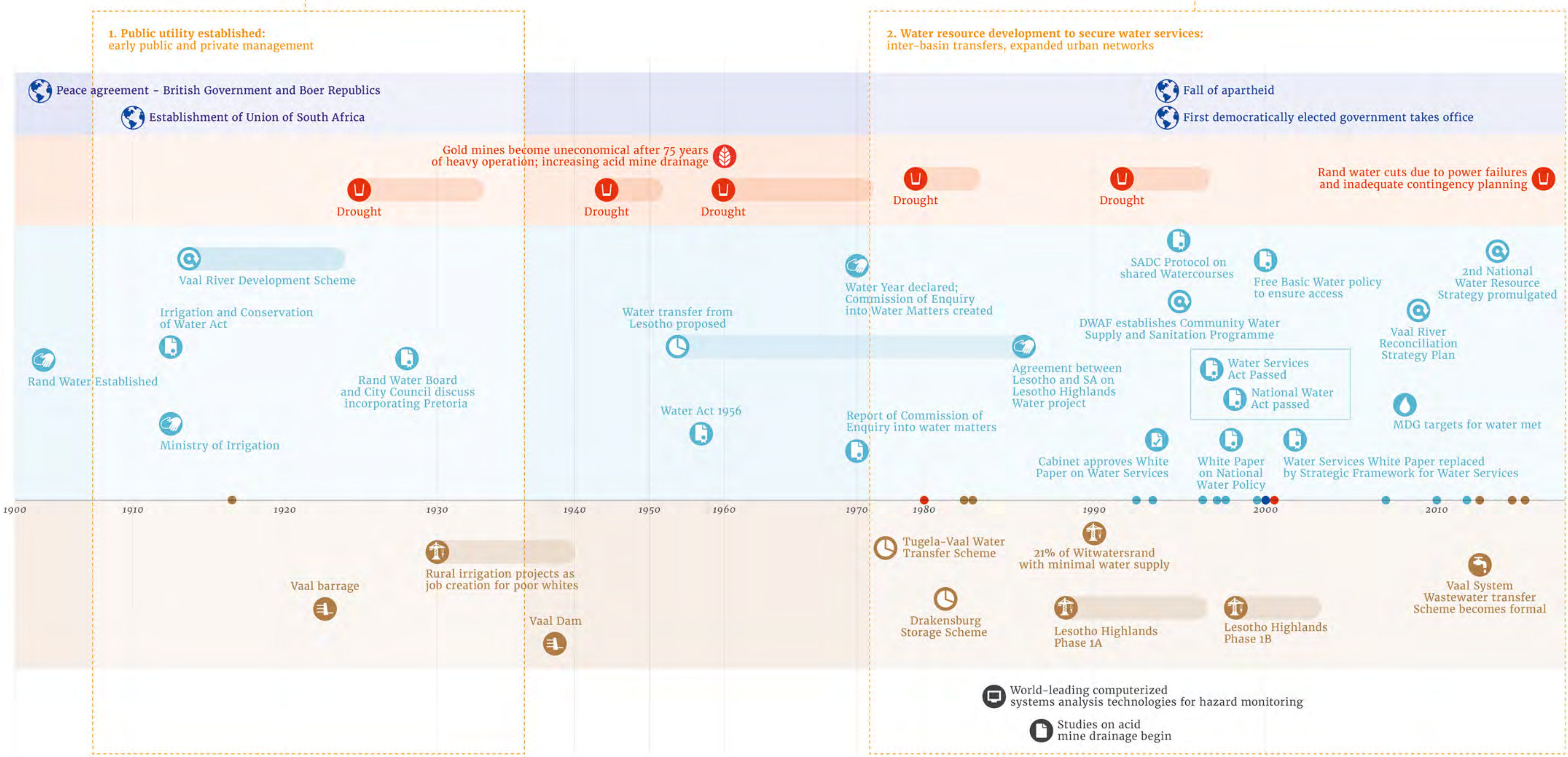
Gauteng *(Fig 44)*

First colonized at the beginning of the nineteenth century, South Africa's Gauteng Province, including the cities of Johannesburg and Pretoria, is the highly urbanized core of a larger economic zone encompassing the rich goldfields that attracted settlement and economic development to the region in the nineteenth century. Gauteng is the smallest of South Africa's nine provinces, yet the most populous and wealthy – accounting for 60 percent of national GDP. Although situated on the Witwatersrand, the watershed between two major river systems, Gauteng's achievement of water security shows how centres of economic growth can interact effectively with their surrounding urban and rural regions, even across multiple river basins and national borders, to manage and develop water resources for sustainable water services.

*Each timeline is indicative, and not exhaustive. Major elements have been selected based on expert consultations to depict broad patterns of water-related risks, opportunities and investments. The schematic below features additional elements essential to the pathway, conveying a cycle of challenges and responses unique to **Gauteng Province.***



Current and future challenges:
97% of Gauteng's population (13 million) have access to safe water



DWAF (Department of Water Affairs and Forestry); MDG (Millennium Development Goals); SADC (Southern African Development Community).

Aquifers

Aquifers offer an opportunity that is not widely recognized in the current debates on water security, which is their very large and relatively resilient storage capacity (Box 10). Groundwater already makes a key contribution to water security in many regions of the world.

Effective groundwater management and development require a sound knowledge of the resource and robust institutional mechanisms, to ensure that groundwater dependence does not become a source of insecurity over time due to overdraft or pollution. The case studies presented in this section are both large transboundary aquifer systems, where groundwater exploitation has been triggered by different pressures and followed different paths. The Guaraní Aquifer System (shared by Argentina, Brazil, Paraguay and Uruguay) is located in a region endowed with abundant but often polluted surface water. Groundwater development is growing locally to meet increasing water demands by a variety of sectors, including domestic supply, geothermal uses, and incipient irrigation. The Nubian Sandstone Aquifer System (shared by Chad, Egypt, Libya and Sudan) is the only water resource available for the development of the oil industry and agriculture in the Libyan desert. The future of groundwater exploitation here, however, faces major uncertainty because the abstracted resource is non-renewable.[28] In both aquifer systems, major international efforts have been made to establish a framework for transboundary cooperation, to pre-empt possible disputes over the shared groundwater resource.

28 *Non-renewable groundwater includes fossil groundwater that has accumulated over geologic time, and therefore is not replenished over human timescales.*

The Guaraní Aquifer System: a lightly-exploited aquifer with precautionary transboundary cooperation

The Guaraní Aquifer System (GAS) has only been developed very locally for municipal water supply systems in parts of Brazil, Uruguay, and Paraguay for about 50 years. It was first recognized as a single, massive groundwater system during deep geological exploration for hydrocarbons in the 1990s.[29] The GAS underlies an area of over 1 million km^2 mainly in the Paraná River Basin of Brazil (62 percent of its known area), Paraguay, Uruguay, and Argentina. It stores an estimated 30,000 km^3 of mainly high quality water. Groundwater extraction is estimated to be only about 1 km^3/yr (about 80 percent of which currently occurs in Sao Paulo State, Brazil), for public water supply (80 percent), industrial processes (15 percent) and geothermal uses for spa facilities and industrial processes where hot groundwater occurs (5 percent), with groundwater-irrigated agriculture an incipient activity. In São Paulo State there are many wells extracting water from the deep confined areas, usually for public water supply of medium-sized cities (100,000-300,000 inhabitants).

Triggers and sequencing

The GAS is an example of a large transboundary groundwater system with vast storage (stocks) and significant flows (flux) but limited development and demand for groundwater. The area occupied by the aquifer has plentiful surface water resources and experiences drought occasionally. There have therefore been few triggers for development in the Guarani. In contrast to many other aquifers, groundwater exploitation has primarily been driven by public and industrial water supply needs, and not by irrigated agriculture, because of its high quality water and drought reliability, compared to local surface water.

29 *Foster et al. (2009).*

Aquifers as vast freshwater reservoirs: using groundwater storage for water security *(Box 10)*

Extensive aquifers can have much more water in storage than the world's largest surface reservoirs. Groundwater systems constitute the planet's predominant freshwater reserve. All aquifer storage buffers rainfall-related inputs, transforming highly variable recharge into more constant discharge. Groundwater in large aquifer systems has long residence and response times, greatly increasing water security, as storage can offset the impacts of scarcity and drought.[28] Given the role of water storage in water security, groundwater plays a fundamental role and must be taken into account. Examples of the role that groundwater storage plays include:

- the alluvial aquifer underlying Lima, Peru, developed conjunctively with surface-water for water supply in a hyper-arid area
- the alluvial aquifer of the Indian Punjab used for intensive irrigation, securing high grain yields irrespective of monsoon rainfall.

Aquifers vary with geology and are not uniformly present in the subsurface. Aquifer recharge varies considerably with land use and vegetation cover (notably irrigated agriculture) and with urbanization processes (notably water-main leakage and on-site sanitation). Excess infiltration can cause rising water-tables and waterlogging, damaging urban infrastructure and reducing crop yields.

Groundwater resilience varies by aquifer type. The 'resilience' of water-resource systems to climate variability and change is now being applied to groundwater systems. Two scenarios need to be considered: resilience to long-term (inter-decadal) 'climate change' and to shorter-term (inter-annual) 'climate shocks'.[29] Large sedimentary formations in what are today more arid climatic regions usually contain groundwater recharged long ago (and may be essentially a non-renewable or 'fossil' resource). All such groundwater can be regarded as highly resilient to current climate variability. In contrast, groundwater in lower-storage aquifers is more dependent on modern recharge and, therefore, less resilient to long-term climate change – but even these often have sufficient residence times to buffer short-term climatic variations. However, some groundwater systems (for example, shallow alluvial and karstic limestone formations) can have rapid connection with overlying surface water, and their storage does not contribute significantly to water security in drought.

Managed aquifer recharge and storage is an innovative solution. Excess wet-season and flood flows can increase groundwater in storage by recharging aquifers in different ways, for example:

- management measures on agricultural land to recharge groundwater over large land areas for water supply
- recharge structures (wells, lagoons) to inject water for later recovery from wellfields, for urban water supply.

Natural groundwater storage can also be enhanced through conjunctive use with surface water for urban or irrigation supply, resulting in higher water supply volumes and associated water security than depending on a single source.

Good groundwater governance and management are essential if groundwater is to improve urban and irrigation water security, and to avoid serious depletion and pollution and associated irreversible degradation. This will include:

- real-time monitoring of groundwater withdrawals, levels, and quality as the basis for adaptive management
- innovative approaches to regulate groundwater abstraction and use, in coordination with power consumption
- stakeholder engagement in financial and regulatory matters
- alignment of fiscal provisions to become an incentive for sustainable use
- regulatory provisions to constrain point-source pollution and diffuse agriculture pollution.

30 *Foster et al. (2013).*

31 *Foster and MacDonald (2014).*

Groundwater quality is generally high, although pollution poses local challenges. Urban centres tap the Guarani mainly due to its high quality water compared to local surface water. Development of groundwater resources for public water supply has been promoted by municipalities and state government agencies in Brazil, and by central government in Uruguay and Paraguay (Figure 45 traces this evolution and interplay of risks, opportunities and investments).

Whilst natural groundwater quality is high, in its outcrop recharge areas, the aquifer is vulnerable to pollution from inadequate disposal of urban wastewater and solid waste and the intensification of agriculture. However, these issues are local and availability of water is not a limitation. The aquifer still has a large development potential, constrained by the relatively high cost of drilling wells. In the absence of clear triggers for investment, the management of the GAS has involved pre-emptive efforts to establish a transboundary cooperation framework to study the aquifer before pressures mount.

Elements of the pathway

The aquifer has only been subjected to intensive exploitation locally around a few urban centres – most notably in north-eastern São Paulo State. As a consequence, groundwater levels in Ribeirão Preto have fallen by an estimated 30-40 m since 1970, with a consequent increase in water supply costs and degradation of local watercourses, where natural groundwater discharge has been replaced by wastewater discharge.

The GAS has also recently been considered for supplying the Piracicaba-Campinas region (São Paulo State) with water from a large well field (1m^3/s), as a strategy to alleviate the water crisis in the Metropolitan Region of São Paulo. Geothermal use for the tourism sector is promoted by the private sector, but in some cases also receives financial support from the public sector because of tourism's importance for employment.

Groundwater use for irrigation is limited due to reliable rainfall and the high cost of developing groundwater for the occasional droughts, although this might grow with climate change. There is a gradual increase in groundwater used for irrigation to secure citrus yields, to increase water supply for the sugar-alcohol industry in São Paulo State, and to provide supplementary irrigation for soybeans in the southwest of Rio Grande do Sul State.

The four 'Guaraní countries' have opted for precautionary cooperation, pre-empting possible problems arising from future groundwater development. This cooperation is both on technical and legal aspects, with a legal framework for the management and protection of groundwater resources and culminated in 2010 with the signing of the Guarani Aquifer Agreement. This Agreement creates a legal framework for future cooperation, although it has yet to be ratified by the Brazilian and Paraguayan governments. However, there is a good understanding of the aquifer system, due to a Global Environment Facility (GEF) supported Strategic Action Program for the Guarani Aquifer during 2003-2009, which catalyzed national efforts in data collection and pilot management. At the local level, however, detailed knowledge is patchy and understanding of the impact of rapidly occurring land-use change is very limited. The main challenge now will be to implement the 2010 Agreement, and, in particular in Brazil (where groundwater use is expanding), to ensure increased human and financial resources in some of the key state water agencies. To date, there have been very few transboundary disputes related to groundwater use, and good cooperation was achieved in two pilot transboundary management projects in the GEF Program.

Nubian Sandstone Aquifer System

The Nubian Sandstone Aquifer System (NSAS) is the largest groundwater system in the world, stretching over 2 million km^2 across Chad, Egypt, Libya, and Sudan. Northern Libya has been an important agricultural region depending on groundwater from Roman times to the twentieth century. Today, the NSAS is mostly exploited in Libya, which relies almost exclusively on the NSAS for water supply.

Although relying mainly on the Nile, Egypt also taps the NSAS, while groundwater development in Chad and Sudan is still limited. The NSAS challenge is its long-term viability, as it overwhelmingly comprises 'fossil' palaeowater that was recharged tens of thousands of years ago with naturally declining water levels since the last glacial period. Due to the magnitude of aquifer reserves, there is limited room for development, although the depletion of storage, potential risks of increasing salinity, falling water levels, and associated damage to or loss of oasis ecosystems will all need to be managed.

Triggers and sequencing

Oil exploration drilling in the early 1960s led to modern discovery of major fresh groundwater reserves in the NSAS (Figure 46 traces the interplay of risks, opportunities and investments). The initial trigger for NSAS development was to meet the needs of the petroleum industry, as in the desert groundwater is the only possible water source for petroleum recovery. The petroleum industry supported aquifer analysis and exploitation, creating dependence on foreign technology and expertise. Since then, groundwater development in all NSAS countries has been led by central government, to provide water for domestic supply and for economic activities (the oil industry, mining and irrigation).

Elements of the pathway

Traditionally in Libya, there has been low-intensity exploitation of groundwater in oases, directly from springs or from shallow wells, which still support a variety of local needs of settled agriculturalists and nomadic herders. Since the 1960s, groundwater use has intensified with the construction of well fields whose wells are equipped with high-capacity pumps to meet the needs of petroleum-related industry, domestic water supply, and mining. Petroleum development has also provided the economic resources needed to build large-scale irrigation projects both in oasis and coastal areas. However, the NSAS is also vulnerable to water quality deterioration due to inadequate treatment of petroleum industry wastes and domestic wastewater.

Irrigation along the Mediterranean coast received a substantial boost with the so-called Great Man Made River Project (GMMRP), whose implementation by the Libyan government started in the 1980s. The GMMRP comprises major infrastructure to pump groundwater from the NSAS in the Sahara desert in the south and pipe it to the northern coastal areas, where most of the population is concentrated, and where traditionally-irrigated agriculture has water supply problems due to local groundwater exhaustion and salinization. Groundwater from the NSAS has ensured a water supply of excellent quality for urban centres on the Libyan coast, but this supply is still affected by failures in the distribution system and inadequate wastewater management.

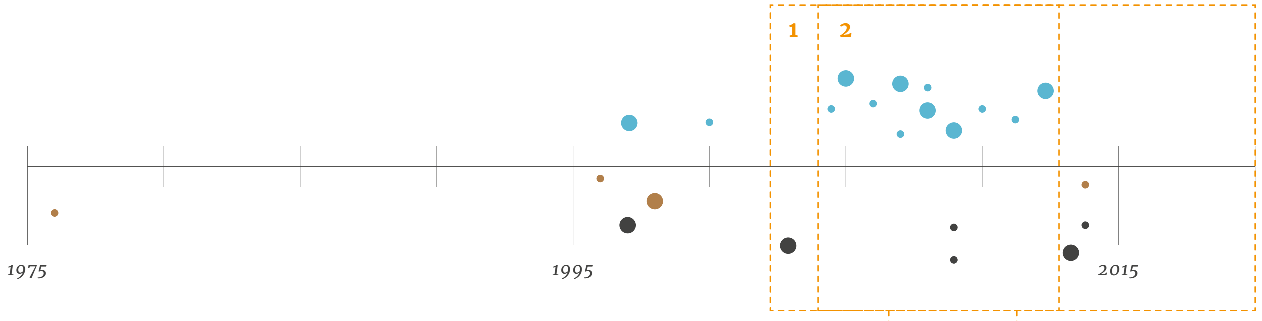
In the 1960s and 1970s foreign research agencies assessed aquifer dynamics, established its non-renewability, and considered its exploitation potential. Since the 1980s, international and regional agencies have acted as catalysts for knowledge generation and cooperation. One of the many achievements was the establishment of a programme for formulating a regional NSAS development strategy and a regional monitoring programme (Nubian Aquifer Regional Information System, NARIS) in 1997. Several international studies and initiatives have also paved the way for transboundary management. While there are regional NSAS monitoring networks and models, the spatial and temporal coverage of data collection is patchy, as is local technical capacity.

The two main Libyan government agencies managing groundwater use are the General Water Authority (1972), and the Great Man Made River Authority (1983). There is current instability within the water management structure, due to civil strife, leading to supply disruption and problems of maintenance. At a transboundary level, the Joint Authority for the Study and Development of the Nubian Sandstone Aquifer System was established by Egypt and Libya in 1989, later joined by Sudan (1996) and Chad (1999). Problems associated with groundwater abstraction (aquifer depletion, quality problems, ecosystem degradation), while occurring across the NSAS, rarely involve international borders.

Guaraní *(Fig 45)*

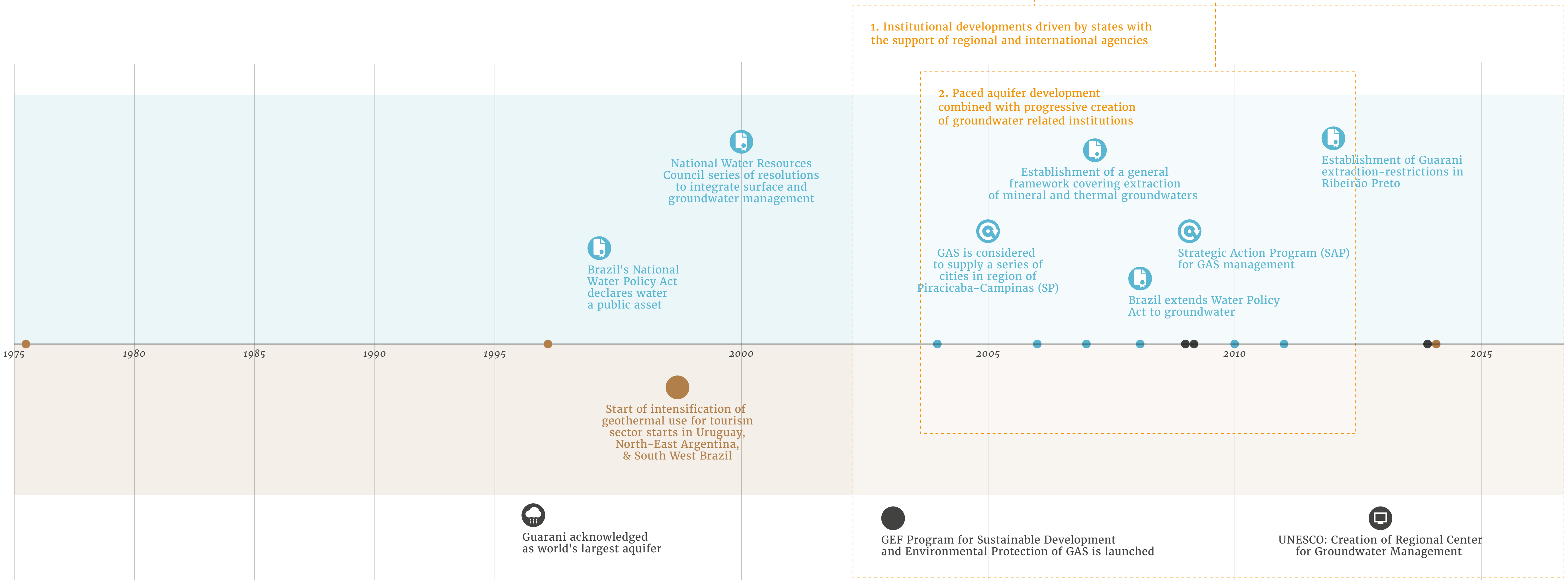
The Guaraní Aquifer System (GAS) has only been developed very locally for municipal water supply systems in parts of Brazil, Uruguay, and Paraguay for about 50 years. It was first recognised as a single, massive groundwater system during deep geological exploration for hydrocarbons in the 1990s. The GAS underlies an area of over 1 million km² mainly in the Paraná River Basin of Brazil (62 percent of its known area), Paraguay, Uruguay, and Argentina. It stores an estimated 30,000 km³ of mainly high-quality water. Groundwater extraction is estimated to be only about 1 km³/yr (about 80 percent of which currently occurs in Sao Paulo state, Brazil), for public water supply (80 percent), industrial processes (15 percent), and geothermal uses for spa facilities and industrial processes where hot groundwater occurs (5 percent), with groundwater-irrigated agriculture an incipient activity. In São Paulo state there are many wells extracting water from the deep confined areas, usually for public water supply of medium-sized cities (100,000-300,000 inhabitants).

Each timeline is indicative, and not exhaustive. Major elements have been selected based on expert consultations to depict broad patterns of water-related risks, opportunities and investments. The schematic below features additional elements essential to the pathway, conveying a cycle of challenges and responses unique to ***the Guaraní Aquifer System.***



Current:
The GAS is still lightly developed and overdraft and pollution problems so far are felt mainly only close to some water use hotspots (e.g., cities).

Future:
In the future challenges could come from already increasing water demand from urban users, irrigation, and geothermal development, as well as higher surface water variability due to climate change.

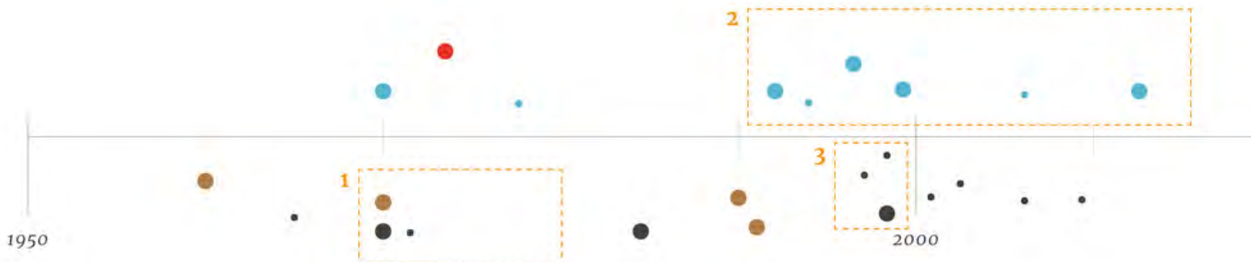


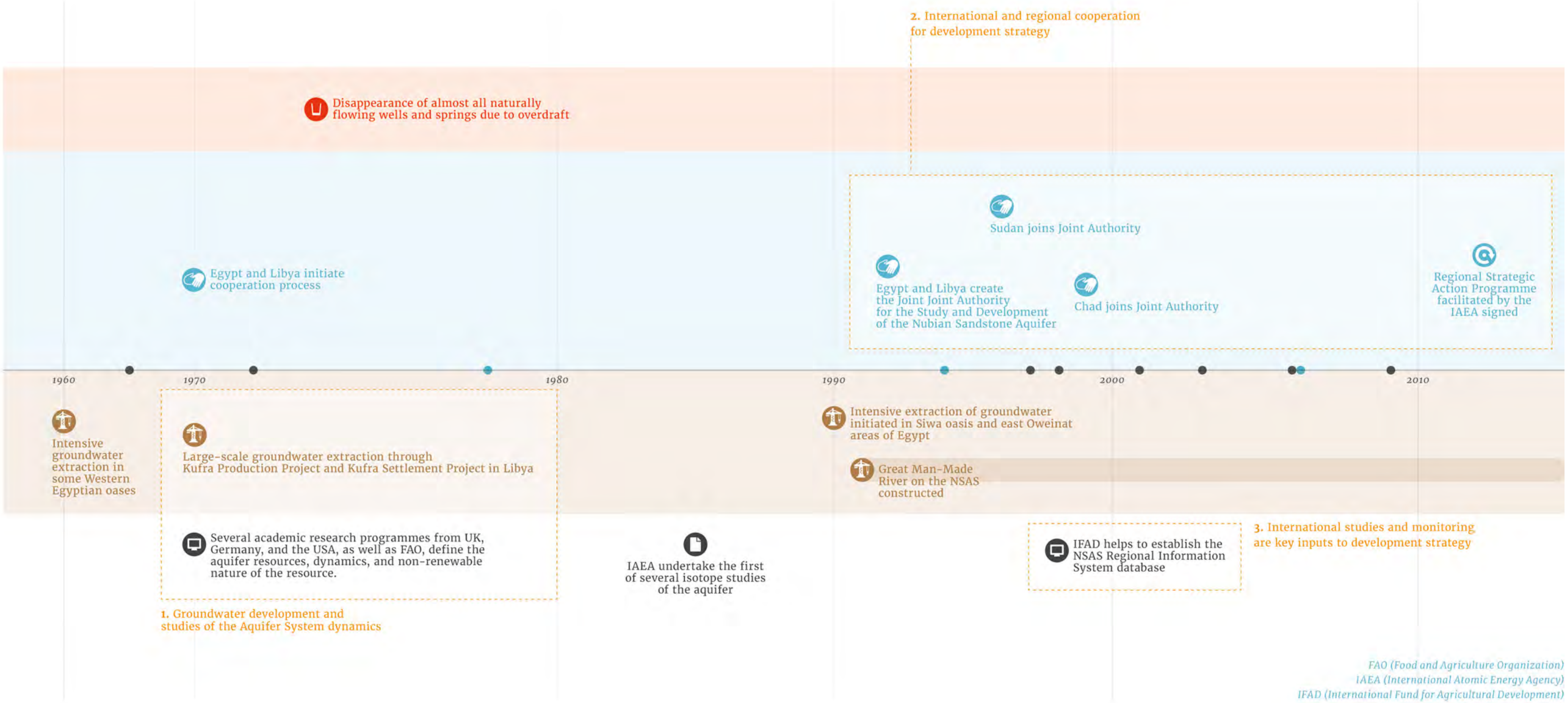
GEF (Global Environment Facility); UNESCO (United Nations Educational, Scientific and Cultural Organization)

Nubian Sandstone *(Fig 46)*

The Nubian Sandstone Aquifer System (NSAS) is the largest groundwater system in the world, stretching over 2 million km² across Chad, Egypt, Libya, and Sudan. Northern Libya has been an important agricultural region depending on groundwater from Roman times to the twentieth century. Today, the NSAS is mostly exploited in Libya, which relies almost exclusively on the NSAS for water supply. Due to the magnitude of aquifer reserves, there is still room for development, although the potential risks of increasing salinity, falling water levels in areas of shallow water table, and associated damage to or loss of oasis ecosystems will all need to be managed. Although relying mainly on the Nile, Egypt also taps the NSAS, while groundwater development in Chad and Sudan is still limited. The NSAS challenge is long-term viability, as it overwhelmingly comprises 'fossil' water that mostly entered the aquifer tens of thousands of years ago and has been slowly draining since the last glacial period 20,000 years ago.

Each timeline is indicative, and not exhaustive. Major elements have been selected based on expert consultations to depict broad patterns of water-related risks, opportunities and investments. The schematic below features additional elements essential to the pathway, conveying a cycle of challenges and responses unique to ***the Nubian Sandstone Aquifer System.***





FAO (Food and Agriculture Organization)
IAEA (International Atomic Energy Agency)
IFAD (International Fund for Agricultural Development)

4.5 Findings

'A longer, historical, view suggests that ... the history of water management is a history of challenges (which change over time) and responses.'

'... The implication is that context matters, a lot, and that great care needs to be taken in extrapolating findings from one period to another, or from a rich country to a poor country.'[32]

We can draw general and context-specific lessons from the historical timelines and narratives of these cases. Here we summarize what we have learned about pathways, including general lessons and insights across different phases and scales, to achieve and sustain water security. Looking forward, we explore insights about decision-making in strategic and adaptive pathways.

General lessons

Each pathway is unique, shaped by its starting point and context. And yet broad lessons emerge, offering insights about pathways to water security – what they are, and how they have worked.

Lesson 1
From projects to pathways: investments in institutions, information, and infrastructure are interdependent and can be mutually reinforcing

- No investment stands alone – institutions, information, and infrastructure are interdependent and can be mutually reinforcing.
- Investment priorities and options are not stationary – they change with development and the shifting values and capacity that it brings.
- Pathways never end, only evolve –new risks, opportunities, and values prompt adaptation.

The case studies show that institutions, information, and infrastructure are interdependent. Significant investment is generally needed in all three to derive the full benefits of investment. Sequencing is strongly influenced by socioeconomic context and the type and scale of risks faced and opportunities created. Some common trends can be identified. Early in the pathway to water security, investments tend to be opportunistic, often in simple infrastructure, with limited information and fledgling institutions. In wealthy nations, complex water systems are often analyzed and managed using advanced information systems, including systems analysis models for the development of future scenarios and analysis of institutional and infrastructure options,

32 Briscoe (2014).

based on multi-stakeholder planning and engagement. Information needs become more refined as wealth increases and lower tolerance of risks resets water security objectives, requiring more investment in institutions and infrastructure. Institutions may prioritize participatory governance and economic instruments to achieve social, ecological and economic objectives, as competition and trade-offs intensify. Infrastructure design may become incrementally more complex, because of the need to integrate with existing assets and systems. In terms of what comes first – institutions, infrastructure, or information, analysis shows that there is no best sequencing, only emphasis on one or another at specific moments of the system's history, depending on context.

While in many cases it is possible to identify key investments that represent a turning point in the development pathway (e.g., the 1995 Mekong Agreement; the construction of Hoover Dam in the Colorado or the joint effort to study the Guaraní Aquifer System), these are the consequence of antecedent steps along a pathway. The benefits of investment accrue non-linearly and a given system requires coordinated investment to increase and optimize cumulative benefits. Solutions are always provisional and pathways are never complete, requiring periodic adaptation to new circumstances and challenges.

Lesson 2
Information: knowledge and trust are 'pillars' of legitimacy and cooperation

- Shared knowledge and trust are assets – they create the foundation for the pathway to water security.
- Political debate and contest is part of the process – omission of key groups or viewpoints may undermine the pathway to water security.
- Comprehensive monitoring feeds databases that can build systems models for adaptive planning.
- Early, in-depth understanding of rivers, aquifers, or urban water networks enables and sustains their development.

Investments in water security are built on knowledge – a shared understanding of the water resource system, its boundaries and dynamics, dominant risks and opportunities, and the values of different stakeholders. In the case of the Murray-Darling Basin in Australia, for example, a series of parliamentary inquiries occurred at critical junctures, resulting in: interstate water sharing and infrastructure financing and construction in the early 1900s; construction of Lake Victoria in the 1930s; responses to salinity problems in the late 1960s and 1970s; and the establishment of water diversion limits since the 1990s. An audit of water use in the 1990s was followed by a government audit of current and future water availability under climate change, conducted by the Commonwealth Scientific and Industrial Research Organisation, 'CSIRO'. This knowledge enabled basin institutions to establish diversion limits, modify water rights systems to facilitate water trading, and plan irrigation efficiency improvements. Joint enquiries stabilize the knowledge base that guides policy change and infrastructure investment. Shared knowledge requires participation by affected stakeholders – in order to provide legitimacy, and to prevent any participant or group from dominating the way knowledge is tabled and fed into decisions.

Lesson 3
Triggers: plan for the future. Don't waste a crisis, but don't wait for one

- Good planning is dynamic – as good plans will be ready for the opportunity when it comes; the next crisis is the next opportunity.
- Populations and their expectations change – plan for expanded and diversified water services.

There are multiple triggers for investments in water security: opportunities, chronic impacts, and acute shocks, and both water-related and external factors, such as political changes, natural hazards, and international trends. In any given situation, multiple different factors coincide to trigger investment.

Triggers include: opportunities offered by the exploitation of natural resources (Gauteng, Nubian Sandstone, Ica Valley); **economic or natural hazards** (e.g., earthquakes, major flooding, or drought), prompting a strong response, often by the national government and in some cases backed by international initiatives/funds (Mexico City, Colorado, Murray-Darling); and **major political and economic events that contribute to removing constraints, opening up new opportunities, or creating new frameworks where different actors can interact** (Indus).

Specific events can open windows of opportunity – perhaps economic or natural crises, perhaps the end of political instability or of conflict. If regular and robust planning is already in place, such opportunities can be seized quickly and effectively. Without prior planning, ad-hoc responses are likely to be insufficient. As a case in point, Mexico initiated a water planning effort in 1972 that laid the groundwork for more comprehensive activities under the Salinas administration, in office from 1988. During the start of the Salinas government, water services were at the top of the new administration's agenda due to myriad problems of reliability, equality of access, conflicts, and scarcity. The planning from the early 1970s identified the need for a comprehensive approach to water development, supporting the creation of a national water agency (CONAGUA) in 1989.

Lesson 4
Everybody counts: build capacity, cooperation, and political will

- Communities are part of the solution – water users have a direct stake in the problem, and are central to the solution when river basins and aquifers are threatened (Yellow, Colorado, Murray-Darling, Western La Mancha, Ica Valley, Ogallala, Arizona).
- A shared vision of the basin future builds stakeholder support for water management and development (Rhine, Mekong, Senegal, Nile).
- Foster inter-state and international cooperation to design, finance, and operate infrastructure for shared benefits (Colorado, Murray-Darling, Senegal).
- Coordinate infrastructure development and operations to support multiple purposes and optimize benefits for upstream and downstream jurisdictions (Colorado, São Francisco).

The importance of institutional actors will depend on context. National governments provide leadership and coordination, along with the impetus and financing for development planning. Sub-national governments also play a role, particularly in federal countries where authority over water development may be reserved for sub-national units. The private sector also has an important role to play, such as the oil industry in the Nubian Sandstone case, or agribusiness in the São Francisco Basin. Quasi-governmental organizations and local districts organize water users and service providers. Basin organizations can act as catalysts for development at all levels, if they are provided with adequate mandates, competencies, and resources. International financial institutions and other external agencies can play an important supporting role.

Political will and institutional capacity, as well as coordination across scales, are critical for cities, rivers, and aquifers. In Gauteng and Mexico City, for example, the urban development pathway was and remains of strategic national interest, although water service institutions remained the domain of municipalities and relevant local bodies. In aquifers, the Guarani experience illustrates the priority placed on 'preventive' transboundary cooperation. Political will and institutional capacity is particularly important in international rivers to foster transboundary cooperation. For example, the establishment of the Senegal River Basin Organization (Organisation pour la Mise en Valeur du fleuve Sénégal) on the common principles of solidarity and equity facilitated commitments at the highest political level to joint development. This institutional capacity enabled investments in two large, jointly-owned and managed storage and hydropower reservoirs, attracting external support from the international financial institutions.

Lesson 5
Not all investment is beneficial: planning needs to be smart and strategic

- The pathway to water security is an integral part of national development: be inclusive, strategic, and spend wisely (São Francisco, Mexico City).
- Flexibility reduces the costs of changing direction: beware path dependency (Colorado, Murray-Darling, Rhine).
- Protecting water quantity and quality protects the future: pay close attention to urban-rural linkages (New York, Gauteng, Mexico City, Sao Paulo).
- Values will change with growth and time: conserve ecosystems or face the inevitability of costly restoration (Yellow, Colorado, Murray-Darling, Rhine).

Many historical investments have underestimated costs, overestimated benefits, and foreclosed alternatives. Water resources development can bring growth, but can also have negative consequences. All water development paths have social and environmental costs; historic pathways demonstrate the importance of accounting for such costs in the design and implementation of investments in order to avoid, or reduce, the need for costly restoration efforts.

In aquifers, declining water tables have the potential to jeopardize the economic viability of groundwater use and cause environmental damage to groundwater-dependent ecosystems. Groundwater overdraft also causes contamination associated with salinization and mobilization of toxic substances, leading to further resources loss. Pathways show that instead of reactively responding to aquifer depletion, policies need to ensure sustainable yields, where abstraction levels do not exceed recharge (Ica Valley, Western La Mancha, North and Western Gangetic Plain).

In a similar way, water resource development in river basins can lead to competition between sectors and across political boundaries – both within and between countries. For example, irrigation can lead to salinity, high nutrient contents, waterlogging, and alteration of river pulses, while pollution and river fragmentation are by-products of industrial and urban uses and intensive agriculture. These risks point to the need to maintain flexibility in allocation and re-allocation of water rights to leave room for adaptation when water users increase and values change (Murray-Darling, Colorado, Yellow). In the Murray-Darling, for example, despite a 70 percent decrease in the water available for irrigation in the 2008/09 water year compared with the baseline of the 2000/01 water year, due to the impacts of the Millennium Drought (1997-2009), the gross value of irrigated agriculture declined by less than 20 percent, due to the existence of water markets and infrastructure to reallocate water among competing uses.[33] Water trading and infrastructure efficiency enhancements have also been used to recover water for the environment, and to address the consequence of over-allocation.

Path dependency is as high in urban settings as it is for the other scales (river basins, countries, and aquifers). Technologies adopted early in a development path (e.g., combined sewer and stormwater systems) may prevent the adoption of more efficient and cost-effective alternatives due to the high costs of switching.

Efforts to experiment with new technologies and governance have encountered political resistance, rigid institutions, and complacency with ageing, large-scale networked infrastructure systems that impede innovation and adaptation.

What emerges clearly, is that yesterday's innovation can become today's constraint if there is not enough flexibility built into the system. For instance, having a system of fixed volumetric water rights to regulate water uses has clear advantages in exercising control on uses, and providing certainty to water users, but those rights become a constraint when existing users resist changes in water planning and allocation, hampering opportunities to make substantial changes if the basin or aquifer is overallocated, or is faced with severe drought.

33 *Kirby et al. (2014).*

Learning from contexts: cities, rivers, and aquifers

The case studies are descriptive rather than prescriptive, exploring actual pathways, not optimal ones; each of these has different triggers, water security investments, and economic activity. The case studies suggest several challenges and opportunities for innovation and tailoring adaptation actions to specific risks in different types of cities, rivers, and aquifers.

Urban pathways

Inadequate water supply and sanitation services cause public health risks and may impede municipal and industrial development. Inadequate urban drainage exacerbates public health risks and inhibits economic activity. Large-scale flooding can be highly damaging to the urban economy and propagate through supply chains nationally and globally. Urban water security requires addressing all of these challenges. The pathway to water security starts with water supply, piped, delivered, or collected (e.g., from kiosks), treated and untreated, as no settlement can survive without it. This is followed by sanitation, with sewerage coverage expanding slowly. The new city, rich or poor (and there will be many of the latter as the developing world urbanizes rapidly in this century), has the opportunity to employ innovative solutions, perhaps moving from centralized, water-intensive systems to newer, better systems that conserve water, harvest rain and storm water, reduce waste loads, and balance urban, rural, and ecosystem needs (e.g., with resource recovery and wastewater re-use). Integration of green infrastructure into the urban environment, in particular to mitigate stormwater flows and pollution, will require sustained planning and regulatory attention.

We examine our cases of urban pathways to water security in three contexts: mature cities in advanced economies; rapidly developing cities in emerging economies; and predominantly poor cities with rapidly expanding informal settlements.

Mature cities in advanced economies

London and New York are examples of mature cities in advanced economies, with potable water supply and wastewater collection and treatment presumed by consumers and generally functioning adequately. Behind this, however, is a story of rising operational costs and capital investment needs, not least due to ageing water and wastewater infrastructure and growing environmental concerns. With rising costs and reducing subsidies, cost recovery is important, but politically difficult. Flooding is a significant and a growing problem, with already high and increasing values of assets at risk, compounded by climate change. Major re-investment is needed but political inertia is a challenge to overcome, unless there is a specific trigger (such as a crisis).

A water secure future is likely to stem from investments in information and institutions that provide incentives for innovation, ensure efficiency improvements, and recover costs through smart tariffs. Investments in infrastructure will be needed to manage scarcity and navigate urban-rural trade-offs, to replace essential underground assets, and to provide resilience to hydrological variability and climate change.

Conversely, a water insecure future is one of continuing deterioration of urban water networks, declining reliability and quality of drinking water, increasing vulnerability to floods, public health risks, and environmental degradation.

Rapidly developing cities in emerging economies

Beijing, Delhi, Gauteng Province, Mexico City, and Sao Paulo are examples of rapidly developing cities in emerging economies, with reliable services to high-income housing and industry. Access to and reliability of service is typically much less in low-income settlement and lower still in informal settlement. Economic growth has triggered rapid infrastructure development to establish urban water networks, where conventional water supply and wastewater solutions are the default option. Increasing water resource demands exhaust local supplies and require identification of (typically more distant and costly) alternative water supplies from rural hinterlands. Wastewater services typically lag behind water supply, with consequently deteriorating environmental water quality. The rapid growth of urban water supply networks brings challenges for financing capital and operation and maintenance costs, with conventional financing models and tariffs often inadequate for full cost recovery. Some new infrastructure is financed through utility structures with access to market finance, involving public and private contributions. The expansion of urban water supply networks to serve the urban poor and peri-urban settlements need provisions, including subsidies, to ensure affordable services for the poor.

A water secure future is likely to stem from innovative financial, institutional, and infrastructure approaches to accelerate pathways to urban water security, ensuring universal access, well targeted subsidies, and sustainable financing, appropriate urban water and wastewater networks and services, and integrated management of risks associated with water resource access, wastewater discharge and pollution, urban floods, and climate change.

Conversely, a water insecure future is one dominated by inequitable access and water service delivery models with high construction, operations, and maintenance costs and limited reliability and flexibility, as well as rapidly rising numbers of people and values of assets at risk, particularly from flooding.

Cities with rapidly expanding informal settlements

Rapidly expanding informal settlements in the peri-urban fringe present some of the greatest challenges in poorer cities and the poorest parts of cities in emerging economies. Water and wastewater services are mostly adequate in formal settlements, yet water and sanitation service is a chronic challenge in the rapidly expanding peri-urban fringe. Wastewater collection and treatment are limited, contributing to severe health and environmental impacts and chronic flooding and drainage problems. Water utilities are ill equipped to confront these challenges, due to inappropriate delivery and financing models.

A water secure future is likely to stem from an appropriate pathway to urban water security, including alternative options, where 'conventional' water and wastewater services and business models may not be the best options. Future pathways will require dynamic knowledge-based institutions responsible for water resources development, sustainable water services, and land-use planning to protect water sources and mitigate pollution, flood, and other risks. Resilience to extreme events and climate change will become increasingly important, particularly when droughts and floods disrupt economic activity.

Conversely, a water insecure future is one with weak urban water utilities and conventional urban water and wastewater services as the sole option providing improved services, and expanding settlement in vulnerable locations such as watersheds and floodplains, which cities must protect to mitigate risks.

River & lake basin pathways

River basin development involves systems to store, distribute, and manage water resources and sustain land and ecosystem services in the context of hydrological variability. The pathways to water security strive to put water to use in a manner that increases returns to other resources (land, energy, ecosystems), motivated by urban and industrial development and hydropower, mining, irrigation, and other opportunities.

Most human settlement has occurred in close proximity to surface water sources, evidenced by the ancient civilizations of the Nile, Tigris-Euphrates, Indus, and Mekong. This provided ready access to water, but also exposure to floods – both positive (flood recession agriculture) and negative (loss of life, economic damages). Hydrological variability and other water-related risks and opportunities typically stimulate capital-intensive investments in storage, flood management, irrigation, and energy development and associated institutions. Development, increasing demands, competition between sectors and between upstream and downstream users, and prolonged droughts can lead to river basin closure – where downstream needs are unmet due to temporary or chronic imbalances of supply and demand, or to pollution. Urbanization creates linkages between cities and rural regions, characterized by inter-basin transfers or competition between agricultural and urban water uses. Vulnerability to floods and droughts place economic and ecological assets at risk, prompting efforts to enhance flexibility to adapt in the face of uncertainty and shifting social, economic, and environmental values. Adaptation emphasizes actions to buffer variability, manage demand, restore riverine ecosystems, and enhance resilience to shocks.

We examine three hydro-climatic contexts: highly variable/monsoonal, semi-arid or arid, and temperate river basins and lake systems.

Highly variable / monsoonal river basins

The Mekong and the Gangetic Plain are examples of highly variable, 'monsoonal' systems located mostly in poor and emerging economies with high and growing population density. In these settings, river-related livelihoods are both dependent on and vulnerable to hydrological variability, with unpredictable seasonal and annual rainfall and runoff impacting both rainfed and floodplain agriculture. Inadequate forecasting and communication results in high vulnerability to flood and drought risks, with occasional major flooding incidents, particularly, but not only, impacting poor settlements. Inevitable trade-offs between floodplain development, ecosystem services, and other consumptive and non-consumptive uses are often unmanaged. Climate change is predicted to impact these regions most, with increased variability and unpredictability.

A water secure future is likely to stem from robust knowledge-based institutions adopting: innovative solutions to the variability challenge (such as artificial groundwater storage, floodplain zoning); alternative pathways to reduce the impact of extreme variability and flooding at the least social and environmental costs, leaving space for the river; strategies to decouple economic growth from dependency on highly vulnerable sectors, particularly rainfed agriculture; and robust strategies for climate change adaptation.

Conversely, a water insecure future is one of cities and extensive rural communities with large numbers of people and livelihoods vulnerable to severe floods and droughts, severely degraded ecosystem services, and inadequate capacity to adapt to climate change, all of which could contribute to stalled economic growth, increased poverty and social and political tension.

Arid and semi-arid basins

The Aral Sea, Colorado, Murray-Darling, Lower Senegal, Lower Niger, Lower Indus, Lower Nile, Lower São Francisco, and Yellow are examples of arid or semi-arid rivers. Basins with these hydroclimatic conditions range from poor to wealthy. The pathway to water security has involved intensive groundwater and surface water development to manage chronic scarcity and drought impacts. Agriculture has become the dominant use and irrigation systems a development priority, with allocation, capital financing, and cost recovery issues. The growth of cities intensifies competition for water between urban development, rural development, and ecosystems. The development of some rivers for economic and regional development has led to 'river basin closure' with inadequate environmental flows and water quality deficits. Social, economic, and environmental values change with economic growth, creating the need for adaptation to secure alternative sources, improve efficiency, and create more flexible allocation mechanisms to resolve conflicts and make trade-offs across competing uses and priorities. The dual challenges of water scarcity and variability have resulted in very high levels of investment in semi-arid parts of wealthy nations (Colorado, Murray-Darling) and in wealthy arid nations. In poorer nations and emerging economies, water management challenges are great (Aral Sea, Indus, Nile, Niger). The scale of the challenge can also increase rapidly with economic growth (Yellow, São Francisco), but so do the resources and capacity needed to address the challenge.

A water secure future is likely to stem from robust knowledge-based institutions, innovative storage alternatives to the use of large reservoirs alone (e.g., aquifer storage and recovery); conjunctive use of multiple sources (e.g., reuse, rainwater harvesting, desalination, dual pipe systems); water use efficiency; and economic instruments allocating scarce water wisely. In addition, 'soft pathway' solutions will manage demand, re-operate existing infrastructure to optimize economic and ecological benefits, and make wise trade-offs.

Conversely, a water insecure future is one of little information, weak institutions, inflexibility in water allocation, exclusive reliance on supply side infrastructure, irreversible degradation of ecosystems, and maladaptation to climate change – all contributing to social exclusion and political instability.

Temperate river basins

The Apalachicola, Ebro, Great Lakes, and Rhine are examples of temperate basins. These basins are typically characterized by advanced economies and mature cities with high levels of basin modification during industrialism. Like the arid and semi-arid rivers, wealth is associated with major historic investments in infrastructure, including storage and hydropower development, flood control, and urban water supply and wastewater networks. Industrialization resulted in heavy pollution and ecosystem degradation with high restoration costs. The economic growth enabled by this development has increased the value placed on environmental assets, which motivates the political will to remediate. Development in floodplains has increased and economic growth has resulted in very high values of assets at risk, while tolerance of flood risk has decreased. This has renewed emphasis on flood management and spurred programmes to create room for the river to move within the floodplain. Relatively strong institutions and information systems enable innovative approaches to reducing pollution and flood risks, where political will exists. Even in temperate rivers, population and economic growth can lead to localized supply-demand imbalances. Complacency and the lack of political will delay adaptation to future risks, until crises create windows for policy reform and infrastructure investment.

A water secure future is likely to stem from innovative and adaptive multipurpose institutions and infrastructure to (i) safeguard growth and wealth by mitigating water security risk broadly and flood risk in particular, in the context of climate change; and (ii) enhance environmental water quality, in the context of growing demand for recreation, biodiversity conservation, and public health. Investment in water security innovation may have useful applications in other contexts around the world.

Conversely, a water insecure future is one with complacent dependence on existing infrastructure (e.g., dams and flood control structures) to manage risks and the buildup of vulnerability, without incentives and information systems to reduce vulnerability, protect environmental assets, and adapt to uncertain futures.

Aquifers

Aquifer development contributes to water security in two primary ways: by providing water for domestic and industrial supply when surface water is insufficient, unreliable, or polluted, and by creating economic opportunities through groundwater-dependent irrigation in otherwise water-scarce areas. Aquifer characteristics determine the scale and recharge rate of water resources, their ease of exploitation, their natural quality, and their vulnerability to pollution. In the early stages of aquifer development, groundwater is typically exploited sustainably by springs and individual wells, then later by increasingly sophisticated well fields. Without considerable information and strong institutions, this can lead to local or generalized overdraft, with declining water tables, pollution associated with salinization, mobilization of natural contaminants (e.g., Arsenic), and anthropogenic contamination, and even significant land subsidence. Aquifers are often exploited conjunctively with surface water to provide additional resources or to buffer the effects of drought on surface water supply. While groundwater resources act as a buffer to rainfall variability, droughts may raise the scale and cost of pumping, temporally exacerbating overdraft.

We can identify two primary contexts of aquifer development: aquifers where significant surface water is available and aquifers where society is dependent on groundwater for urban development and irrigated agriculture.

Groundwater development with surface water available

The Guarani Aquifer System and the Eastern Gangetic Plain are both examples of major aquifers where there is significant surface water available. In both cases, there is limited groundwater dependency for irrigation, but significant opportunity if exploitation becomes economically or technically viable. There is, however, an important role for groundwater in urban and rural water supply to compensate for polluted or unreliable surface water resources. In most aquifers, there are local or wider problems of water quality due to one or more reasons, including insufficient wastewater treatment and solid waste disposal (mostly in developing economies) and agrochemical and industrial pollution (mostly in developed economies). There can be local overdraft problems beneath or close to urban areas, as a result of poorly controlled or uncontrolled development. With rising groundwater levels, there is also a risk of waterlogging and soil salinization. An innovative and largely unexploited opportunity is the medium- to large-scale use of artificial aquifer storage to augment storage in surface water reservoirs, achieving multiple water security objectives with relatively limited social and environmental impacts.

A water secure future is likely to stem from investments in information for monitoring and modelling aquifer dynamics, and in institutions to ensure robust groundwater regulation, planning, and protection. Investments in infrastructure will include systematic groundwater development, with well fields for urban water supply, often in conjunctive use with surface water, and the development of multipurpose aquifer storage.

Conversely, a water insecure future is one by aggravated water quality deterioration and local overdraft due to unplanned distribution of wells, resulting in major aquifer restoration costs and even irreversible damage, and water logging and soil salinization, due to rising water levels caused by unplanned recharge (such as from leaking water and wastewater systems).

Groundwater development for cities and irrigation

The Nubian Sandstone Aquifer System, the Ogallala, Arizona, Gnangara, Ica Valley, North China Plain, Upper Guadiana, and Mexico Valley are all in locations with groundwater-dependent development, typically either cities or irrigated agriculture in arid and semi-arid regions. In these settings, groundwater is the primary resource for all human settlement as well as for irrigation development, where it supports poverty alleviation (in low-income economies) or high value agricultural production (in emerging and high-income economies). Unregulated groundwater development and overdraft create water security challenges due to declining water levels, water quality deterioration and competition among users. Efforts to regulate groundwater depend on information on resource characteristics and use. Inconsistency between estimates of groundwater resources and authorized abstraction permits leads to overdraft. Groundwater development can be energy intensive, creating trade-offs between energy and water security. Subsidence, sometimes serious (Mexico City), can occur due to over-pumping and falling groundwater levels, which damages infrastructure and networks. Groundwater overdraft will also cause decline in baseflows to rivers, wetlands, and other groundwater-dependent ecosystems. While groundwater is resilient to climate, buffering variability, if poorly managed over time, the damage caused can be very difficult to repair or even irreversible, which would be extremely serious in these cases, where society is groundwater dependent.

A water secure future is likely to stem from participatory institutions with access to (i) advanced knowledge systems managing aquifers and groundwater abstraction with appropriate tools, including monitoring networks and systems models, quantity and quality regulation with flexible permits to enable reallocation and aquifer recovery, and (ii) innovative infrastructure, both in terms of wellfield design and aquifer storage and recovery, as well as in water supply and wastewater service delivery, where demand management and loss reduction will be essential strategies.

Conversely, a water insecure future is one with unregulated, unplanned, or over-allocated groundwater abstraction resulting in declining water levels, (potentially irreversibly) deteriorating water quality, and land subsidence and associated infrastructure damage. The consequences of aquifer mismanagement, in terms of society-wide impacts, could be serious and pose major challenges for large cities and irrigation developments.

International transboundary basins: rivers, lakes, and groundwater

In addition to the typologies above, we describe the incremental challenges introduced by the international transboundary nature of shared watercourses. The Aral Sea, Colorado, Great Lakes, Indus, Mekong, Nile, Niger, Rhine, and Senegal river basins – and the international transboundary aquifers of the Nubian Sandstone, Guarani, and Gangetic Plain – are shared by at least two countries (and 11 in the case of the Nile). In most of these cases, we can observe a key element of the pathway to water security, which is the investment in information and institutions represented by a defined platform for dialogue and shared information. In some cases, a formal agreement has established a basin institution with a shared knowledge base and established guidelines for some degree of joint decision-making and monitoring. In the case of the Senegal, high level of cooperation is seen in joint investment in multi-country, jointly-owned and managed infrastructure assets, including the Manantali and Diama dams.

A water secure future is likely to stem from some level of cooperation in all international transboundary basins, to ensure robust basin management; this may be best served by information sharing alone, or together with coordinated action, or even with joint action (such as joint infrastructure development, as in the Senegal Basin). In all cases this requires an appropriate joint institutional mechanism.

Conversely, a water insecure future is one where unilateral, uncoordinated water resources development by individual nations in international transboundary basins leads to suboptimal resource management and development, at best; or, at worst, resource over-exploitation and degradation with potentially serious environmental, economic, and political consequences.

Toward strategic and adaptive pathways

Our analysis of case studies has revealed cycles of adaptation in the quest for water security. Important decisions and actions have been triggered by seminal events. Pathways to water security have co-evolved with economic development and public expectations. On the one hand, there seems to be inevitability to this process of adaptation. On the other hand it is clear that there are genuine choices, which may lock in particular pathways of development.

At each stage decision makers have had options at their disposal and have made choices with a view to reaching goals. The evidence available to inform decision-making is always uncertain. The methodologies of system analysis, decision analysis, and benefit-cost assessment, which are central to strategic choices about investment in water security, have matured in recent decades. They provide the opportunity to shift from reactive management of the impacts of water insecurity to the pro-active management of risks.

Recognition of the importance of sequences of investments has stimulated interest in appraisal methodologies that deal with sequential decisions under uncertainty. These methods have their origins in the 'decision trees' of decision analysis.[34] However, recognition of the severe uncertainties associated with climate change and other accelerating processes of global change has stimulated much greater emphasis on the role of uncertainty in long-term decision-making, and in particular on the role of 'severe' or 'deep' uncertainties that are not amenable to quantification with probabilities,[35] which is the conventional approach for incorporating uncertainty in decision analysis. Moreover, an emphasis on adaptive management has led to the uptake of methodologies for valuing the benefits of flexibility in the face of uncertainty, in particular real options theory.[36] These methods have now reached a level of maturity that allows them to be routinely used to inform major investment planning decisions (e.g., in the Rhine delta). The extent of analysis always needs to be in proportion to the scale of the decision: small investments will not warrant the same scale of analysis as large investments. However, given the amount of investment that is required in water security, and the scale of future uncertainties, more widespread use of methodology for sequential decision-making under uncertainty is justified.

The theory of decision analysis stresses the importance of learning and adaptation when circumstances are changing and uncertainties are high. This has also been the main lesson from practice that has emerged from the case studies presented in this chapter and the broader range of cases reviewed as part of this study. Looking forward, we see the pathways to water security being informed by rigorous analysis of costs, benefits, impacts, and trade-offs. But alongside that we emphasize the lessons from practice and the importance of adapting to particular contexts, which this chapter has sought to illustrate.

Figure 47 depicts the principles of staged decision analysis under uncertainty. The fundamental structure of the analysis is a decision tree: a decision maker confronts a sequence of choices through time (which proceeds from left to right), and at each decision point (only two are shown in the figure) there is a set of alternatives at their disposal. The alternatives depicted in Figure 47 are various combinations of investments in information, institutions and/or infrastructure as a means of managing water security. The top pathway shows the 'baseline' case in which no investments are made to add to the portfolio that the decision-maker has at the start of the pathway. For all other pathways, there will be investment costs, which need to be weighed against the benefits of investment in water security.

34 *Raiffa (1968).*

35 *Brown et al. (2010); Lempert and Groves (2010).*

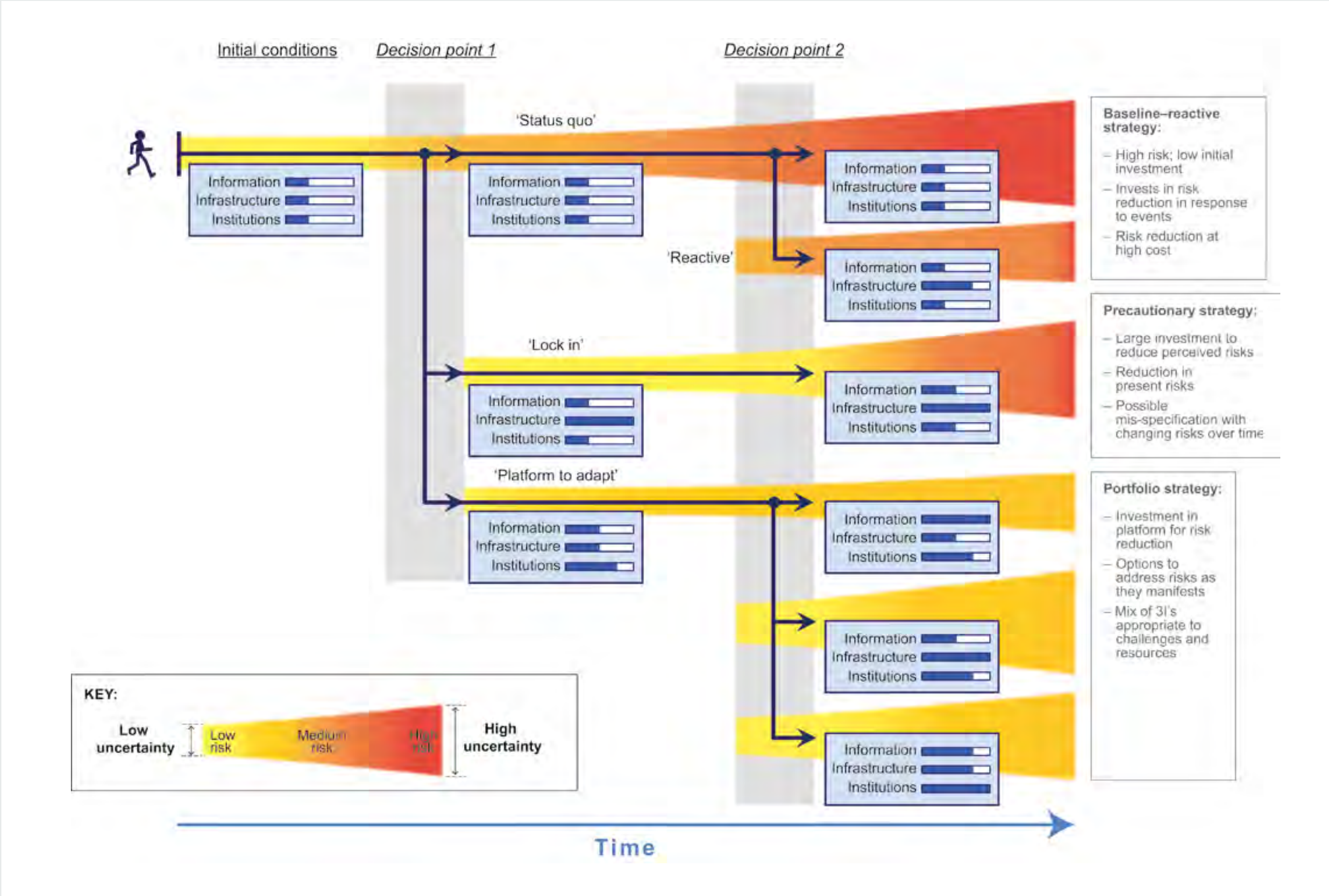
36 *Haasnoot et al. (2013); Jeuland and Whittington (2014); Zhang and Babovic (2012).*

The performance metric against which these management options are appraised is risk of water-related losses. The severity of risk is depicted in Figure 47 with red shading. Risk increases most markedly in the baseline pathway, because no additional steps are taken to manage the increase in risk, which may originate from any combination of increasing economic exposure, deteriorating infrastructure and climate change. The other pathways make a contribution to reducing risk, but the underlying drivers that increase risk are not removed, so sustained management of risk through both decision points is needed to keep risk to a manageable level.

Figure 47 also shows the effects of uncertainty in decision-making. The scale of uncertainty is depicted as the width of the coloured bars. Uncertainties increase in future, and the uncertainty is greatest when no steps are taken to reduce risk (the upper, 'baseline' pathway). Taking active steps to manage water security can reduce uncertainty, as well as reducing risk, in particular by investing in information.

Finally, Figure 47 illustrates some of the trade-offs and dynamics of risk, uncertainty, and investment, albeit in a stylized way. As we have already seen, the most appropriate combination of investments will depend upon context. The figure starts to demonstrate how decision makers can plan and analyze alternative pathways in the face of uncertainty. In practice, this will involve quantification of costs, benefits (in terms of risk reduction), and, as far as possible, uncertainties. Not all institutions are equipped to do this, but given the scale of investments and uncertainties on the pathway to water security, greater rigour in investment appraisal is needed.

Stylized sequential decision analysis *(Fig 47)*



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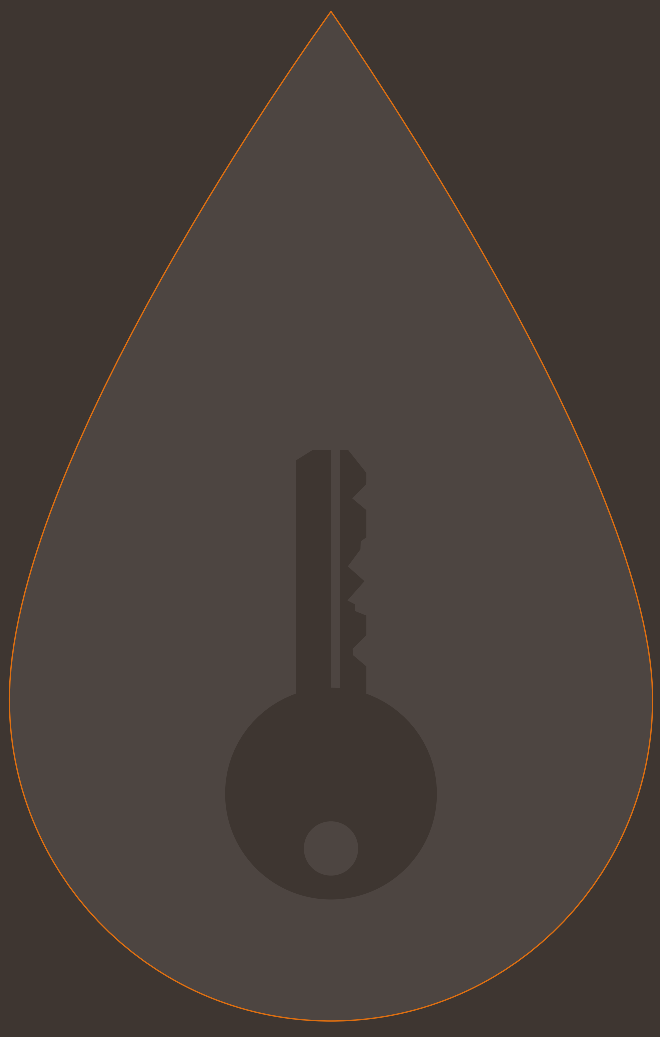

Chapter 5: Conclusions

5.1 Key findings

Water insecurity acts as a drag on economic growth. The empirical and theoretical analysis in this report provides new evidence that economic growth is vulnerable to negative hydro-climatic effects, and confirms that the relationship is causal and statistically significant.

Our econometric analysis of countries across the world focused on climate factors, including temperature, precipitation, and runoff. While the direct consequences of hydrologic or temperature extremes are understood, it wasn't known if these individual events can accumulate to affect economic growth in significant ways. The results find that the answer is 'yes'. And, because these are exogenous variables – unaffected by policy decisions, wealth, or infrastructure – evidence of effects on economic growth can be attributed to the climatic factors with some confidence.

With regard to climate change in particular, it is notable that the effect of water and water-related hazards on economic growth was shown to be at least as important – and likely more important – than the effect of temperature, in the historical times series used in the econometric analysis. This finding is significant because analyses of the potential economic costs of climate change have typically focused primarily on temperature rather than on water-related impacts.

This report focuses on the economic impacts of water security, but social and environmental impacts also require vital attention. This is so because the impacts of bad water management decisions greatly affect the poor, women, and the environment. While the accuracy and reliability of economic growth statistics are sometimes questioned, the data and valuation techniques relating to social and environmental factors are even more problematic; we have therefore been limited by the evidence that is available to record changes in these factors. Furthermore, in a globalizing world, the impacts of water-related risks can be transmitted not only through the global economy, but also through species and habitat losses, social disruptions, population displacement, and disease. Developing methodologies adequate to measure and monitor these processes, is a priority.

Some countries are more vulnerable to water-related risks than are others. A country's hydrology, the structure of its economy, and its overall level of wealth (and associated level of institutional capacity and infrastructure stock), will all be key determinants of its vulnerability to water risks. The impact of hydro-climatic factors on economic growth is significantly higher in countries that are poor, have high water stress, and/or are highly dependent on agriculture. Countries with these profiles are seen largely in Africa and South Asia. Even in the most water-vulnerable countries, however, a blend of water-related and unrelated investments is needed to generate and sustain broad-based growth. This growth, in turn, enables the investment necessary to sustain water security.

Global econometric analysis confirms the impact of hydro-climatic variables on growth, but these impacts are very unevenly distributed across countries. We find that the poorest economies around the world tend to bear the greatest relative burden of water insecurity. At the same time, we find that many of the world's most advanced and diversified economies are also subject to sizeable and growing water-related risks, although in large part, this is because they have increasingly valuable assets at risk from flooding. To better understand the nature and distribution of water-related risks, we examined the status of four 'headline' risks:

Water scarcity

materializes because of imbalance between water use and water availability, and can be acute in some locations where demands are high, or hydrological variability is not buffered by storage. We found the risks of water scarcity to be most severe in South Asia, northern China, the Middle East, and arid parts of the United States and Africa (Figure 8 and Tables 4 and 5, Chapter 3). Scarcity and hydro-climatic variability contribute to volatility in food crop production (Figures 11 and 12, Chapter 3), which is particularly pronounced in Africa, but also notable in South America, Central Asia, and parts of Europe. Investments in water security can lower food prices, and significantly diminish food price volatility. The potential global welfare gains from securing water to existing irrigators, was estimated at US$94 billion. This analysis does not capture the potentially significant benefits of additional investments in agricultural efficiency, or expansion in irrigated area, that might be fostered by greater water security.

Floods

are a major, and increasingly destructive, water-related hazard. The available evidence suggests expected global annual flood damages of US$120 billion per year from urban property damages alone. By the 2030s – in the absence of adaptation – the coastal flood risk is projected to increase by a factor of four. During the same period, the risk of fluvial flood could more than double. As with any global-scale analysis, this estimate is subject to considerable uncertainties, in particular related to the levels of flood protection that are not well known on a global scale. The economic risks from flooding are increasing in all locations worldwide, due to increasing economic vulnerability. The numbers of people threatened by flood are overwhelmingly concentrated in Asia (Figures 22 to 24, Chapter 3), in particular in India and China; and Asia is set to overtake North America and Europe as having the greatest economic concentration of flood risk (Figure 25, Chapter 3).

Inadequate water supply and sanitation

continues to have the greatest economic consequence of all water-related risks, and it remains the most harmful risk to people. WHO estimated that the total global economic losses associated with inadequate water supply and sanitation are US$260 billion annually (Figure 31, Chapter 3), much of which reflects per capita estimates of the value of time spent fetching water, or walking to open defecation sites. While the largest numbers of people without access to sanitation are in India and China, the highest percentages of population without access are seen in Sub-Saharan Africa (Figure 29, Chapter 3). Sub-Saharan Africa is the only region in which water supply and sanitation risks are growing (Figure 30, Chapter 3).

Water-related risks to the natural environment

arise from: pollution, over-abstraction, interruption of the natural variability of flow regimes, and interference in river, wetland, and coastal morphology. These risks are dispersed, but seen largely in Europe, the United States, India, and China (Figure 32, Chapter 3). Taking a water security perspective, estimates were made to determine the frequency of failures to meet benchmark estimates for environmental water requirements (Figure 33, Chapter 3). In every continent, there are rivers whose water use patterns put aquatic ecosystems at risk – indicating that water security is a global threat to environment. Monetization of environmental risks, and the ecosystem services that the aquatic environment renders, is a pressing challenge that we have not been able to address.

Aggregating across the range of major water-related risks (Figures 35 and 36, Chapter 3), regional challenges become apparent:

South Asia

has the largest global concentration of water-related risks, including severe impacts across the full range of hydrological variability (droughts to floods); the largest global concentration of people without adequate sanitation; and growing environmental threats. India, with its very large population, is the top-ranked country globally for the number of people exposed to water shortage; people at risk of flooding; people without adequate water supply and sanitation; and number of undernourished children.

East and Southeast Asia

have significant exposure to flood risks, and this risk is rapidly increasing. China and Vietnam have the second- and third-highest economic risks for flooding, globally (led only by India); with expected annual flood damages in Vietnam estimated at more than 10 percent of GDP per annum. Vulnerability to water scarcity varies markedly across the region, with northern China being particularly challenged.

Sub-Saharan Africa

is estimated to suffer the greatest impacts of inadequate water supply and sanitation, measured as a proportion of GDP. Africa also exhibits the greatest variability in crop production, highlighting African economies' sensitivity to hydro-climatic variability. This variability in food production, in turn, is reflected in high levels of child malnutrition. North Africa stands out in terms of both the absolute number of people, and the percentage the population, at risk of water scarcity.

Europe and North America

generally enjoy water security, with risks reduced to tolerable levels. Yet, the United States is estimated to have the world's greatest economic exposure to flood risk, with expected annual property damage from fluvial and coastal flooding estimated at US$54 billion, or 0.3% of GDP per annum. And flood risks in both North America and Europe are anticipated to rise. Various environmental risks are also seen across these regions. Increased investment in water supply and wastewater treatment systems, agricultural water management, and water management institutions, will be needed to sustain current levels of water security.

South America

experiences significant variability in agricultural yields. However, thanks to its relatively high potential for productivity-enhancing water-related investments, the region is expected to see the greatest percentage increase in global food production. South America is also shown, by our econometric analysis, to be a region that stands to reap some of the greatest benefits from drought reduction.

Taking a historical perspective, our analysis of pathways to water security highlights the fact that water security and its associated risks are dynamic. In each case, specific risks, opportunities, and prior investments influence the priorities for action, and the range of possibilities for achieving and sustaining water security. Moreover, water security is a 'moving target': reflecting growing economies and asset stocks; changing climates; and evolving social, cultural, and aesthetic priorities and values. As a consequence of this dynamism, all solutions are provisional. Successful strategies must therefore plan for uncertainty. Investments that incorporate options to deal with an uncertain future will be more likely to provide the greatest long-term returns.

The case studies underscore the importance of investing in portfolios of sequenced projects that combine institutions (agencies, rules, and incentives), information systems (hydro-meteorological, economic, and social), and infrastructure (natural and constructed) in the management of water resources and water-related risks. These generally mutually reinforcing investments must be combined, sequenced, and sustained in order to achieve their full benefits. The pace and direction of these development pathways are often driven by triggers (e.g., crises, chronic pressures) and by political champions. Careful consideration of the concept of alternative pathways is important for planning, because there is a great deal of path-dependency in water resource development: past investments decisions will affect the feasibility, costs, and benefits of future options.

5.2 Key gaps

This report does not provide a wholly monetized value for global water security. The range and nature of water-related risks do not lend themselves to consistent valuation, and some cannot be monetized with available data and methods – making an aggregate value indefensible. Taking the economic risks of water security that can be monetized as a lower bound, however, the scale of the challenge exceeds hundreds of billions of dollars annually.

Even if precise calculations could be made, it would not be prudent – nor be possible – to design investment programmes to fully mitigate these global risks. It is never possible, or economically desirable, to reduce risk to zero. The marginal cost of risk reduction increases, and a point is reached when further investment to reduce risk cannot be justified. For the purposes of investment planning, targeted responses need to be crafted by assembling specific strategies (or pathways) for specific places; and, by carefully assessing the economic desirability of specific investments.

No matter how large the global economic risks associated with water security might be, not all investments in water security will be beneficial. As this report shows, achieving water security requires a continuous process of sound decision-making, founded on a basis of careful analysis at the local scale. There is no substitute for thorough appraisal of specific investments and investment pathways.

The 'upside' economic opportunities associated with water security are not always presented in this report. Our primary focus is water-related risks, and their negative impacts upon growth. Risk calculations focus on estimated losses of existing assets, or expected losses of current production. We also note, however, that investments in water security can create opportunities and incentives for enhanced productivity, and for additional growth-generating investments in agriculture, hydropower, services, industry, and navigation.

There are clear limitations to attempts at summarizing water security benefits and costs at global scales. We are coming to understand the scale of water-related risk and its impacts on economies. However, operating at a broad scale has limited our capacity to understand and quantify the mechanisms of inter-relation between water security and the economy. The implications of changing hydrological variability are still very poorly understood. There is rapidly increasing capability for modelling runoff, water resources, and extreme events, on a global scale – yet at the same time, there has been disinvestment in observation systems that are essential for validation of simulations, and the provision of evidence for risk managers on-the-ground.

Understanding the evolution of risk also means tracking and predicting processes of demographic, economic, social, institutional, and environmental change. The global socio-economic datasets that we have made use of are an exciting advance, but to date they provide a limited picture of vulnerability and exposure – often at a coarse resolution.

Records of the impacts of risks rely heavily on reported events, providing an incomplete picture. Scarcest of all are the data needed to quantify the effectiveness of investments for reducing risk. These data are essential to build a robust business case for investment in water security.

5.3 Toward a more water-secure future

The profile of water security risks will change in the future, as countries invest and adapt. The headline risks examined in this report all show increasing trends globally – with the important exception of water supply and sanitation.

Worldwide economic losses from poor water supply and sanitation are falling as a result of strong gains in all regions other than Sub-Saharan Africa; but aging infrastructure in many developed countries, and rapidly growing urban centres in developing countries, require continuous investment in order to sustain current levels of service – and hence, similar levels of water security. In addition, we found that the hydro-climatic effects on growth are stronger in countries with high water stress, and that water stress will grow with population. By 2050, the OECD's baseline projections indicate that 3.9 billion people will be subject to severe water stress.

The impact on economic growth, however, does not need to increase. A portfolio of policies and investments in water security can dampen the growth impacts of water risks. We have learned from the case studies that pathways to water security combine sustained investments in institutions (e.g., basin organizations, zoning, watershed protection, and expert know-how); associated legal and economic instruments (e.g., water allocation and property rights, regulation, water pricing and trading, insurance, and food trade); investments in infrastructure (e.g., in storage, transfers, groundwater wells, dikes, treated water supplies, and wastewater treatment); and the information collection, analysis and transfer that support them (e.g., monitoring, forecasting and warning systems, agricultural outreach, modelling and decision support systems). In the face of scarcity, the most cost-effective responses are likely to make use of available water through conservation; efficiency enhancing technologies; irrigation; drought management; and natural and man-made water storage, including aquifer storage and recharge. Promoting a transition to less agriculturally dependent economies – for example, through public and private investments that result in economic diversification – will reduce vulnerability to the vagaries of water availability.

Investment in water security can help safeguard growth against increasing water-related risks. There will be many investment pathways to water security, but it is likely that successful pathways will share certain characteristics. They should be devised and assessed in terms of outcomes and trade-offs among economic, environmental, and social criteria. Investments in physical infrastructure will need to be accompanied by sound water management institutions, integrated into wider governance frameworks and improved information systems. As economies mature, emphasis will shift to making the most of existing assets, and deploying innovative institutions and policy instruments. Investments should be developed to be robust to uncertainties, and to support adaptive management as risks, opportunities, and social preferences change. And always: investments should be tailored to their social and environmental context. All of this will require refined analytic tools, more holistic perspectives, innovation, and continuous monitoring, assessment, and adaptation.

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