UNDERSTANDING AND REDUCING THE RISKS OF CLIMATE CHANGE FOR TRANSBOUNDARY WATERS

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December 2009

PACIFIC INSTITUTE

In cooperation with the United Nations Environment Programme

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ISBN: 1-893790-22-3

ISBN-13: 978-1-893790-22-3

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Funding for this report was provided by the United Nations Environment Programme.

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Abbreviations and Acronyms

CIC – Coordinating Inter-governmental Committee of the Plata Basin countries

CSDP – Guarani Aquifer Steering Council

GAO – Government Accountability Office

GEF – Global Environment Facility

GRACE – Gravity Recovery and Climate Experiment

GRAHIC – Groundwater Resources Assessment under the Pressures of Humanity and Climate Change

ICMA – Intentionally Created Mexican Allotment

ICPR – International Commission for the Protection of the Rhine

IBWC – International Boundary and Water Commission

ILA – International Law Association

IPCC – Intergovernmental Panel on Climate Change

IWRM – Integrated Water Resources Management

MDCCF – Mekong Delta Climate Change Forum

MRC – Mekong River Commission

NASA—National Aeronautics and Space Administration

NBI – Nile Basin Initiative

OSU – Oregon State University

SISAG – Geographic Information System of the Guarani Aquifer System

SRES – Special Report on Emissions Scenarios

TKK – Helsinki University of Technology

SEA START RC – Southeast Asia START Regional Center

START – Global Change System for Analysis Research and Training

USBR – United States Bureau of Reclamation

UN – United Nations

UNDP – United Nations Development Programme

UNECAFE – United Nations Economic Commission for Asia and the Far East

UNECE – United Nations Economic Commission for Europe

UNESCO – United Nations Educational Scientific and Cultural Organization

UNESCO-IHP – United Nations Educational Scientific and Cultural Organization - International Hydrological Programme

UNEP – United Nations Environment Programme

USDA – United States Department of Agriculture

Contents

Introduction

Freshwater is a fundamental resource, integral to all ecological and societal activities including food and energy production, transportation, waste disposal, industrial development, habitat for fish species, and human health. Yet freshwater resources are unevenly and irregularly distributed, with some regions of the world extremely short of water. Political borders and boundaries rarely coincide with borders of watersheds, ensuring that politics inevitably intrude on water policy. Indeed, more than 260 river basins are shared by two or more nations. Just as oil creates disputes between states, water also plays a role in international conflicts. Inequities in the distribution, use and consequences of water management and use have been a source of tension and dispute. In addition, water resources have been used to achieve military and political goals, including the use of water systems and infrastructure, such as dams and supply canals, as military targets.

In 1994, the Pacific Institute created and has since maintained a Water Conflict Chronology that summarizes historical disputes over water resources (Gleick 1994, Hatami and Gleick 1994). In each volume of the biennial water report, *The World's Water* (published by Island Press, Washington D.C.), detailed chronologies of water-related disputes are prepared. In December 2009, an updated version of the complete Water Conflict Chronology was released by the Pacific Institute, linking historical information with Google Earth and an interactive timeline (see www.worldwater.org). This chronology suggests that one of the most important changes in the nature of conflicts over the past several decades has been the growing severity and intensity of local and sub-national conflicts and the relative de-emphasis of conflicts at the international level. A growing number of disputes over allocations of water across local borders, ethnic boundaries, or between economic groups have also led to conflict.

The good news is that water disputes are generally resolved diplomatically, and shared water resources are often a source of cooperation and negotiation. An estimated 300 agreements have been developed between riparian States – those States that border a shared river. But the long history of violence associated with transboundary water resources highlights the challenges associated with managing shared water resources.

Future pressures, such as population and economic growth and climate change, could increase tensions, even in areas that in the past have been characterized by cooperation. Global climate change will pose a wide series of challenges for freshwater management as a result of changes in water quantity, quality, water-system operations, and more. For countries whose watersheds and river basins lie wholly within their own political boundaries, adapting to increasingly severe climate changes will be difficult enough. When those water resources cross borders, bringing in multiple political entities and actors, sustainable management of shared water resources in a changing climate will be especially challenging.

A question thus arises: To what degree can existing transboundary agreements or international principles for sharing water handle the strain of future pressures, particularly climate change? Climate changes will inevitably alter the form, intensity, and timing of water demand, precipitation, and runoff, meaning past climate conditions are no longer an adequate predictor of the future. At the same time, new disputes are arising in transboundary watersheds and are likely to become more common with increasing pressures. Thus, transboundary agreements are needed now more than ever, but new forms or arrangements for such agreements may be necessary and old agreements may need to be renegotiated in the context of a changing climate. As Goldenman noted in 1990:

"One of the major challenges ahead for the international community will be to develop the principles, procedures, and institutions for managing and protecting shared resources, such as watercourse systems, at the same time that the Earth adapts to climate change."

Little progress has been made in this area in the subsequent two decades.

This report outlines some of the risks that climate change poses to transboundary water agreements. In the following sections, we define the extent and general characteristics of transboundary rivers and aquifers and describe some of the institutional structures that have developed to manage them, including both international guidelines and specific transboundary agreements. We then provide a brief overview of the current understanding of climate change, focusing on potential impacts on water resources in order to analyze how transboundary water management could better adapt to and incorporate climate change impacts. We provide four case studies to demonstrate the range of potential impacts of climate change and degree of integration into transboundary water management. We conclude with a series recommendations to reduce the risks that climate change poses to transboundary water resources.

Transboundary Rivers and Aquifers

Many rivers, lakes, and groundwater aquifers are shared by two or more nations and most of the available freshwater of the Earth crosses political borders. International basins cover about half of the earth's land surface, and about 40% of the world's population relies on these shared water sources (Wolf et al. 1999). In 1958, the United Nations published the first comprehensive collection of information on shared international rivers of the world (UN 1958). This early assessment identified 166 major international river basins. In 1978, the United Nations published an updated assessment (UN 1978) identifying 214 such basins. By today's standards, the analysis and mapping of these river basins were crude and subject to large errors. Measurements were based on regional maps and taken by hand with a planimeter – a tool today's generation of digital mappers has never used. In the 1978 assessment, only "first order" basins, or those that drain directly to the final water body (the ocean or a closed inland sea or lake) were included to distinguish them from tributary basins. This approach is still used today, even though some second- or even third-order tributaries of major rivers may be substantially larger in size than most first-order coastal basins. Many tributary basins may also be more important politically and economically. Thus, the scale of analysis is of vital importance and one should not presume that river basins excluded here are unimportant or irrelevant for regional or even international politics. For example, the Cauvery River basin is entirely contained within one nation – India – and hence is not included in international registries. Yet, the Cauvery River has been the source of intense inter-state rivalry, and even violent conflict, between the Indian states of Karnataka and Tamil Nadu (Gleick 1993).

The world has changed significantly since the 1978 assessment. The current Registry, prepared by Aaron Wolf and several colleagues (Wolf et al. 1999) and updated in 2002, now identifies 263 major transboundary river basins, covering nearly half of the ice-free land surface of the Earth (Table 1). The increase in the number of basins since the last comprehensive survey reflects changes in the political landscape, improvements in mapping technology, and the inclusion of river basins on island nations. Our abilities to precisely measure topography, identify geographical characteristics in flat terrain, and accurately map both geophysical and geopolitical borders have dramatically improved. The most important of these changes has been the disintegration of the Soviet Union – once the largest single county in the world – into 15 separate nations. Many of the world's largest rivers flow in the territories of these nations and the breakup of the Soviet Union has resulted in many new international rivers.

Table 1. The World's Transboundary Rivers and Aquifers

	Transboundary River Basins		**Transboundary Aquifers**	
	Number	Percent of Area in International Basins (%)	Number	Percent of Area in International Aquifers (%)*
Africa	59	62	40	-
Asia	57	40	70	-
Europe	69	55	89	-
North and Central America	40	37	41	-
South America	38	59	29	-
Total (global)	263	48	269	-

Notes: *Data on areas of transboundary aquifers is limited, and only available for select aquifers. Sources: International river basins from Wolf et al. 1999 and updated in 2002; international aquifers from UNESCO 2009.

Until recently, little information was available at the global level on shared groundwater basins. Yet, an estimated 99% of the Earth's accessible freshwater is found in aquifers, and about 2 billion people rely on aquifers as the sole source of their water (UNESCO 2009). In October 2009, UNESCO released the Atlas of Transboundary Aquifers, which identified 269 shared groundwater basins. Thus while groundwater is typically ignored, there are in fact more shared aquifers than shared river basins. The areal extent of shared aquifers has not yet been compiled due to uncertainties about the spatial extent of many transboundary aquifers.

Table 2 lists the rivers and aquifers of the world shared by five or more states.[1] In total, 21 river basins and 5 aquifers are shared by five or more states. Topping the list is the Danube, with 18 political entities, up from only 12 in 1978. This change is the result of changes in the political landscape of Europe. Second on the list is the Congo/Zaire River shared by 13 nations, up from nine in 1978. This change is the result of better geographical information and watershed mapping, which identifies four more nations as part of the watershed: Sudan, Gabon, Malawi, and Uganda. Among aquifers, the Amazonas and Central Asian aquifer are shared by the largest number of states at six apiece.

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[1] In some cases "states" without formal national status are included in this register. Examples include the West Bank for the Jordan River and some of the republics of the former Yugoslavia.

Table 2. Transboundary Rivers and Aquifers Shared by Five or More States

River basin	Area (km^2)	Number of nations	Aquifer	Number of nations
Danube	790,100	18	Amazonas	6
Congo/Zaire	3,691,000	13	Central Asia	6
Niger	2,113,200	11	Chad Basin	5
Nile	3,031,700	11	Eastern Mediterranean	5
Amazon	5,883,400	9		
Rhine	172,900	9		
Zambezi	1,385,300	9		
Aral Sea	1,231,400	8		
Lake Chad	2,388,700	8		
Jordan	42,800	7		
Ganges-Brahmaputra-Meghna	1,634,900	6		
Kura-Araks	193,200	6		
Mekong	787,800	6		
Tigris-Euphrates/ Shatt al Arab	789,000	6		
Volta	412,800	6		
Tarim	1,051,600	5/6*		
Indus	1,138,800	5		
La Plata	2,954,500	5		
Neman	90,300	5		
Struma	15,000	5		
Vistula/Wista	194,000	5		

Note: *Part of the watershed is claimed by both India and China. If counting India as well, total is 6.
Source: International river basins from Wolf et al. 1999; updated in 2002; international aquifers from UNESCO 2009.

Managing Transboundary Basins

Since transboundary watersheds traverse political and jurisdictional lines, heterogeneous and sometimes conflicting national laws and regulatory frameworks make management a major challenge, particularly when no single national government has authority over another. As such, transboundary water management often requires the creation of international guidelines or specific agreements between riparian states. Thus, transboundary water agreements typically take two forms: general principles of international behavior and law and specific bilateral or multilateral treaties negotiated for particular river basins. We describe each, below.

General Principles of International Behavior and Law

At the turn of the nineteenth century, the Attorney General of the United States (Justice Judson Harmon) gave an opinion regarding the uses of the Rio Grande, a transboundary watershed shared by the United States and Mexico. He concluded that a state could use the waters of an international river within its own territory in any manner, without concern for the harm or adverse impact that such use may cause to other riparian states. This approach – now known as the Harmon Doctrine – was criticized and ultimately rejected. In its place, international tribunals drew up a series of general principles that would prohibit riparian states from causing harm to other states, and call for cooperation and peaceful resolution of disputes (Salman 2007). One of the first of these sets of principles was the Helsinki Rules on the Uses of the Waters of International Rivers (the Helsinki Rules), adopted by the International Law Association (ILA) in 1966.

The Helsinki Rules were the first comprehensive, international guidelines to regulate the use of transboundary rivers and their connected groundwater aquifers. The Helsinki Rules established the principle of "reasonable and equitable utilization" of the waters of an international drainage basin among the riparian states as the basic principle of international water law (Salman 2007). Article V of the Helsinki Rules states that the relevant factors to be considered in determining reasonable and equitable utilization include, but are not limited to: (a) the geography of the basin, including the extent of the drainage area in the territory of each basin state; (b) the hydrology of the basin, including the contribution of water by each basin state; (c) the climate affecting the basin; (d) the past utilization of the waters of the basin; (e) the economic and social needs of each basin state; (f) the population dependent on the waters of the basin in each basin state; (g) the comparative costs of alternative means of satisfying the economic and social needs of each basin state; (h) the availability of other resources; (i) the avoidance of unnecessary waste in the utilization of waters of the basin; (j) the practicability of compensation to one or more of the co-basin states as a means of adjusting conflicts among uses; and (k) the degree to which the needs of a basin state may be satisfied, without causing substantial injury to a co-basin state (ILA 1966). While these principles are widely recognized and have greatly influenced subsequent agreements, there is no mechanism in place by which they can be enforced.

After long negotiations, the Helsinki Rules were followed by the Convention on the Law of the Non-navigational Uses of International Watercourses (UN Convention), adopted by the UN General Assembly in May 1997.[2] This UN Convention is the strongest international legal instrument regarding transboundary water management to-date. Articles 7, 8, and 33 are among the sections of the UN Convention most relevant for reducing the risks of disputes over shared rivers: Article 7 obliges States to take all appropriate measures to prevent harm to other States from their use of water; Article 8 obliges watercourse States to cooperate on the basis of equality, integrity, mutual benefit, and good faith in order

[2] The full text of the Convention can be found at the United Nations, http://untreaty.un.org/ilc/texts/instruments/english/conventions/8_3_1997.pdf.

to optimally use and protect shared watercourses; and Article 33 offers provisions for the peaceful settlement of disputes by negotiation, mediation, arbitration, or appeal to the International Court of Justice. Among the weaknesses of the Convention is the inherent conflict between reasonable and equitable utilization and the obligation not to cause appreciable harm. More than a decade after its adoption by the vast majority of the General Assembly of the United Nations, the Convention has not yet obtained the necessary number of signatures to enable it to enter into force and effect. As of December 2006, only 16 countries have ratified or acceded to the Convention; 35 signatures are needed for the Convention to enter into force (Salman 2007).

Finally, the most recent set of international rules for transboundary water management were established in 2004 and are known as the Berlin Rules. Beginning in 1996, the ILA began a reformulation of the Helsinki Rules in order to incorporate recent advances in international environmental and human rights law. These rules draw heavily from both the Helsinki Rules and the UN Convention, however, they also attempt to better integrate emerging principles such as ecological integrity, sustainability, and public participation. These principles, according to Dellapenna (2007), are not reflected in the Helsinki Rules and only developed in rudimentary form in the UN Convention. Thus, the Berlin Rules are an effort to bring all relevant established and emerging international law together in regard to transboundary water resources. Salman (2007) points to three basic features that distinguish the Berlin Rules from their predecessors:

1) Provisions in the Berlin Rules apply to both national and international waters;
2) The Berlin Rules incorporate emerging principles from international environmental and human rights law; and
3) The Berlin Rules have developed co-equal goals of both equitable and reasonable utilization, and the obligation to cause no harm.

In regard to the last point, both the Helsinki Rules and the UN Convention categorize harm as only one of the factors for determining equitable and reasonable utilization, and thus have been interpreted to subordinate the obligation not to cause harm to the principle of equitable and reasonable utilization (Salman 2007). The Berlin Rules, however, establish these as co-equal goals, reflecting a departure from these earlier agreements.

Specific Transboundary Agreements

In addition to basic principles of international law, as represented by the international guidelines discussed above, hundreds of bilateral and multilateral river treaties have been signed by parties to allocate water, regulate navigation and power, monitor and control water quality, and influence all other aspects of joint water management. Under traditional notions of international law, nations are most tightly bound by agreements they sign and promises they make in formal treaties. Given the lack of enforceable international guidelines for transboundary water management, specific transboundary treaties are currently the strongest mechanism for encouraging transboundary cooperation. The International Court of Justice has shown its desire to uphold the power of these treaties by not allowing Hungary to nullify its 1977 treaty with Slovakia regarding management of the Danube River (the Budapest Treaty) based on increased understanding of the environmental harm associated with planned infrastructure (the Gabcikovo-Nagymaros case).

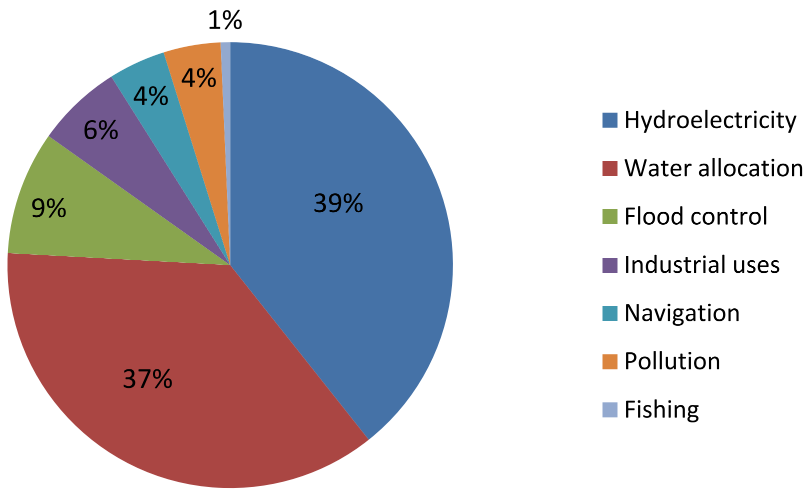
The first transboundary water agreements were written in the early and mid-nineteenth century between countries that share the Rhine River, which flows from its headwaters in Switzerland through Germany, Luxembourg, France, and the Netherlands, emptying into the North Sea.[3] These treaties established rules

[3] Treaty of Limits Between France and the Netherlands, 1820; the Convention between the Delegates of the Riparian

for allowing navigation, dividing fish harvests, and withdrawing water along the Rhine. Today, there are approximately 300 transboundary agreements on record (Gleick 2000, UNEP/OSU 2002). Of the 145 agreements negotiated in the twentieth century, an overwhelming 86% are bilateral, suggesting that many states that should be a party to the agreement are excluded (Jägerskog and Phillips 2006). The Nile Basin Treaty, for example, was negotiated only between Egypt and the Sudan, despite that fact that nine other nations are located upstream of these nations.

Figure 1 provides a summary of the transboundary agreements negotiated during the 20th century. Most treaties (40%) focus on hydropower and, not surprisingly, are often amongst mountainous nations at the headwaters of the transboundary rivers; for instance, Nepal has four treaties with India (Hamner and Wolf 1998). Surprisingly few treaties, only 37%, address water allocation and include volumetric allocations among riparian countries (Hamner and Wolf 1998). In cases where volumetric allocations are specified, they often are fixed, leaving little flexibility for changing flow conditions. As discussed below, this characteristic is especially problematic in the context of climate change.

Figure 1. Primary Focus of Transboundary Water Agreements Adopted During the 20th Century



Source: Jägerskog and Phillips 2006

A number of important elements of the hydrologic cycle are commonly left out of transboundary agreements, including groundwater and water quality provisions. Groundwater is typically excluded; if it is mentioned at all, it is usually in reference to contamination rather than use of groundwater resources. Likewise, many transboundary agreements that identify water allocations fail to include any standards for the quality of that water. This omission proved problematic for Mexican farmers in the 1950s and 1960s, where increasingly saline Colorado River deliveries impaired crop production. Extensive negotiations and several amendments were made to the treaty (Hundley 1966), and today, deliveries to Mexico are subject to salinity thresholds. Annual water deliveries to Mexico at Morelos Dam, for example, must have an average salinity no more than 115 parts per million (ppm) (±30 ppm) greater than the salinity of the river at Imperial Dam.

Many transboundary agreements also exclude monitoring, enforcement, and conflict resolution

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States of Lake Constance: Bade, Bavaria, Austria, Switzerland and Wurtemberg, Concerning the Regulation of the Flow of Water of Lake Constance near Constance, 1857; and Treaty for the Regulation of Water Withdrawal from the Meuse, Signed at the Hague, 1863).

procedures. Only about half of treaties have provisions for monitoring, and most monitoring efforts require only the most basic elements. This is particularly problematic given that data collection and sharing can provide an important base for negotiation. While disputes can be resolved by technical commissions, basin commissions, or government officials, 22% make no provisions for dispute resolution, and 32% of treaties are either incomplete or uncertain as to the creation of dispute-resolution mechanisms (Hamner and Wolf 1998).

While the conflict-resolution mechanisms in most treaties are undeveloped, new monitoring technology has introduced new enforcement possibilities. It is now possible to monitor a watershed from afar, using remote-sensed images (see Box 1). Hamner and Wolf (1998) suggest that the next major step in treaty development may be mutually enforceable provisions, based in part on objective and highly detailed remote images, better chemical testing, and more accurate flow computations than previously available.

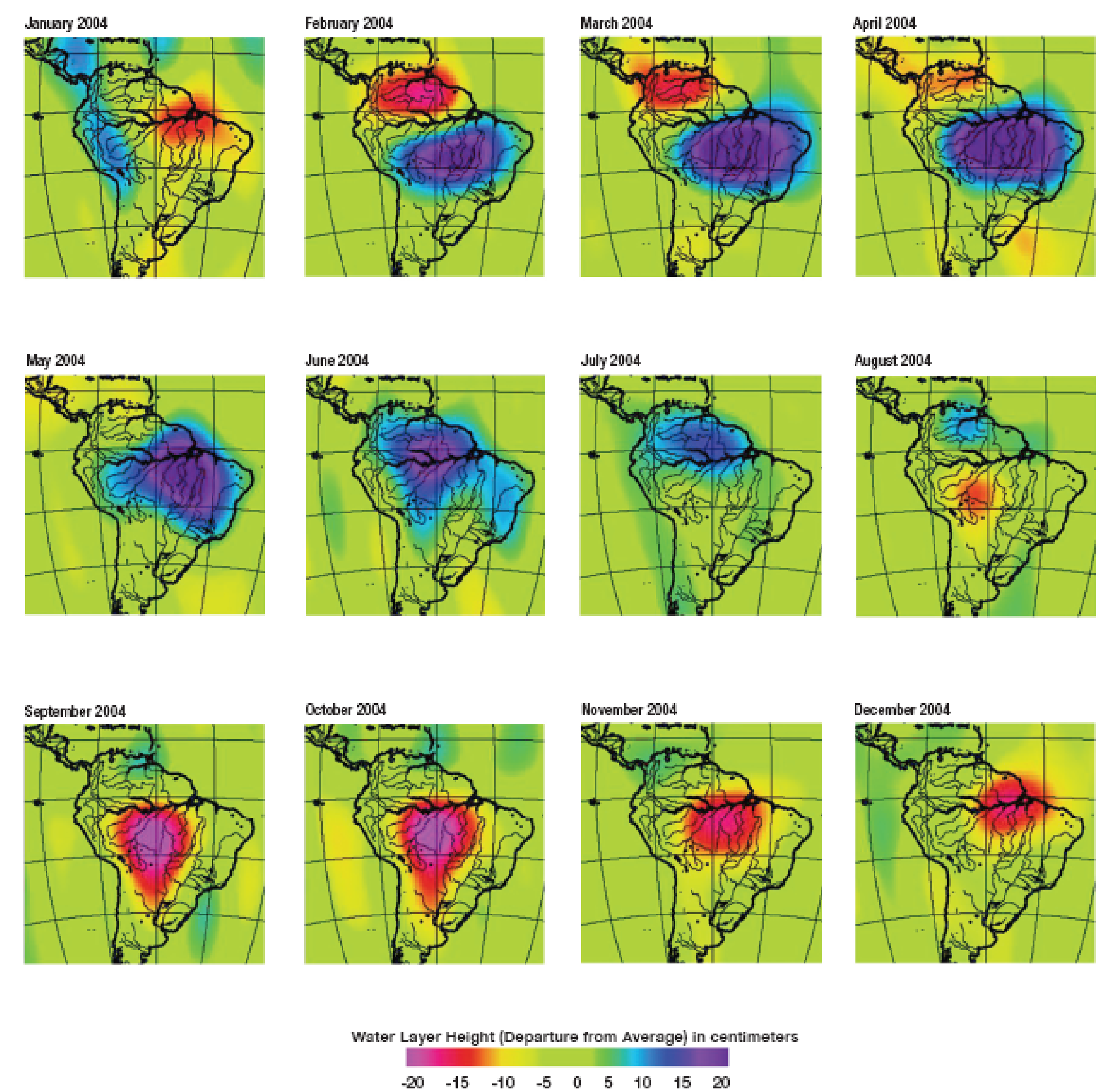
Box 1: GRACE Satellites

New technologies are introducing new enforcement and management opportunities. GRACE, or the Gravity Recovery and Climate Experiment, launched twin satellites in March 2002 to make detailed measurements of the Earth's gravity field. One of the important applications of this technology is tracking the movement of water around the globe, particularly groundwater about which little is known. For example, the amount of water flowing through the Amazon Basin varies from month-to-month and can be monitored from space by looking at how it alters the Earth's gravitational field. Figure 2 shows month-by-month water mass changes (relative to a 3-year average) over the Amazon and neighboring regions (NASA 2006). Oranges, reds, and pinks show where gravity is lower than average; greens, blues, and purples show where gravity is higher than average.

Results from the first few years of data have already delivered stark news about the status of groundwater resources world-wide. Using GRACE, scientists have found that groundwater levels in northern India have been declining by as much as 33 centimeters (1 foot) per year over the past decade. More than 108 cubic kilometers (26 cubic miles) of groundwater disappeared from aquifers in areas of Haryana, Punjab, Rajasthan and the nation's capitol territory of Delhi, between 2002 and 2008. This is enough water to fill Lake Mead, the largest man-made reservoir in the United States, three times (NASA 2009). In the United States, valuable agricultural regions are discovering that their groundwater is rapidly disappearing as well. Groundwater beneath California's San Joaquin Valley is dropping up to 198 centimeters (6 feet) a year in some locations (NASA 2008).

New efforts are linking remote sensing of water movement with climate change projections in an attempt to better understand the impacts on surface and groundwater resources. Recently, United Nations Educational, Scientific, and Cultural Organization-International Hydrological Programme (UNESCO-IHP) initiated the GRAPHIC project, or Groundwater Resources Assessment under the Pressures of Humanity and Climate Change. GRAPHIC integrates data on groundwater storage and flows, to model potential nonlinear responses to atmospheric conditions associated with climate change (Taniguchi 2008).

Figure 2. Monthly Water Mass Changes (Relative to a 3-Year Average)



Source: NASA 2006

Transboundary Water Management Policies and Climate Change

Rising greenhouse-gas concentrations from human activities are causing large-scale changes to the Earth's climate system. Because water is a fundamental element of our climate system, these changes will have important implications for the hydrologic cycle. Indeed, all of the comprehensive climate reports from the Intergovernmental Panel on Climate Change (IPCC) conclude that freshwater systems are among the most vulnerable to climate change. The Fourth Assessment Report notes that climate change will lead to "changes in all components of the freshwater system" (Kundzewicz 2007) and include impacts on water availability, timing, quality, and demand.

Most transboundary water agreements, however, are based on the assumption that future water supply and quality will not change. Climate change is rarely discussed in relation to transboundary agreements. Goulden et al. (2009) note that the IPCC Fourth Assessment Report, along with the technical report "Climate Change and Water," makes little mention of transboundary waters. The 2006 Human Development Report devoted an entire chapter to transboundary water management (UNDP 2006). Yet, climate change was not mentioned once. Recent work indicates that this is beginning to change. The literature on climate change adaptation and transboundary water management is growing. Natural Resources Canada evaluated the impacts of climate change on all of its transboundary water resources (Bruce et al. 2003). The United Nations Economic Commission for Europe (2009) recently produced "Guidance on Water and Adaptation to Climate Change," which focuses on issues specific to transboundary basins. Although drawn largely from experiences in Europe, North America, and countries in central and western Asia, the recommendations for improving the management of transboundary waters in the face of climate change, e.g., climate-proofing transboundary management, have general applicability.

Below, we describe the current state of the science on climate change impacts and water resources, emphasizing those elements that will affect transboundary agreements. We provide case studies of four shared basins (the Nile River, the Mekong River, the Colorado River, and the Guarani Aquifer) to illustrate a range of potential climate change impacts and response strategies. We conclude with a series of recommendations for climate-proofing transboundary agreements.

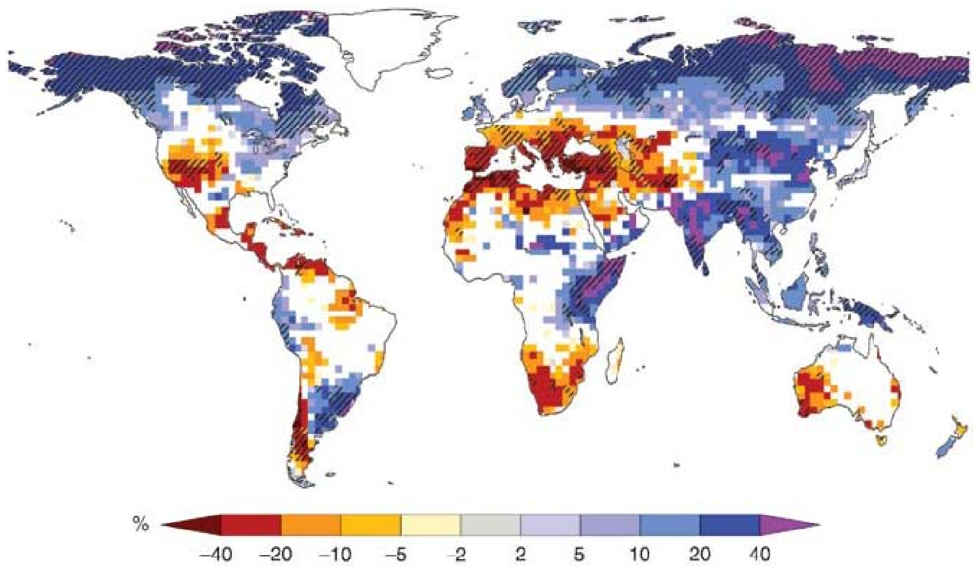
Climate Change and Transboundary Waters: the Science

Climate research is continuously updated as our understanding of the Earth system improves and modeling efforts advance. Below, we describe recent work on the projected impacts of climate change on global freshwater resources, emphasizing those changes that affect transboundary waters. This discussion is largely drawn from the IPCC Fourth Assessment Report, which was released in 2007, but includes additional studies, where appropriate.

Surface Water Runoff

The IPCC notes that several hundred studies have been done on the impacts of climate change on river flows (Bates et al. 2008). The vast majority of these studies has been done at the catchment scale and has been concentrated in Europe, North America, and Australasia. Figure 3 shows the projected change in annual runoff in river basins around the world from an ensemble of 12 climate models. Values represent the median of 12 climate models under the SRES A1B scenario. White areas indicate where less than 66% of the 12 models agree on the sign of change, and the hatched areas indicate where more than 90% of models agree on the sign of change. Results indicate that runoff is projected to increase in the high latitudes and wet tropics and decrease in the mid-latitudes and parts of the dry tropics. Expected changes exceed 40% in some areas. Note that models are not in agreement (white areas) on whether runoff will increase or decrease for large parts of Africa, South America, Australia, Greenland, and North America.

Figure 3. Large-Scale Relative Changes in Annual Runoff for the Period 2090-2099, Relative to 1980-1999.

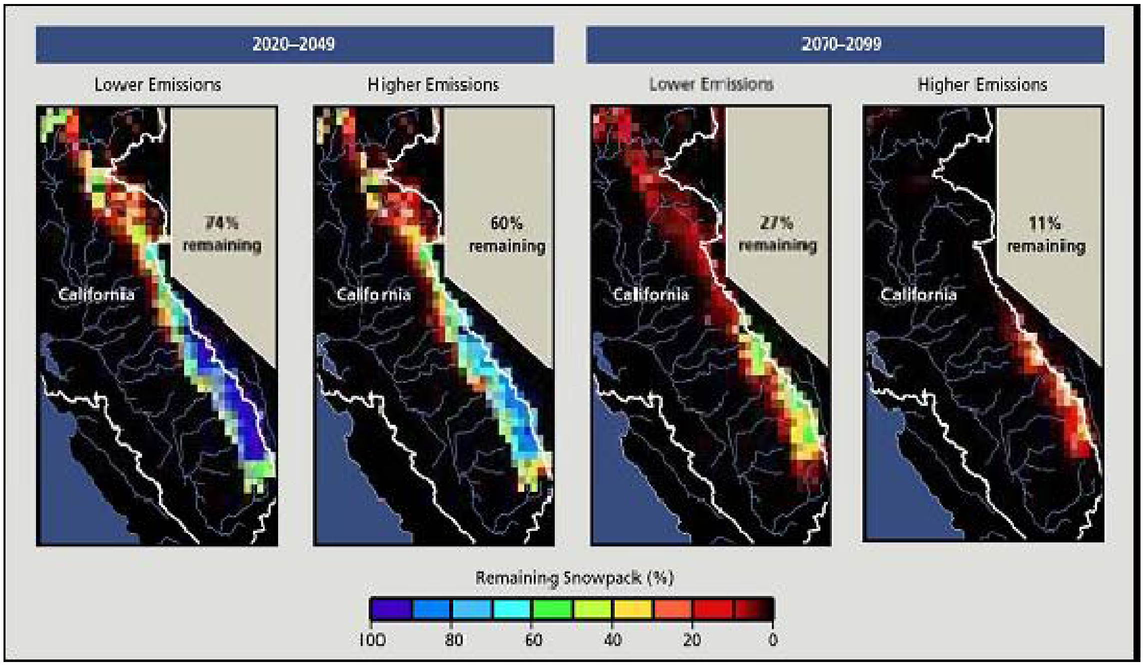


Note: Values represent the median of 12 climate models under the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change, and the hatched areas are where more than 90% of models agree on the sign of change.

Source: Bates et al. 2008

Models are in general agreement that climate change will affect the timing of runoff. In snow-dominated basins, hydrologic studies have long agreed that warming will result in earlier peak flows, greater winter flows, and lower summer flows. These effects are more pronounced in basins at or near the current snowline. For example, scientists forecast that as much as 70% of California's snowpack will be lost due to warming by the end of this century (Figure 4). Similar results have been seen in studies over the past two decades for the Colorado River basin, shared by seven states and Mexico (see, for example, Nash and Gleick 1991 and Barnett et al. 2008). In rain-dominated basins, studies suggest that changes in precipitation will have a greater effect on flows than warming temperatures.

Figure 4. Loss of California Snowpack Under Two Climate Scenarios by Mid- and Late-Century.



Source: Hayhoe et al. 2004

Groundwater

Because our understanding of groundwater and its uses are limited, the potential impacts associated with climate change are less well understood than for surface water. According to the IPCC, climate change will affect groundwater recharge rates, but these effects are site-specific; in some areas, recharge rates will increase whereas in other areas, it will decline. Higher evaporation rates will likely lead to salinization of groundwater, and sea level rise will increase saltwater intrusion in coastal aquifers. Additionally, demand for groundwater may increase as a means of offsetting reduced surface water flows in some regions (Kundzewicz et al. 2007), putting further pressure on transboundary groundwater systems. More data on groundwater use and recharge, would improve our understanding of these systems and our ability to examine and manage climate change impacts.

Floods and Droughts

Climate models suggest that warmer temperatures will very likely lead to greater climate variability and an increase in the risk of extreme hydrologic events such as floods and droughts. The frequency and intensity of both floods and droughts are expected to increase, e.g., a one-in-100 year event could become more frequent or severe. Many regions are expected to see an increase in the intensity of precipitation events, thereby increasing the risk of a flood. In areas that are projected to dry, the increase in intensity will be offset by a reduction in the number of precipitation events (Meehl et al. 2007). As described above, warmer temperatures will cause more precipitation to fall as rain rather than snow, thereby increasing the likelihood of winter floods. To make matters worse, the higher temperatures mean that what does fall as snow will melt faster and earlier, increasing the risk of summer drought. Mid-continental regions are also expected to dry during the summer, further increasing the risk of drought.

Water Quality

The connections between climate change and water quality are less well understood than impacts on quantity, although the literature on these connections is growing. Climate change is expected to increase water temperatures in lakes, reservoirs, and rivers, leading to more algal and bacterial blooms and lower dissolved oxygen concentrations. As temperatures rise and oxygen levels decline, the habitat available may decline for some cold water species but expand for some warm water species (Lettenmaier et al. 2008). More intense precipitation events could increase erosion rates and wash more pollutants and toxins into waterways, thereby threatening the health of freshwater species and humans (USDA 2008), increasing water treatment costs, and raising water rates (GAO 2007). Reductions in summer flows may further exacerbate water-quality concerns. And in coastal systems, rising sea levels could push salt water further into rivers, deltas, and coastal aquifers, threatening the quality and reliability of these systems.

Water Demand

The effects of climate change on water demands are far less studied than impacts on hydrology. Water demands in some sectors are sensitive to climate, particularly agriculture and urban landscapes. Plants typically require more water as temperatures rise, although higher atmospheric CO_2 concentrations can reduce water requirements under some conditions. Because agriculture accounts for about 70% of water use, demand changes in this sector may have broad implications. In some urban areas, lawns have become an increasingly important consumer of water, accounting for up to 70% of total residential water use in some hot, dry areas. Warmer temperatures will also increasing cooling water requirements for power plants and industrial operations. All of these demands could be mitigated by efficiency improvements.

Climate-Proofing Transboundary Agreements

Most treaties and international agreements fail to have adequate mechanisms for addressing changing social, economic, or climate conditions (for an early analysis of this problem, see Goldenman 1990). In many cases, adapting to climate change will require changes in the institutions and policies that have been put in place under international treaties. As noted by McCaffrey (2003) in an analysis of a treaty dispute before the International Court of Justice between Hungary and Slovakia, “the law of treaties itself will not ordinarily permit unilateral modification or withdrawal” under changing circumstances, including climate change. Rather, “Parties will be required to work within the framework of existing treaties to respond to changes.”

There are a variety of mechanisms that can be incorporated into existing treaties to allow for flexibility in the face of climate change. Fischhendler (2004) and McCaffrey (2003) identify four categories: (1) flexible allocation strategies; (2) drought provisions; (3) amendment and review procedures; and (4) joint management institutions. Although important, these mechanisms are highly focused on water scarcity. They are less applicable to other potential climate change impacts on water resources, including increased frequency and intensity of floods and water quality concerns. Below, we expand the scope of these mechanisms to include other potential water-related climate change impacts and provide examples where these mechanisms have been implemented.

Flexible Water Allocation Strategies and Water Quality Standards

Given the impact of climate change on water resources, transboundary agreements should address how riparian states will adapt to altered timing and availability of flows. Few treaties, however, address water allocation, perhaps due to its intensely political nature. Among those that do, about a quarter require equal allocations and the rest assign specific amounts to the various riparian states (Hamner and Wolf 1998). In most cases, these water allocations remain fixed (UNEP/OSU 2002), which does not provide the flexibility needed to adapt to changing conditions (McCaffrey 2003).

There are several legal and institutional arrangements for transboundary cooperation that can accommodate flow variability. A treaty may specify that an upstream riparian state deliver a minimum flow to a downstream riparian state in order to maintain human health and key ecological functions. While this approach may be less restrictive than requiring fixed deliveries, downstream riparians may consider minimum flows to offer too little protection while upstream parties may be concerned about their ability to always deliver the minimum flow. Another way to enhance treaty flexibility is to allocate water based on a percentage of the flow. This allows flow regimes to respond to both wet and dry conditions, although it requires flexible infrastructure, effective operating rules, and regular communication.

Much of the literature on transboundary agreements and climate change has focused on how changes in water flows will affect various water allocation strategies. Climate change, however, may also exacerbate water quality concerns in some locations. For example, sea level rise may intensify saltwater intrusion in deltas; in some cases, downstream water diversion facilities may become unviable unless freshwater inflows are increased. Greater discussion is needed on how water quality will be affected by climate change within the context of transboundary agreements. Furthermore, climate change assessments must include all of the potential impacts of climate change on water resources in order to inform transboundary management.

Response Strategy for Extreme Events

Many transboundary agreements include provisions for exceptional circumstances, such as droughts. In the agreement over the Rio Grande between the United States and Mexico, for example, Mexico is allowed to supply less than the minimum amount of water to the United States during an extraordinary drought for up to five years. During this period, Mexico incurs a water debt that they must then repay by increasing flows during the next five-year cycle. Provisions on the Colorado River are much more defined. In 2007, the United States implemented the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lake Powell and Lake Mead*. This agreement, developed in the eighth year of the worst drought in over 100 years of record keeping, establishes specific guidelines for reduced water deliveries among Basin states under drought and low-reservoir conditions. These shortage guidelines, which were developed in consultation with the Mexican government, are triggered at specific reservoir water levels in major reservoirs on the Colorado River (Lake Mead and Lake Powell), thereby providing water users with some indication of the frequency and magnitude of these events. While these guidelines were drawn up among the U.S. Basin states and do not address deliveries to Mexico, they can be used as a model for transboundary agreements.

Much of the literature on transboundary agreements and climate change emphasizes the impacts of droughts on water allocation schemes (Fischhendler 2004; Kistin and Ashton 2008; McCaffrey 2003). Floods are often ignored in transboundary water management. Yet, floods pose a real risk for downstream riparian nations and are expected to increase in frequency and intensity as a result of climate change. The failure to manage these risks can have catastrophic consequences. In a recent analysis, Bakker (2009) found that flood losses were higher in basins that lacked the institutional capacity for managing these events. [4] An overwhelming 43 international river basins where transboundary floods were frequent during the period 1985-2005 lacked the institutional capacity for managing these events.

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[4] Here, institutional capacity is defined as international water management bodies and freshwater treaties related to transboundary river flood events.

Coordinated flood management can greatly reduce the risk of these events. Flood management was one consideration in the Columbia River Basin Treaty, which stipulates that Canada (the upstream party) will adjust its operation of hydroelectric dams to mitigate flooding in the United States. In the Agreement on the Cooperation for Sustainable Development of the Mekong River Basin, maximum river flow rates are set, and upstream dam operations must be adjusted to meet these requirements. Basin-wide coordination of flood management activities is critical, and flood management protocols should be integrated into all transboundary agreements.

Amendment and Review Process

Even when the understanding about the hydrological dynamics of a particular basin is fairly advanced, conditions may change. Population and economic growth can create new demands for water resources. New water-quality criteria may develop. Scientific knowledge may advance. Societal perceptions about the importance of ecosystems may shift. In addition, global climate change may cause fundamental changes in the hydrologic cycle and be more severe and occur more quickly than anticipated. An amendment and review process in transboundary agreements is needed to allow for changing hydrologic, social, or climatic conditions or in response to new scientific knowledge (Fischhendler 2004). Treaty amendments can be made through a variety of mechanism. Within the Colorado River Basin, for example, amendments are made using “minutes” that then must be approved by all parties. A treaty could also be designed such that a separate body, such as a joint commission, could make treaty amendments (McCaffrey 2003).

Joint Institutions

Joint institutions can play an important role in managing transboundary water resources, particularly in light of changing conditions. According to a recent survey, only 106 international river basins have water institutions. And while approximately two-thirds have three or more riparian states, less than 20 percent of the accompanying agreements are multilateral (UNEP/OSU 2002). The roles and authority of these institutions vary widely. The ideal institution would have a broad scope, include all riparian nations, and have management and enforcement authority. Yet, the creation of such a supra-national authority can be perceived as a threat to more politically powerful nations for fear of losing power (Fischhendler 2004).

A joint body can fulfill a variety of roles to facilitate adaptation to climate change. In particular, such a body could convene a technical committee to develop a common hydrologic model of the basin and common climate change scenarios. The International Commission on the Protection of the Rhine, for example, recently commissioned an assessment of the state of knowledge on climate change and its expected impacts on the water regime of the Rhine (ICPR 2009). Most of the hydrological models of future climate change in the Rhine Basin show a risk of an increase in winter runoff and a reduction in summer runoff, indicating a need to adjust the water management regime to accommodate greater variability, especially the equitable allocation of lower summer flows. The Commission established a climate change expert group to develop a basin-wide adaptation plan that will be finalized in 2010. This approach has helped facilitate a shared understanding of the potential impacts of climate change and is paving the way for the implementation of adaptation measures throughout the entire Rhine River Basin.

Case Studies

As described above, most transboundary agreements remain inflexible and efforts to integrate climate change into transboundary management have been limited. We provide four case studies to demonstrate the range of potential impacts of climate change, including greater uncertainty in the Nile River Basin; wetter conditions in the Mekong River Basin and Guarani Aquifer Basin; and drier conditions in the Colorado River Basin. In each of these regions, climate change has been integrated into transboundary water management, although to varying degrees.

The Nile River Basin

The Nile River is of tremendous regional and historic importance. It supported one of the world's earliest civilizations, which depended on its annual floods to replenish fertile agricultural lands. Today, the basin is home to an estimated 160 million people that depend on its waters for navigation, irrigation, drinking water, hydroelectricity generation, and waste disposal.

The Nile is the world's longest river, flowing nearly 6,700 kilometers (km) across northeastern Africa. The Nile drains an area of approximately 3.3 million square kilometers (km^2), about 10% of the African continent, across eleven countries - Egypt, Sudan, Ethiopia, Eritrea, Uganda, Kenya, Tanzania, Burundi, Rwanda, the Democratic Republic of Congo, and the Central African Republic (Figure 5). Natural flows in the Nile River average 110 cubic kilometers (km^3) per year but are subject to significant spatial and temporal variation (NBI 2009). Nearly all of the Nile flows originate in the headwaters, whereas half of the river's length flows through countries with no effective precipitation, i.e., Egypt and Sudan, where demands and dependence on the river are especially high (UNEP 2000).

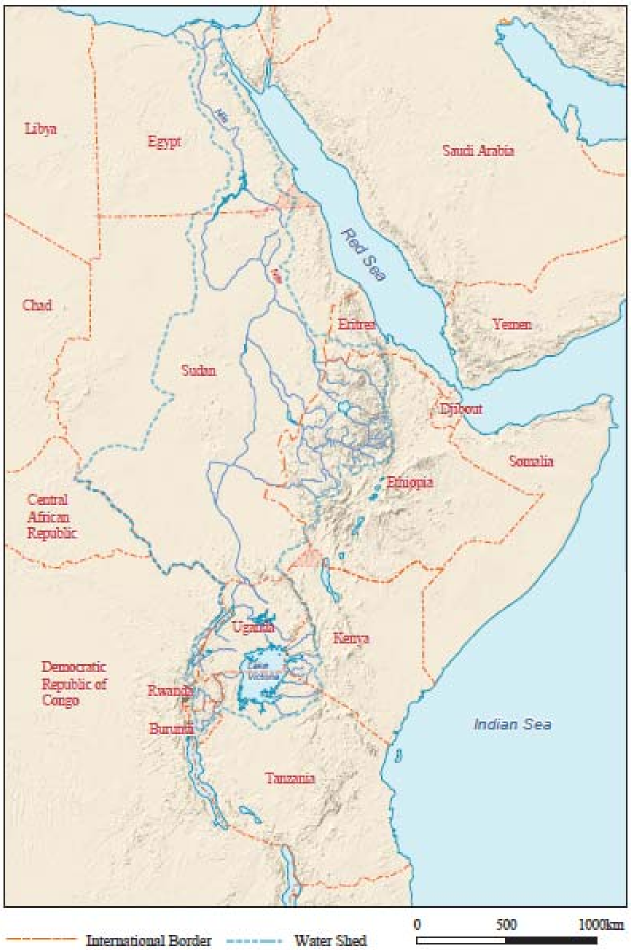
Water scarcity is the primary water management challenge in the Nile River Basin. Currently, concerns about water scarcity have been limited to drought periods, such as the prolonged drought that gripped the region from 1978-1987. Rapid population growth in both upstream and downstream countries, especially Ethiopia and Egypt, is increasing demand for scarce resources. Irrigated agriculture is also on the rise, placing additional pressure on the region's limited water resources. Egypt is planning a major expansion of irrigated agriculture in the Western Desert and Sinai and has initiated work on what may be the world's largest pumping station (Conway 2005). In a recent analysis, Conway (2005) notes that "Scarcity at the moment is not compelling as there is still some slack in the system but it is rapidly approaching and potentially a huge threat to the status quo." Environmental degradation and threats to water quality are also major regional challenges.

Legal framework for Managing the Nile River

The Nile River has been the subject of numerous treaties, many of which were from the colonial era. Today, the distribution of Nile water is governed by the Nile Waters Treaty, a bilateral agreement between Egypt and Sudan that was signed in November 1959. Under this agreement, Egypt and Sudan are apportioned 55.5 km^3 and 18.5 km^3 per year, respectively. An additional 10 km^3 was allocated to evaporation from the Aswan Dam. The cost of projects that increased water flows in the Nile and the water produced by such projects would be split equally among Egypt and Sudan. The Nile Waters Treaty also established a Permanent Joint Technical Commission to resolve disputes and review claims made by other riparian countries. The Commission was also tasked with devising a fair water allocation scheme for persistent low-flow periods that would then be presented to each government for approval.

Figure 5. Map of the Nile River Basin

Source: Nile Basin Research Programme (http://www.nile.uib.no)



There have been numerous activities and initiatives within the region designed to promote cooperation among the Nile Basin countries. The first of these was the Hydromet Survey Project, which was established in the 1960s and designed to collect and process hydrometeorological data in support of more effective management of the Nile (see UNEP 2000 for an overview of many of these initiatives). A more recent and ongoing effort, the Nile Basin Initiative (NBI), was established in 1999 by the water ministers of 9 riparian countries – Egypt, Sudan, Ethiopia, Uganda, Kenya, Tanzania, Burundi, Rwanda, and the Democratic Republic of Congo.[5] The Initiative "seeks to develop the river in a cooperative manner, share substantial socioeconomic benefits, and promote regional peace and security." With support from its member countries and a series of bilateral and multilateral donors, e.g., the World Bank, African Development Bank, and Global Environmental Facility, the Initiative has funded projects to build trust and cooperation among Basin countries and contribute to technical information and scientific knowledge about the Basin. The Initiative also funds projects related to the common use of the Nile Basin water resources, such as the construction of water supply projects or electricity transmission lines to improve energy security among Basin countries. Rather than focusing on reallocating flows, the Nile Basin Initiative has worked on the concept of sharing the many benefits of water, including energy generation, industrial use, and navigation (Jägerskog and Phillips 2006). Upon conclusion of the decade-long negotiations over the Agreement on the Nile River Basin Cooperative Framework, the Nile Basin Initiative is to be replaced by the Nile River Basin Commission.

Climate Change and the Nile River Basin

Studies on the impacts of climate change on water resources in the Nile basin are numerous and span nearly three decades (see, for example, Kite and Waititu 1981, Hulme 1990, Gleick 1991, Conway and Hulme 1996; Yates and Strzepek 1998, Strzepek et al. 2001, Kim et al. 2008). The Nile is a rain-dominated system and changes in precipitation and evaporation are likely the primary driver for changes

[5] Eritrea and the Central African Republic, which lies within a very small portion of the Nile Basin but are not a riparian countries, are not a member of the Initiative.

in runoff. While most general circulation models are in agreement that temperatures will rise in the region, the direction and magnitude of changes in precipitation and, by extension runoff, remain uncertain. Yates and Strzepek (1998), for example, found that runoff increased in two out of three scenarios. In a later study, however, the Nile became drier and runoff declined (Strzepek et al. 2001). In a recent study focused on the Upper Blue Nile, Kim et al. (2008) projects that the region will become warmer and wetter by mid-century, low flow periods may decline, and "severe mid- to long-term droughts are likely to become less frequent throughout the entire basin."

Efforts to integrate climate change into long-term planning and management of the Nile River Basin have been limited, although recent efforts suggest this may be slowly changing. The Nile Waters Treaty dates back to 1959 and, not surprisingly, makes no explicit mention of climate change. Water allocations are fixed, which raises concerns about the ability to adapt to changing runoff patterns. The Treaty does, however, have provisions that offer some degree of flexibility. In particular, the Permanent Joint Technical Commission can make recommendations for new water allocations in response to flow reductions, although this power has never been exercised by the Commission (Conway 2005). In recent years, the Nile Basin Initiative has supported research and analysis to better understand the vulnerability of the Basin to climate change and evaluate adaptation actions to reduce climate-related risks. They are now developing a Nile Basin decision-support system that will provide a framework for sharing information, understanding river system dynamics, and evaluating alternative development and management schemes. Although climate change was not explicitly mentioned in the project scoping information, the tool may prove useful in integrating climate change into management of the Nile Basin water resources.

Mekong River Basin

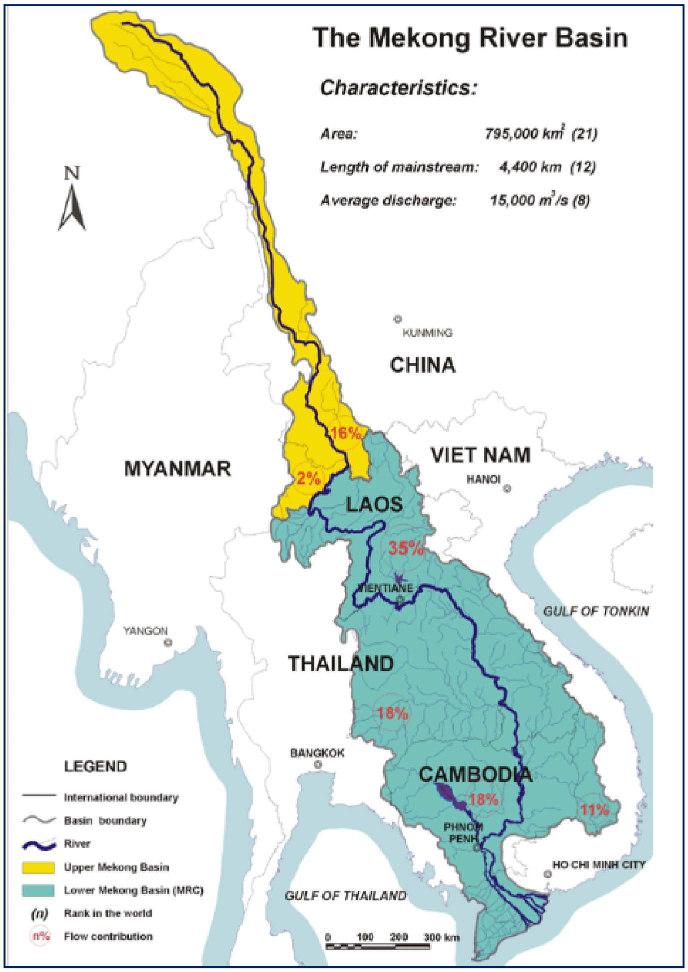
The Mekong is among the world's longest river, flowing 4,800 km across southeastern Asia. The Mekong drains an area spanning 795,000 square kilometers across six countries - China, Myanmar, Vietnam, Thailand, Cambodia and Loa PDR (Figure 6). Flows in the Mekong average around 470 km^3 per year but are subject to significant seasonal variation.

The Mekong basin includes some of the world's poorest regions; in some areas, 40% of the population lives in poverty (MRC 2009). Currently, the river is used for irrigation, production of electricity, transportation, and fishing. Development of the basin to reduce poverty, while minimizing impacts on ecosystems that also support local economic activities such as fishing, is a major challenge. Countries have different and potentially conflicting strategies for development and corresponding uses of the river. China, in particular, has proposed 15 hydroelectric dams in the upper basin to support the country's economic growth (Wolf and Newton 2008). Because of the dependency of the river ecosystem and lower basin farming on annual flood pulses, the impacts of hydro-electric dams on the flood regime of the river may adversely impact productivity and biodiversity, particularly in Cambodia and Vietnam (Jägerskog and Phillips 2006).

Managing the river's complex flooding regime is also a challenge. While both humans and ecosystems have adapted to natural seasonal flooding, changes to flood patterns could potentially be devastating. Deforestation in Thailand has contributed to flash floods in the rainy season. Additional development of the basin, as well as climate change, has the potential to further alter natural flooding patterns (Hirji and Davis 2009).

Figure 6. Map of the Mekong River Basin

Source: Vietnam National Mekong Committee 2009



Legal Framework for Managing the Mekong River

Unlike in many other transboundary basins, an international committee and management framework were created in the Mekong basin before water stress or other tensions became a problem. Studies by the United Nations' Economic Commission for Asia and the Far East (UNECAFE) and the U.S. Bureau of Reclamation in the 1950s noted the potential for irrigation and hydroelectric development and the need for coordinated development of the Mekong River basin (MRC 2009). The first treaty was signed by the four lower-basin countries – Cambodia, Laos, Thailand and Vietnam—in 1957, establishing a joint committee for investigation, planning, and development projects in the basin. Cambodia left the committee in 1977, at which point an interim committee was set up among the remaining 3 countries. Cambodia rejoined in 1995 when the Agreement on the Cooperation for Sustainable Development of the Mekong River Basin (Mekong Basin Agreement) was signed. This agreement established the Mekong River Commission that exists today. Cambodia, Laos, Thailand and Vietnam are full members of the commission. China and Myanmar are not parties to the agreement and have observer status within the Mekong River Commission.

When it was created, the Mekong River Commission was charged with writing a Basin Development Plan. This plan is designed to help balance economic development and environmental protection in the basin, combining three elements: development scenarios, an Integrated Water Resources Management (IWRM)-based strategy, and structural and non-structural investment. The IWRM strategy is meant to integrate development concerns and resource protection in order to create a sustainable management strategy (MRC 2009).

The Mekong Basin Agreement does not allocate water, but requires that the countries "utilize the waters of the Mekong River system in a reasonable and equitable manner" (Mekong Agreement 1995). Uses of water that will significantly impact water flows or quality must be reviewed and approved by the Commission. The Commission has developed minimum monthly flows, along with a requirement to prevent daily average peaks greater than what naturally occurs during flood season (MRC 1995).

Climate Change and the Mekong River Basin

A number of studies have assessed the potential impacts of climate change on the Mekong Basin. The basin is expected to be affected by climate change through warmer, wetter weather, and by sea level rise, both of which will change flooding patterns. All recent studies that modeled climate change in the basin (Kiem et al. 2008, TKK & SEA START RC 2009, Eastham et al. 2008, Hoanh et al. 2003) agree that temperatures will rise in the basin. One study found that the increase will be relatively homogenous throughout the basins (Hoanh et al. 2003), while others found that it will be greatest in the cold, northern part of the basin (Kiem et al. 2008, Eastham et al. 2008). Precipitation is predicted to increase, although some studies suggest that increases will not be notable until the second half of the century (TKK & SEA START RC 2009, Hoanh et al. 2003). It is unclear whether increased annual precipitation would be caused by an increase in the length of the rainy season, or only by increased intensity of rain events. As a result of increases in precipitation, some studies found that the number of river "low flow" days will decrease (Kiem et al. 2008), or that minimum flows will increase (Eastham et al. 2008).

The river's flood regime will be altered by climatic changes in the basin. One study found that the impact of sea-level rise on flooding will be modest in most of the basin compared to that caused by changes in hydrology (TKK & SEA START RC 2009); other studies did not compare impacts of sea level rise and hydrologic changes. A study specifically on sea-level rise found that the average water level in the Vietnamese Mekong Delta will rise 11.9 cm during peak flood season with 20 cm of sea level rise, and 27.4 cm with 45 cm of sea level rise, based on sea level rise alone (Wassman et al. 2004). Various studies found that there will be higher water levels during flooding (TKK & SEA START RC 2009), increased area of land flooded (TKK & SEA START RC 2009, Eastham et al. 2008), longer flood duration (TKK & SEA START RC 2009), and more frequent flooding in some areas (Eastham et al. 2008).

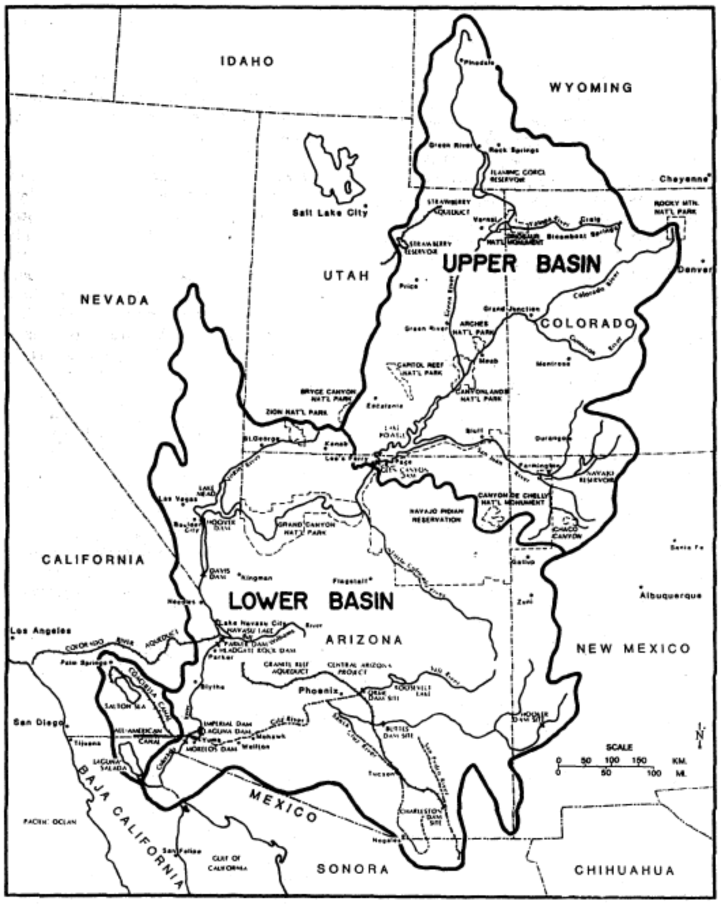
Treaties in the basin do not explicitly mention climate change, so there is no legal framework for collectively addressing climate change. The Mekong River Commission, however, has developed a climate change adaptation initiative. At a forum held in 2009, all six basin countries met and shared research and data, discussed national climate change adaptation strategies and challenges, and identified research gaps. Challenges identified included the need to integrate climate change considerations into development planning and the need for adequate funding and institutional capacity to implement adaptation strategies. The forum expressed the need for continued meetings of basin countries to discuss climate change and a basin-wide mitigation and adaptation plan (MDCCF 2009). Additionally, the Mekong River Commission has agreed on certain mainstream flow maintenance requirements, which may be important in the future as continued hydroelectric development and climate change alter river flows.

The Colorado River Basin

The Colorado River basin covers 632,000 km^2, roughly 95% of which is in the southwestern U.S. and 5% is in northwestern Mexico (Figure 7). The river itself runs more than 2,300 km from its headwaters in the Rocky Mountains to its mouth at the Gulf of California. The river's estimated natural, undepleted average annual flow near the border for the period 1950-2006 was 19.4 km^3, but annual runoff in the basin is highly variable, ranged from 7.9 km^3 to 33.8 km^3 per year. An estimated 70-80% of the river's waters are diverted by farmers to irrigate some 12,000 km^2. Much of the remaining water satisfies the domestic and municipal needs of at least 27 million people in the United States and Mexico, including the burgeoning cities of Las Vegas, Los Angeles, Mexicali, Phoenix, San Diego, and Tijuana. The Colorado River system also has some of the world's largest dams and reservoirs, capable of storing over 70 km^3, or between four and five times the river's average annual flow.

Figure 7. Map of the Colorado River Basin

Source: U.S. Bureau of Reclamation



More than 80% of runoff in the basin originates from less than 20% of the basin area, generally in the Rocky Mountains at elevations above 2,500 meters (Hoerling et al. 2009). The hydrology of the Colorado is largely snowmelt-driven, with 70% of the river's annual pre-impoundment flow occurring from May through July (Harding et al. 1995). Much of the basin, especially the border region, is extremely arid, with less than 8 cm of precipitation per year. Tight institutional and structural controls severely constrain the river's natural variability and significantly reduce the volume of water actually flowing to the border. In recent years, the river rarely has had enough water to reach the sea.

The basin is suffering from a decade-long drought, with annual flows during this period at about 75% of average. Continued rapid population growth at a time of declining supplies is one of the major challenges facing the region. The basin is home to some of the fastest-growing cities in the U.S. Growing municipal demands have been the greatest single driver behind recent institutional changes, increasing opportunities to conserve and move water around the system. An additional demand on the system, though at a much smaller scale, is for instream flows to sustain native mainstem and off-channel habitats (Glenn et al. 1996, Kowalewski et al. 2000, Pitt et al. 2000, Zamora-Arroyo et al. 2008).

Legal Framework for Managing the Colorado River

A dense yet dynamic set of regulations, interstate compacts, agreements, contracts, judicial decisions, and an international treaty with 317 "minutes" (essentially, amendments and clarifications of the treaty), known collectively as the "Law of the River," govern the allocation and use of the Colorado River. By treaty, the U.S. delivers a minimum of 1.85 km^3 of water to Mexico each year, within a prescribed salinity range. Within the U.S., the Law of the River has allocated to users around 18 km^3/yr (15 million acre-feet/year) of Colorado River water, divided equally between the upper basin (comprised of the upper division states of Colorado, New Mexico, Utah, and Wyoming) and the lower basin (comprised of the lower division states of Arizona, California, and Nevada).

The recent drought in the Colorado River Basin has spawned a number of important changes to the management of the shared waters. Despite the current drought, deliveries to lower basin and Mexican users have not been reduced, causing reservoir levels to drop by more than 37 meters and total system storage to fall by roughly 27 km^3 – nearly double the river's average annual flow. In response, water users in the United States adopted the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lake Powell and Lake Mead* ("Interim Guidelines") in December 2007. These Interim Guidelines define and allocate water shortage among lower basin users, providing certainty and predictability about future deliveries. The Interim Guidelines also create a novel multi-year water augmentation and banking program known as "Intentionally Created Surplus," allowing lower basin water users to invest in water conservation efforts and store the water saved by such efforts for delivery in future years. A related program, called "Developed Shortage Supply," creates similar mechanisms to generate and store water to be delivered during declared shortages, buffering the users against major reductions. Although the Interim Guidelines create a loophole to allow Mexican users to participate in such programs at some future time, they explicitly apply only to U.S. users and do not affect deliveries to Mexico.

The 1944 Treaty with Mexico governs deliveries to Mexico. The Treaty stipulates that deliveries to Mexico may be reduced "in the same proportion as consumptive uses in the United States are reduced" (Article 10(b)) during an "extraordinary drought." The Treaty, however, offers no definition of "extraordinary drought," and no agency is charged with determining or declaring an "extraordinary drought." At the time the treaty was signed, and for the following 55 years, the prospects of reducing consumptive uses in the U.S. were remote. Now, with the impetus of the Interim Guidelines and the prospect of a unilateral determination of "extraordinary drought" by the upstream riparian, representatives from Mexico and the U.S. have begun discussions about potential reductions in deliveries to Mexico. These discussions have purposefully avoided the definition of "extraordinary drought," choosing instead to explore conditions under which Mexico would voluntarily reduce its annual delivery, the conditions that would trigger such a voluntary reduction, and initial modeling efforts to project potential reductions in deliveries under various scenarios and operating guidelines. Facilitating these discussions have been parallel discussions among Mexican and U.S. water agency staff, non-governmental organizations, and state and federal water authorities, who have been exploring opportunities to develop an "Intentionally Created Mexican Allotment" (ICMA) similar to the U.S.-specific "Intentionally Created Surplus." Through ICMA, U.S. and Mexican water users or other entities could invest in efficiency and augmentation programs in Mexico, such as lining canals or automating irrigation systems or building desalination plants, in return for either permanent or temporary use of a portion of the water conserved or generated. Additionally, Mexican users could have the opportunity to store some portion of the conserved water in Lake Mead, potentially as a buffer against future delivery reductions and as a means to create environmental pulse flows. These discussions are still preliminary and years from agreement and implementation. Yet the renewed cross-border discussions mark a dramatic departure from the antagonism and litigation that clouded discussions several years ago.

Climate Change and the Colorado River Basin

Drought is a natural feature of the Colorado River Basin. Recent analysis of tree-ring records shows several multi-year droughts that dwarf the current drought, both in duration and severity. Layered atop this normal variability lies the projected increase in temperatures and changes in precipitation due to climate change. Estimates of average temperature increases in the basin by the year 2050 range from 2 °C to 4 °C (Christensen and Lettenmaier 2007, Barnett and Pierce 2009). Eighteen of nineteen climate models show a drying trend in the lower and Mexican portions of the Colorado River basin, with the hydrology becoming consistently drier throughout the century (Seager et al. 2007). However, 80-85% of Colorado River runoff originates from precipitation at elevations above 2500 meters, where projections of changes in the timing and magnitude of precipitation are less certain. Nonetheless, a recent study projects that greater water losses to evaporation and infiltration to drier soils will likely reduce Colorado River runoff by 6-20% by 2050 (Ray et al. 2008).

These reductions in runoff will come just as the combination of rising temperatures and decreasing precipitation will increase irrigation demands, already the largest user of Colorado River water.

Population growth will also place additional demands on the declining resource. The massive storage capacity of the Colorado River system has, so far, masked the impacts of the tension between these rising demands and declining supply, including tensions between users on both sides of the border. Extensive modeling by the U.S. Bureau of Reclamation projects a greater than 30% probability of reduced deliveries to lower basin users in 2026, even without climate change. Studies of conditions in the basin under climate change project that shortages will be chronic by mid-century, though the frequency and magnitude of such shortages depend upon assumptions about future runoff and upper basin use (Barnett and Pierce 2009, Rajagopalan et al. 2009).

Most of the climate change literature for the Colorado River basin does not address impacts on water quality, though Nash and Gleick (1991, 1993) evaluated how climate-induced changes in flow would affect salinity. Increasingly saline Colorado River deliveries in the 1950s and 1960s led to protests from Mexican farmers (whose crop production was impaired) and Mexican officials, resulting in extensive negotiations and several amendments to the treaty (Hundley 1966). Minute 242 (signed in 1973) to the treaty creates salinity thresholds, for instance requiring that annual water deliveries to Mexico at Morelos Dam have an average salinity of no more than 115 ppm (±30 ppm) greater than the salinity of the river at Imperial Dam. In recent years, as flows have decreased at Imperial Dam, the salinity differential has crept closer to the legal maximum. The U.S. Bureau of Reclamation maintains operational control over the river in the lower basin and can adjust volumes of agricultural return flows to meet the salinity threshold. These manipulations can affect groundwater pumping in the U.S. portion of the border region. To date, upper basin salinity control projects currently remove more than one million tons of salt from the river annually (IBWC 2009).

Neither the 1944 Treaty with Mexico, nor any of the 317 subsequent ‘minutes’ of the International Boundary and Water Commission, contains any reference to climate change. Yet, the treaty has demonstrated resilience in the face of changing conditions, evidenced by the many amendments adopted to date. The precedent of modifying the treaty to address new environmental concerns such as salinity suggests that recognition and integration of climate change impacts is also possible (Tarlock 2000).

Although not directly tied to concerns about climate change, the recently negotiated Interim Guidelines (USBR 2007) and subsequent discussions with Mexico demonstrate the willingness among users to adjust operation and management of the system in the face of changing conditions, especially extreme events. Additionally, the Interim Guidelines included an appendix containing the report “Review of Science and Methods for Incorporating Climate Change Information into the U.S. Bureau of Reclamation’s Colorado River Basin Planning Studies,” laying the foundation for future integration.

Recent remarks by a senior U.S. official (Castle 2009) also indicate that adapting to climate change impacts in the basin is a high priority. The on-going bilateral discussions among federal officials and other parties build upon the long-term efforts of municipal water agencies in the U.S. to develop creative mechanisms to increase the flexibility of the Law of the River, and benefit from the rich historic streamflow record and extensive modeling experience and capacity. These discussions, about criteria for accepting voluntary reductions as well as extension of the market-based conservation and augmentation mechanisms within the Interim Guidelines, offer hope that, at least in the near term, the impacts of the continuing drought on the basin and potentially those of climate change may be managed and mitigated through mutual agreement.

Guarani Aquifer

The Guarani basin is the largest groundwater aquifer in the world, with a storage volume of about 40,000 km^3 and an annual recharge rate of 40-60 km^3. The aquifer lies under 1.2 million km^2 of South America and is shared by four countries - Brazil, Uruguay, Paraguay, and Argentina (Figure 8). About 80% of the water extracted from the aquifer is used for public water supply. Although the total volume withdrawn is still fairly modest, uncontrolled drilling and extraction, along with point and nonpoint source pollution are problems in all four nations that share the groundwater basin (GEF 2000). While conflict has been limited in the past, the importance of the aquifer as a strategic water reserve and the potential for future pressures to diminish its quantity and quality are a major concern (Wolf and Newton 2008).

Figure 8. Map of the Guarani Aquifer

Source: Wolf and Newton 2008

Legal Framework for Managing the Guarani Basin

The existing legal framework for groundwater management is undeveloped and fractured. There are few procedures for allocation and use licensing or decision-making regarding shared groundwater resources in the area (Foster et al. 2006). In Argentina and Brazil (federal countries), groundwater management is left up to individual states or provinces, and in many cases, there is little institutional capacity to monitor and manage groundwater resources. Paraguay and Uruguay do not have a comprehensive water law although groundwater provisions are found in various pieces of national legislation. Uruguay is the only country that has a specific decree regulating the use of the Guarani aquifer (passed in 2000).

In 2003, the four countries initiated the Project for the Environmental Protection and Sustainable Development of the Guarani Aquifer System, also known as the Guarani Aquifer Project to address the absence of national and trans-boundary groundwater development and management policies. The Guarani Aquifer Steering Council (CSDP) was established with national representatives from each riparian state who are responsible for groundwater resources. In 2008, the CSDP approved a Strategic Action Plan that establishes work products and concrete actions for each country to take to maintain the SISAG (a GIS database of the aquifer) and a monitoring network. Beyond this, it seeks to promote cooperation between the actors to protect and incentivize sustainable use of the aquifer. Unfortunately, there is little mention of governance or climate change in the Strategic Action Plan. The goal is for the CSDP to evolve into a permanent structure that will co-evaluate and negotiate major aquifer development with potential trans-boundary effects. However, clear operating rules are still not in place and it remains to be seen how effectively the CSPD will operate in the future.

The countries that share the Guarani Aquifer have a history of cooperation, at least regarding surface waters. In 1969, the countries adopted La Plata River Basin Treaty that addressed the area within La Plata River watershed, which overlies much of the Guarani aquifer (though La Plata River basin it extends further south into Argentina). The treaty established a Coordinating Inter-governmental Committee (CIC) responsible for promoting, coordinating, and furthering multilateral action to maximize the use of La

Plata Basin resources and ensure the harmonious and balanced development of the region. The initial goals of the treaty only applied to surface waters and did not extend to groundwater. In 2003, however, Argentina, Bolivia, Brazil, Paraguay, and Uruguay started a program to monitor and control the effects of climate variability on La Plata River basin; to improve the available data on social, economic, environmental and physical aspects; and to develop a new framework for water resource management. The progress made in the Guarani Aquifer Project generated a demand for the inclusion of the groundwater in the new Framework Program for La Plata Basin. While the Framework Program is still being developed (scheduled to be completed by 2013), it offers a unique opportunity to unify surface and groundwater management, particularly in relation to climate change planning in the region.

Climate Change and the Guarani Basin

Studies on the impacts of climate change on water resources of the Guarani aquifer are limited. Researchers studying the overlying La Plata River basin, however, have developed detailed regional studies. These climate models consistently show a trend toward increasing precipitation (Bello et al. 2009). In the region of La Plata basin, Meehl et al. (2007) showed an increase in precipitation of up to 20% by 2050 under a range of climate scenarios. These changes are expected to increase the risk of flooding. More frequent and intense flooding events could degrade surface and groundwater quality as a result of erosion, sewer overflows, and the dispersion of agricultural chemicals into nearby water bodies.

While most models show an increase in precipitation over the Guarani aquifer, 60% of Latin America is projected to become drier (Magrin et al. 2007). The need for reliable potable water supply sources could grow considerably, and demand for high-value agricultural and industrial uses is also likely to increase substantially. In order to accommodate these demands, water managers are increasingly considering water transfers and greater reliance on groundwater sources (Magrin et al. 2007), including the Guarani aquifer.

Management of the Guarani aquifer is still in the nascent stages. While there is currently no treaty in place to specifically regulate groundwater use, there are efforts underway to integrate groundwater management into La Plata River Basin Treaty through the development of the new Framework Program. Within La Plata River Basin, climate change is beginning to be integrated into the management of the shared waters. In particular, funding for much of the localized climate change studies described above was provided by the Plata Basin Financial Development Fund. Such studies can be an important avenue for developing a shared understanding among those sharing the basin and encourage cooperation in developing adaptation strategies. Additionally, this fund was set up through an amendment to the original La Plata River Basin Treaty, another indication of flexibility under changing conditions.

Summary of Case Studies

These four case studies highlight the diversity of principles, policies, and institutions that guide the management of transboundary waters. Each example of a transboundary agreement was developed under diverse circumstances, addresses different concerns, and has a unique set of constraints. These case studies also demonstrate a range of potential climate change impacts; some areas will become wetter, others will become drier, and many will exhibit greater variability (Table 3).

Given these differences, each agreement must be evaluated independently. Natural Resources Canada, for example, evaluated the potential impacts of climate change and the implications for existing treaties and agreements in each of its shared river basins (Bruce et al. 2003). For each basin, they developed a short list of immediate actions for improving these agreements in the face of climate change. In the Columbia River Basin, for example, Natural Resources Canada recommends shortening the period between operating rule revisions for flood management (the current treaty revises these rules every 5 years) as a way to regularly review changing circumstances. In the Saint Mary and Milk River Basins, they recommend recalculating “natural flows” to take into account increased evaporation from surface reservoirs. This kind of regular re-analysis should be expanded and completed for all shared water basins.

Table 3. Characteristics of Transboundary Basins

Characteristic	**Guarani Basin**	**Mekong River Basin**	**Nile River Basin**	**Colorado River Basin**
Number of nations sharing Water/Number included in treaty	4/0	6/4	11/2	2/2
Annual Flow	Recharge: ~40 – 60 km^3/year Total storage: ~40,000 km^3	~470 km^3	~110 km^3	~19 km^3
Allocation (volume or % of flow)	2-4 km^3/year (average use)	none	>75%	>100%
Water allocation structure	Unregulated	None ("reasonable and equitable use")	Fixed	Fixed for Mexico and for lower basin users in U.S.; proportional for upper basin users in U.S.
Shortage Procedures	None	None	Determined by Permanent Joint Technical Committee	For Mexico, still under negotiation. For lower basin, fixed based on Interim Guidelines. For upper basin, supply constraints based largely on availability.
Conflict resolution processes	Guarani Aquifer Management Framework and Guarani Aquifer Steering Council	Referred to Mekong River Commission	Referred to Permanent Joint Technical Committee	Referred to International Boundary and Water Commission
Hydrologic Modeling experience	Moderate	Moderate	Extensive	Extensive in U.S.; limited in Mexico
Climate Impact Studies	Few	Several	Many	Many
Expected climatic changes (See specific regional scientific assessments for details.)	Precipitation and surface runoff may increase	Increased temperature and precipitation; increased flooding	Increased variability of runoff; large increase in evaporative demand	Increased temperature; Substantial loss of snowpack, leading to changes in timing of runoff; increased evaporative loss from reservoirs. Precip-itation forecasts less consistent, ranging from no change to reductions of about 10%.

Conclusions and Recommendations

Global climate change will pose a wide range of challenges to freshwater resources, altering water quantity, quality, system operations, and imposing new governance complications. For countries whose watersheds and river basins lie wholly within their own political boundaries, adapting to increasingly severe climate changes will be difficult enough. When those water resources cross borders, affecting multiple political entities and actors, sustainable management of shared water resources in a changing climate will be especially difficult.

Shared waters can be a source of conflict, but they can also be a source of cooperation and negotiation. Future pressures, such as population and economic growth and climate change, could increase tensions, even in areas that in the past have been characterized by cooperation. Yet, shared challenges may also be a platform for developing new institutional arrangements to plan for the future. Below, we provide recommendations for improving the management of transboundary waters in the face of climate change. Several of these recommendations make sense to address a range of change conditions, including population and economic growth. Climate change, however, poses new risk; the last two recommendations specifically address climate change.

Establish Agreements in Transboundary Basins

Formal treaties or agreements for the management of transboundary water are not universal. Treaties covering transboundary aquifers, in particular, are rare (UNECE 2009). Climate change increases the need for such agreements to reduce the risk of potential future conflicts. Efforts to reach agreement on new treaties should be initiated before new conflicts or tensions have emerged that would complicate already difficult negotiations.

Bring the UN Convention into Force

The Convention on the Law of the Non-navigational Uses of International Watercourses, adopted by the UN General Assembly in May 1997, has not yet come into force. Dellapenna (2007) observes that “None of the most disputed internationally shared fresh waters are covered by agreements involving all interested States, indicating the need, despite the growing prevalence of international agreements regarding internationally shared waters.” As much as we hope that treaties will be developed in all transboundary watersheds to foster cooperation and collaboration amongst all riparian states, there are political and financial constraints that make this difficult in many areas of the world. Therefore, adopting an effective international legal framework is a critical step for addressing future challenges, particularly climate change.

Expand the Scope of Existing Agreements

Climate change will affect all elements of the hydrologic cycle in complex and non-linear ways. A number of these elements, especially water quality and flood management, are commonly excluded from transboundary agreements. Existing agreements should be expanded to include all elements of the hydrologic cycle. Integrated Water Resource Management, or IWRM, provides one such framework. IWRM recognizes the interdependency of all water uses and seeks to balance social, economic, and environmental objectives in the management of water resources.

Evaluate Existing Treaties and Agreements to Assess Flexibility in Light of Changing Conditions

No two water treaties are the same. Each is developed under diverse circumstances, addresses different concerns, and has a unique set of constraints. Additionally, climate change will affect each basin differently. As a result, each treaty must be evaluated to determine what flexibility mechanisms currently exist and where significant vulnerabilities remain. This process should be started before a problem arises so as to improve the atmosphere for cooperation and negotiation.

Amend Existing Treaties to Improve Flexibility

Most treaties and international agreements fail to have adequate mechanisms for addressing changing social, economic, or climate conditions. The following mechanisms should be incorporated into existing treaties to allow for flexibility in the face of change: (1) flexible allocation strategies and water quality criteria; (2) provisions for extreme events; (3) amendment and review procedures; and (4) joint management institutions.

Establish Joint Monitoring Programs

Joint monitoring programs can improve cooperation among nations and data collection capacities. This exchange of information provides a number of benefits, including expanding and deepening our understanding of climate change impacts and vulnerabilities, and improving hydrological and socio-economic models. Such programs should include water flow and a range of water-quality parameters. Additionally, early warning systems should be developed in order to reduce the impacts of extreme events.

Conduct Climate Impact, Vulnerability, and Adaptation Assessments

Riparian countries should work on common scenarios and models to develop a joint understanding of possible impacts. Transboundary cooperation can broaden our knowledge base, enlarge the range of measures available for prevention, preparedness and recovery, and so help identify better and more cost-effective solutions.

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Appendix

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