Impact of Climate Change on Transboundary Water Sharing

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Abstract: The issue of climate change has surfaced as a potential impediment to effective long-range policies and management of water resources. The Intergovernmental Panel on Climate Change (IPCC) recently published a report substantiating the argument that global warming is occurring. The IPCC reported that while sustainable water yields may or may not be reduced in the long-term average, they will almost certainly be less reliable in the short term. Climate change challenges existing water resources management practices by adding uncertainty. This will be an especially troubling issue for transboundary water sharing agreements. The risks imposed by climate change to transboundary water sharing agreements are discussed and the agreements most at risk are identified by the region in which they are located.

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Introduction

The advancement of civilization as we know it requires adequate supplies of quality water on a regular and sustained basis. The demands for quality water are varied, each with a need for increased quantities of what has become a scarce resource. The various demands for water are all essential to our way of life: economic growth and prosperity, agriculture, and improved quality of life. These demands include sufficient quality water for adequate public health and prosperity of humans as well as the aquatic ecosystem. Every level of the food chain, from bacteria and algae to humans and other mammals, requires quality water on a regular and sustained basis.

The demands for adequate supplies of quality water continue to grow at an accelerating pace while the supply of source water remains essentially constant, at least on a global basis. Water scarcity, once confined to specific arid regions, has become the norm. It is the ultimate goal of water management to allocate the scarce supplies of water to maximize the return from each of the water user sectors. To reach this goal, those involved in the allocation process—lawmakers, policymakers, regulators, engineers, scientists, economists, and others—must be able to predict what source water will be available in the future to allocate. Accurate and reliable data and information on source water supplies are key requirements in effective water planning and management (Dellapenna 1997; Draper 1997; Sophocleous 1998; Vörösmarty 2002).

The problem of water allocation within a single political jurisdiction is difficult enough because of the competing forces vying for water, but issues are usually resolved because a legal process (laws and regulations) in which an allocation process is defined and a legal forum (the courts) in which allocation disputes may be resolved. When the water to be allocated is shared by two or more political jurisdictions, however, the problem becomes more challenging. In these cases, there is frequently no substantive legal process to guide the water allocation process and only tenuous forums in which to resolve disputes. Allocation normally occurs through a consensus among the parties, usually in the form of transboundary water sharing agreement or compact.

Transboundary Water Sharing

Sharing water across political boundaries is not an unusual phenomenon. Basins shared by two or more governments cover almost two-thirds of the global landmass. As noted in the Introduction, forty percent (40%) of the world's population depends on these shared river basins for the water they need. Over 90% of the population in the continental United States depends on waters shared with other states (Draper 2002).

As with water allocation within a single legal jurisdiction, allocation of shared waters is based on being able to accurately predict the quantity and quality of water that can be allocated in the future. A water sharing agreement usually focuses on allocation of water under conditions determined from the historical record. Thus, developing an effective agreement requires accurate and precise knowledge of past hydrological conditions. Otherwise, the result may be significant disputes over the terms of an agreement, significantly impairing the agreement's usefulness for the parties (Berman and Wihbey 1999; The Ohio Valley Sanitation Commission 2000).

Predicting the future yield of shared water sources based on the historical record can result, however, in significant future problems. The question of the reliability of past hydrologic records may be a significant problem. First, even what appear to be long-duration records (say the last 30 or 50 years) may not be representative of the cycles of hydrologic variation. Second, manmade changes in flow conditions (from storage, diversions, and

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changes to impervious surfaces) may skew the reliability of historic data (Draper 2006).

However, even if a detailed, accurate historical flow record of the shared water resource exists, there is a significant likelihood that it will not accurately predict future yields. Climate change has surfaced as a potential impediment to effective long-range policies and management of water resources (Nicholls 2000). There is now little argument that global warming is occurring (IPCC 2007; Jackson et al. 2001; National Academy of Sciences 2001; Bennett and Pendlebury 1998). Sustainable water yields may or may not be reduced in the long-term average, but they will be almost certainly less reliable in the short term (Sophocleous 1998). A rapidly growing body of evidence suggests that we are entering a somewhat warmer and definitely more variable world. Climate change challenges existing water resources management practices by adding to the uncertainty of future source water availability (IPCC 2007; Vorosmarty 2002).

On April 6, 2007, the Intergovernmental Panel on Climate Change published summaries of its fourth assessment that detailed the expected effects of climate change. Among those expected effects, many to a high degree of certainty, were specific direct and indirect effects that will further complicate the quest for adequate supplies of quality water that are needed to sustain civilization as we know it.

Intergovernmental Panel on Climate Change

The scientific community has considered the issue of global climate change from the perspective of various disciplines for many years. During the mid-1970s, many leading climate scientists were warning of the significant problems that might arise from climate change, urging the government to take action to avert disaster (Weart 2007). In 1988, in response to these scientific concerns, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC).

The mandate of the IPCC was limited to assessing "on a comprehensive, objective, open, and transparent basis the scientific, technical, and socioeconomic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts, and options for adaptation and mitigation" (IPCC 2007).

Because the final reports of the IPCC are invariably controversial for a variety of reasons, it is important to recognize two of the principles that govern the work of the IPCC. First, since the IPCC is an intergovernmental body, the final IPCC Assessment Report involves both peer review by experts and review by governments. It is not solely a scientific appraisal of the evidence for climate change. Second, decisions are normally made by consensus (IPCC 2007).

Although the reports are an amalgamation of science and politics (national and international), they are science-based. Consequently, the reports provide tentative conclusions based on the available data and information.

IPCC 2007 Assessment Report

On February 6, 2007, the IPCC issued the first of three working group reports, which will provide the basis for the IPCC Fourth Assessment Report to be published in late 2007. Eight conclusions of the Working Group I, responsible for the Physical Science Basis of the Fourth Assessment, are directly related to water resources (WGI 2007). Conclusions of the IPCC Reports raise different levels of concern for different parts of the globe.

- Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level.
- At continental, regional, and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns, and aspects of extreme weather including droughts, heavy precipitation, heat waves, and the intensity of tropical cyclones.
- Anthropogenic forcing is likely to have contributed to changes in wind patterns, affecting extra-tropical storm tracks and temperature patterns in both hemispheres. However, the observed changes in the Northern Hemisphere circulation are larger than simulated in response to 20th century forcing change.
- There is now higher confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation, and some aspects of extremes and of ice.
- Snow cover is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions.
- It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent.
- Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions.
- Anthropogenic warming and sea level rise would continue for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized.

On April 6, 2007, the IPCC issued the second of three working group reports, Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability, Summary for Policymakers (WGII 2007). The key impacts described in the report are shown in Fig. 1. Many of their general conclusions are directly or indirectly related to water resources.

- The impacts of observed climate change include:
  1. Many natural systems on all continents and some oceans affected by regional climate change and rising temperatures; and
  2. Warming caused by human activities has likely had a discernible impact on the global level on many physical and biological systems.
- Specific systems and sectors are very vulnerable:
  1. Coral reefs and sea–ice regions;
  2. Tundra, boreal forests, mountain, and Mediterranean regions;
  3. Low-lying coasts, mangroves, and salt marshes;
  4. Water resources in midlatitudes and dry Tropics;
  5. Low-latitude agriculture; and
  6. Human health where adaptive capacity is low.
- Some regions will be more affected than others:
  1. Arctic;
  2. Sub-Saharan Africa;

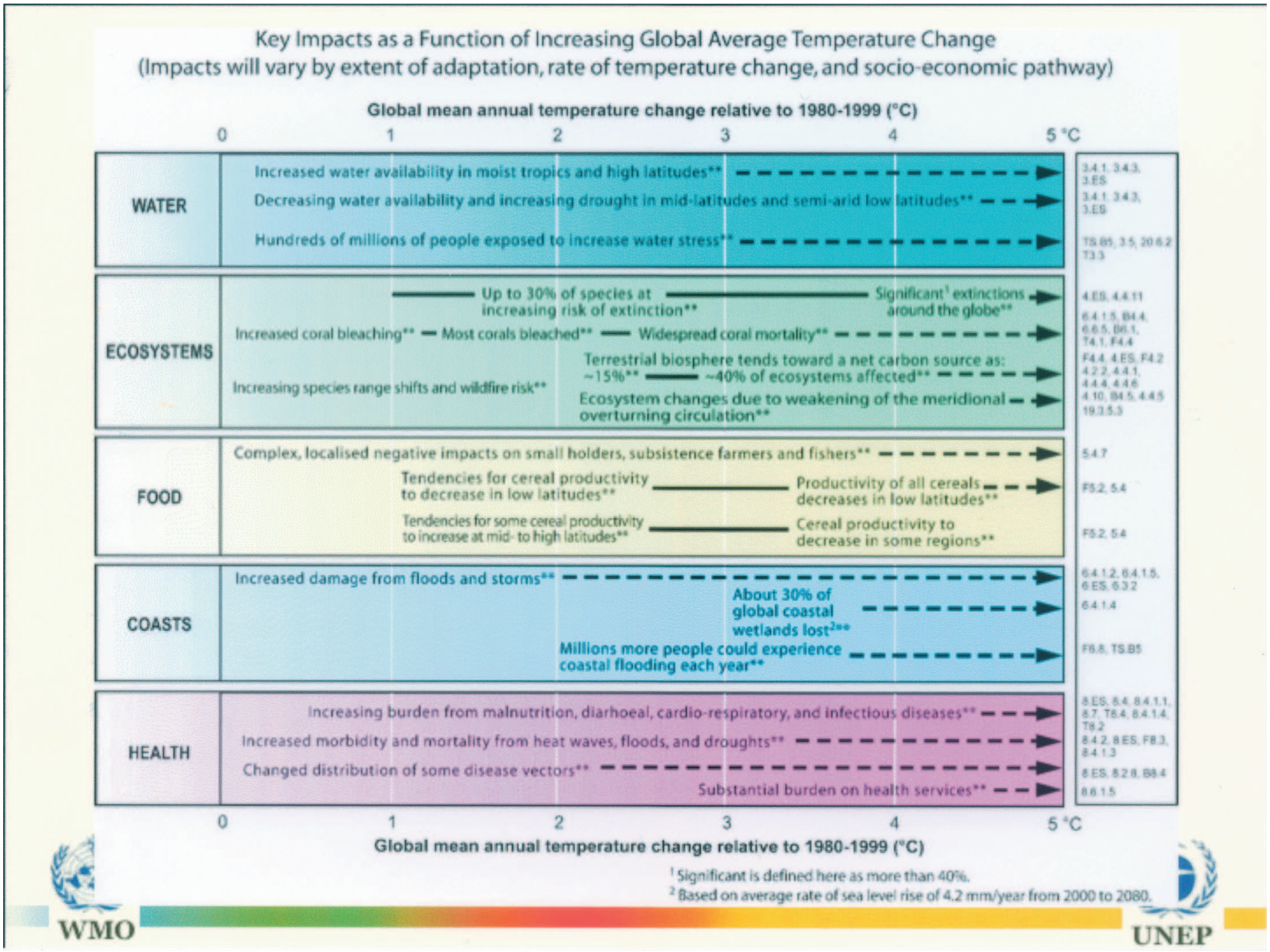

Fig. 1. (Color) Key impacts (WGII 2007b, with permission)

3. Small islands; and
4. Asian megadeltas.

- Impacts of extreme weather events are expected to increase:
- Adaptation will be necessary to address impacts resulting from the warming which is already unavoidable due to past emissions; and
- Vulnerability depends not only on climate change but also on development paths; sustainable development can reduce vulnerability.

The WGII Report presented more detailed impacts on water resources systems (WGII 2007).

1. Based on growing evidence, there is high confidence that the following types of hydrological systems are being affected around the world:
   - Increased run-off and earlier spring peak discharge in many glacier- and snow-fed rivers; and
   - Warming of lakes and rivers in many regions, with effects on thermal structure and water quality.
2. Confidence has increased that some weather events and extremes will become more frequent, more widespread, and/or more intense during the 21st century; and more is known about the potential effects of such changes. (WGII 2007):
   - It is virtually certain there will be warmer and fewer cold days and nights; warmer/more frequent hot days and nights over most land areas. This is expected to have effects on water resources relying on snow melt; and cause increased evapotranspiration rates.
   - It is very likely that the frequency of warm spells/heat waves will increase over most land areas. This effect is expected to increase water demand and aggravate water quality problems, e.g., algal blooms.
   - The increased frequency of heavy precipitation events over most areas is very likely. This will have adverse effects on the quality of surface and groundwater, causing contamination of water supply; water scarcity may be relieved.
   - It is likely that the amount of area affected by drought will increase, causing increased water stress.
   - It is likely that intense tropical cyclone activity increases, causing power outages and disruption of public water supply.
   - Increased incidences of extreme high sea level will likely increase, causing decreased freshwater availability due to saltwater intrusion.

The apparent inconsistency between the prediction of increased frequency of heavy precipitation events over most areas and the prediction of an increase in the areas affected by drought may be explained by separating individual precipitation events from the total amount of precipitation experienced in a particular area. For instance, historically an area may have received an average of 2.5 cm (1.0 in.) of rain over four days each week during a three-month period. This would total 30.5 cm (12.0 in.) for the three-month period. Under climate change conditions, the area might receive 10 cm (3.9 in.) of rain each week during the first month and no rain during the other months. This region will receive more rain—a total of 40 cm (15.8 in)—yet may experience water scarcity during the last tow months. The precipitation intensity has increased but the total amount of precipitation has decreased.

On May 4, 2007, the IPCC issued the third of three working group reports, "Working Group III Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report Climate Change 2007: Mitigation of Climate Change, Summary for Policymakers" (WGIII 2007). Two of their general conclusions are directly or indirectly related to water resources.

The Working Group III report observes that certain climate change mitigation technologies and practices are currently commercially available. Among these are hydropower as a renewable energy source and controlled waste water treatment to reduce methane and N_2O emissions. As a mitigation option in the transportation sector, "model shifts from road to rail and inland waterway shipping," is suggested. The report also notes that "forest-related mitigation activities can considerably reduce (greenhouse gas) emissions" as well as benefiting watershed conservation and helping manage water runoff (WGIII 2007).

Although the report presents no other mitigation efforts that directly relate to water resources, several of the recommendations, if implemented, have an indirect significance on the management of water resource allocation. The most significant is the mitigation report's advocacy of sustainability. "Making development more sustainable by changing development paths can make a major contribution to climate change mitigation . . ."; the report emphasizes energy efficiency and renewable energy but cautions against "displacement of local populations." Reforestation and managing water runoff are again mentioned.

To summarize:

1. Average annual rainfall will increase in some regions and decrease in others. It is important to recognize, however, that the management of water allocation rarely is concerned only with the average annual flow that may be available. Rather, the available water for many users, especially those in urban areas, requires a reliable and consistent source of water. The prediction of more frequent heavier precipitation events and more frequent and/or intense extreme weather events suggests that river flow may not be as dependable as historically experienced, disrupting for example the consistent delivery of urban water supplies or the availability of cooling water for the power industry. The alteration of natural flows will certainly affect the aquatic ecosystem, thereby disrupting significant elements of the food chain that could have dramatic effects. Water-based recreation will be affected.

   This conclusion gives further support to the 2001 prediction that climate change will substantially reduce available water in many of the water-scarce areas of the world, but will increase it in some other areas. However, even in those areas where precipitation is predicted to increase, much of the increase may occur in high intensity events. Flood magnitude and frequency could increase in many regions as a consequence of increased frequency of heavy precipitation events. Flood and drought cycles will probably increase in frequency. Land-use change could exacerbate such events.

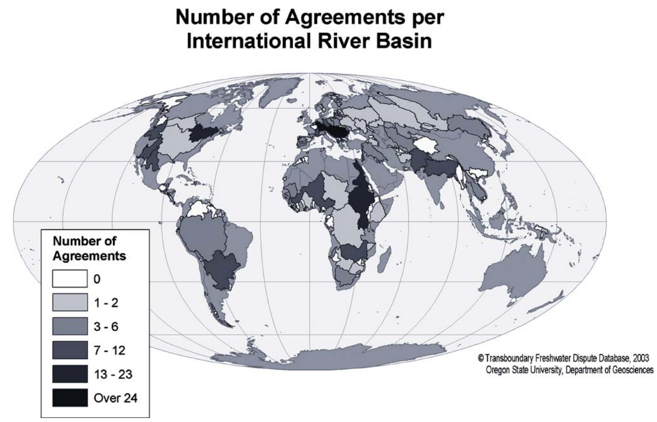

Fig. 2. Basins with water international sharing agreements (Transboundary freshwater dispute database: www.transboundarywaters.orst.edu)

2. The prediction of warmer, more frequent hot days and nights over most land areas will intensify snow and permafrost melt and increase evapotranspiration. The increase in water demand due to warming will be significant in some areas and water quality degradation may result from warming, e.g., algae blooms.

   This conclusion corroborates the prediction that precipitation will increase in some seasons and decrease in others (Hahn and Palmer 2001). Because snowpack is very likely to decrease (National Academy of Sciences 2001) and early snow melt will likely happen due to higher temperatures, "peak streamflow will move from spring to winter in many areas where snowfall currently is an important component of the water balance" (IPCC 2007; National Academy of Sciences 2001). The greatest changes in regions like central and eastern Europe and the southern Rocky Mountain chain, where a small temperature rise reduces snowfall substantially, is the chance for increases of both the "drought of record" and the "flood of record" in most areas (Fig. 2) (Berry 1998; Pearce 2006; IPCC 2007).
3. The prediction of a rise in sea level due to climate change is well known. Such a rise will have an impact on fresh water supplies, especially on groundwater supplies in coastal areas, through increased saltwater intrusion (Jackson et al. 2001; National Academy of Sciences 2001). A significant challenge relates to wetlands during periods of decreased water availability. (Johnson 1998).
4. The most vulnerable industries, settlements, and societies are generally those in coastal and river flood plains, those whose economies are closely linked with climate-sensitive resources, and those in areas prone to extreme weather events, especially where rapid urbanization is occurring. Significant changes in average temperature, precipitation, and soil moisture are very likely to affect demand in most sectors, especially in agricultural irrigation, forestry, power generation, and municipal use (National Academy of Sciences 2001).
5. Local food supplies are projected to be adversely affected by decreasing fisheries resources in large lakes due to rising water temperatures, which may be exacerbated by continued overfishing.
6. Increased deaths, disease, and injury due to heat waves,

floods, storms, fires, and droughts are expected.

7. Management of water resources can reinforce mitigation of global climate change and, in turn, may be affected by other mitigation measures. The call for energy efficiency and renewable energy raises the discussion about the benefits and costs of hydropower. Increased use of navigation transport may increase conflict among users, especially during drought conditions when maintaining navigable channels may limit municipal water supply and irrigation. Reforestation, on the other hand, may bring positive benefits to clean water and flood mitigation.

Impact of Climate Change on Transboundary Water Sharing

Accurate and reliable data and information are key requirements in effective water planning and management (Dellapenna 1997; Draper 1997; Vörösmarty 2002). With increasing variability associated with climate change, existing water management practices may prove less effective (Vörösmarty 2002). Climate change will affect water sharing in many of the same ways it will affect the management of water within a specific legal jurisdiction.

It has been argued that effective and efficient transboundary water sharing faces a number of obstacles. Among these is an incomplete knowledge of the timing and quantity of available source water to be allocated among the parties. In the past, prediction of the timing and quantity of water to be allocated was based on the historical record. Future over-allocation due to an inaccurate historical record is illustrated by the 1922 Colorado River water allocation, which was based on the 30 years hydrological record available at that time. Later research, based on an analysis of tree rings, determined that the amounts of water used in the allocation were abnormally high, resulting in over-allocation of the water source (Stockton and Jacoby 1976; Murakami 1995). Essentially, the accuracy of predictions of the future yield of shared water source leaves a significant uncertainty for developing an effective and efficient water sharing agreement (Tarlock 2000). In times of climate change, the historic record may be unreliable as an indicator of future conditions (Draper 2001, 2006). The underlying issue resulting from climate change will be increasing the uncertainty of the quantity and timing of the source water that may be available to be allocated among the parties.

This increased uncertainty from climate change can be accommodated when new water sharing agreements are developed. For an agreement on water sharing to be effective, it should be able to adapt to potential changes in site-specific circumstances that may develop within the time period the agreement is in effect (Bernauer 2001). The provisions in the agreement should be sufficiently adaptable to allow them to evolve over time and to respond to changes in the climatic, hydrologic, economic, social, and even political conditions (Eaux Partagee 2002; Fitch 2003). The agreement should be able to accommodate unexpected changes in water source availability that may result from extreme events such as prolonged droughts and climate change. Likewise the agreement should be able to accommodate changes in the demand for water that may arise from changes in the economic foundation of one or more of the parties or from sociological or political changes in the value assigned to particular water demands. As with any water management policy, the provisions and rules within a water sharing agreement can best be developed and implemented by retaining and encouraging innovation and diversity (U.S. Advisory Commission 1991). In the case of a new water sharing agreement being developed, some provisions of adaptability of the new agreement to the uncertainties would be appropriate.

The need to adjust existing water sharing agreements to the new uncertainties caused by climate change is complicated for a variety of factors, many of which do not involve the actual increased uncertainty itself. The parties to an existing agreement are loath to change it if it has worked in the past. This reluctance to change is similar to that associated with grandfathered water rights holders who lay claim to their full share while "higher and better" uses are issued junior rights with no certainty that they will actually receive the water they need.

Some existing transboundary water sharing agreements can be modified to accommodate climate change while others may need to be replaced. The likelihood that an existing water sharing agreement can be modified depends on the water sharing strategy that underlies the agreement and the geographic region of the subject source water. The various strategies for transboundary water sharing have been discussed in detail elsewhere (McCormick 1994a,b; Kenney 1995; Draper 2001, 2006) and will only be summarized here. The key issues to be considered are (1) the impacts from climate change on water resources in the hydrogeographic region of the agreement; and (2) how the risks associated with having insufficient source water is apportioned between the parties.

A large number of different water sharing strategies exists in theory. However, as the historical record reveals, only a few of them have actually been used (McCormick 1994a,b). Although some water sharing agreements do not fall into any one of these strategies and many compacts may contain elements of two or more strategies, they are representative of the approaches in use. Generally, five strategies have been applied in water sharing agreements: (1) priorities of use are set according to specific water demands, such as agricultural or municipal; (2) limitations are placed on water storage by upstream parties; (3) delivery of a specific quantity of water by the upstream party is mandated at a particular location on the shared resource; (4) the shared resource is divided among the parties according to a certain percentage of the flow; and (5) comprehensive basin management in which an independent commission, under supervision and policy control of the states involved, allocates water according to a predetermined objective function (McCormick 1994a, b; Kenney 1995; Draper 2001, 2006).

It should be noted that most water sharing agreements referenced in the discussion below are in the western United States, in areas that either primarily depend on snow melt to provide the source water, or otherwise depend on very specific seasonal flows that will be significantly disrupted by the impacts predicted by the 2007 IPCC Assessment. If the predictions are correct, all of the noted compacts will need to be modified or replaced.

The "priority of particular demand" allocation strategy sets priorities by type of use rather than by user location within the water basin, and provides certain quantitative limitations on those priorities. The allocation of the risk of shortage is apportioned among types of users rather than hydrogeographic areas. Lower-value uses, with lower priorities, bear the burden in a period of shortage. Compacts adopting this strategy in whole or in part include *Costilla Creek Compact*, 60 Stat. 246 (1946), amended 77 Stat. 350 (1963); *Bell Fourche Compact*, 58 Stat. 94 (1944); *Kansas–Nebraska Big Blue River Compact*, 86 Stat. 193 (1972); and *Klamath River Basin Compact*, 71 Stat. 497 (1957) (McCormick 1994a,b; Kenney 1995; Draper 2001, 2006). Clearly, this general strategy, since it prioritizes demands in a fashion that favors "grandfathered" uses, will not be simple to modify to respond to reduced yield. Any modification may leave some users without the source water necessary to meet the demand. Any attempts at compact replacement will have to contend with significant political and economic forces. Strategies to augment the available source water from outside the particular basins may be technically feasible but such a strategy of interbasin transfer (or additional interbasin transfer) would itself be politically difficult and raise the cost of water dramatically (Draper 2004).

A "storage limitation" strategy limits the amount of water that an upstream entity may impound annually, seasonally, or other time period base. With regard to risk allocation, the downstream party assumes the majority of the risk because stream flow may not be sufficient to do more than fill upstream reservoirs. Adding users upstream may further diminish flow available downstream. Finally, the downstream party assumes the risk of shortage during prolonged periods of drought or during flood control operations. Compacts adopting this strategy in whole or in part include *Rio Grande Compact of 1938*, 53 Stat. 785, 938; *Arkansas River Compact*, 63 Stat. 145 (1949); *Arkansas River Basin Compact of 1965*, 80 Stat. 1409 (1966); *Canadian River Compact*, 66 Stat. 74 (1952); *Bear River Compact*, 72 Stat. 38 (1955), amended 94 Stat. 4, Art. XIII (2) (1980); *Kansas–Nebraska Big Blue River Compact*, 86 Stat. 193 (1972); and *Upper Niobrara River Compact*, 83 Stat. 86, Art. V (1969) (McCormick 1994a,b; Kenney 1995; Draper 2001, 2006). The impact of climate change as predicted by the IPCC will increase the downstream party's risk. Modification of the compact can come only at the expense of the upstream party, making negotiations difficult at best.

Under a "guaranteed quantity at a point," or "minimum flow," strategy, a guaranteed quantity of water is to be delivered at certain points. The upstream party guarantees that a fixed amount of water will pass a certain point every year or other time periods. The risk of water shortage falls upon the upstream parties, which guarantee the minimum flow, although the upstream parties may also obtain benefit of extra water in periods when stream flow exceeds the base amount. To modify the division of risk, the parties may agree to divide any surplus over a specified minimum flow so that both upstream and downstream parties share part of the surplus. Alternatively, the risk assumed by the upstream party may be lessened by limiting what it should do to ensure the minimum flow. Compacts adopting this strategy in whole or in part include *Colorado River Compact*, approved 45 Stat. 1057 (1928); *Rio Grande Compact of 1938*, 53 Stat. 785, 938; *Arkansas River Basin Compact of 1965*, 80 Stat. 1409 (1966); *Bear River Compact*, 72 Stat. 38 (1955), amended 94 Stat. 4, Art. XIII (2) (1980); *South Platte River Compact*, 44 Stat. 195 (1923); *Sabine River Compact*, 68 Stat. 690 (1953); and *Colorado River Compact*, approved 45 Stat. 1057 (1928) (McCormick 1994a, b; Kenney 1995; Draper 2001, 2006). Clearly, this type of compact will be difficult to modify since the increased uncertainty of flows increases the risks of the upstream party's ability to meet their obligations.

With the "percentage of flow" strategy, the parties allocate water by either a fixed percentage or a formula based on different flow levels. Each participant is entitled to take its specified percentage of the flow. If existing allocations are not grandfathered, those existing rights may be impaired if the allocated percentage results in insufficient water for those rights. In some jurisdictions, this could result in legal "takings" claims. This strategy should include provisions for instream flow maintenance, which may result in less usable water than the strict percentages might indicate. The method is, however, relatively benign with regard to risk allocation as each party shares in surplus or deficit in proportion to its allocated percentage. Compacts adopting this strategy in whole or in part include *Upper Colorado River Basin Compact*, 63 Stat. 31 (1949); *La Plata River Compact*, 43 Stat. 796 (1925); *Yellowstone River Compact*, 65 Stat. 663 (1950); *Snake River Compact*, 64 Stat. 29 (1949); *Red River Compact*, 94 Stat. 3305 (1980); and *Belle Fourche River Compact*, 58 Stat. 94 (1944) (McCormick 1994a,b; Draper 2001, 2006). This strategy is the least likely to be severely strained by the impacts of climate change. The difficulty of using this strategy is the lag time between gathering the hydrologic data and translating the percentage withdrawal rate into actual volumetric extraction.

Finally, transboundary water allocation may be part of "comprehensive basin management." In this alternative, an independent commission, under supervision and policy control of the states involved, is given the regulatory authority to manage all (or most) water-related aspects of the basin to include water supply, pollution control, flood protection, watershed management, recreation, hydroelectric power, regulation of withdrawals and diversions, intergovernmental relations, capital financing, and planning and budgeting. Compacts adopting this strategy include the *Delaware River Basin Compact* (DRBC), Pub. L. 87-328, 75 Stat. 688 (1961); and the *Susquehanna River Basin Compact*, Pub. L. No. 91-575, 84 Stat. 1509 (1970) (McCormick 1994a, b; Draper 2001, 2006). By its very nature, the parties that face the greatest risk are those water users that are not favored by either the terms of the compact or the policies of the independent commission.

Transboundary Water Sharing Agreements at Risk

IPCC describes regional, vulnerability, and key concerns by region (IPCC 2007). Therefore, the transboundary water sharing agreements most at risk can be identified by the geographical region in which the subject source water is located. The Transboundary Freshwater Dispute Database lists over 400 international freshwater agreements (Fig. 3). Of these, approximately one-quarter directly involve water quantity to some degree (Transboundary Freshwater Dispute Database, www.transboundarywaters.orst.edu). While the discussion below relates only to those agreements involving water quantity as their major focus, it should be recognized that freshwater agreements involving water quality, hydropower, and navigation may also be at risk.

When classifying the risks that challenge transboundary water sharing agreements, it must be understood that all risks are relative. The IPCC Reports, as well as other researchers in the field, project a general across-the-board risk in all regions. For the regions that face the highest risk, predictions include both a dramatic reduction in the amount of precipitation the region may experience as well as seasonal variations in the frequency and intensity of storm events. Those regions that face the lowest risk may experience only a change in seasonal variations in the frequency and intensity of storm events, with the amount of precipitation on an annual basis being little changed while reliability may be greatly compromised.

Africa

"By 2020, between 75 and 250 million people are projected to be exposed to an increase of water stress due to climate change. If coupled with increased demand, this will adversely affect livelihoods and exacerbate water-related problems." The 2001 Report concluded that major rivers of Africa are highly sensitive to cli-

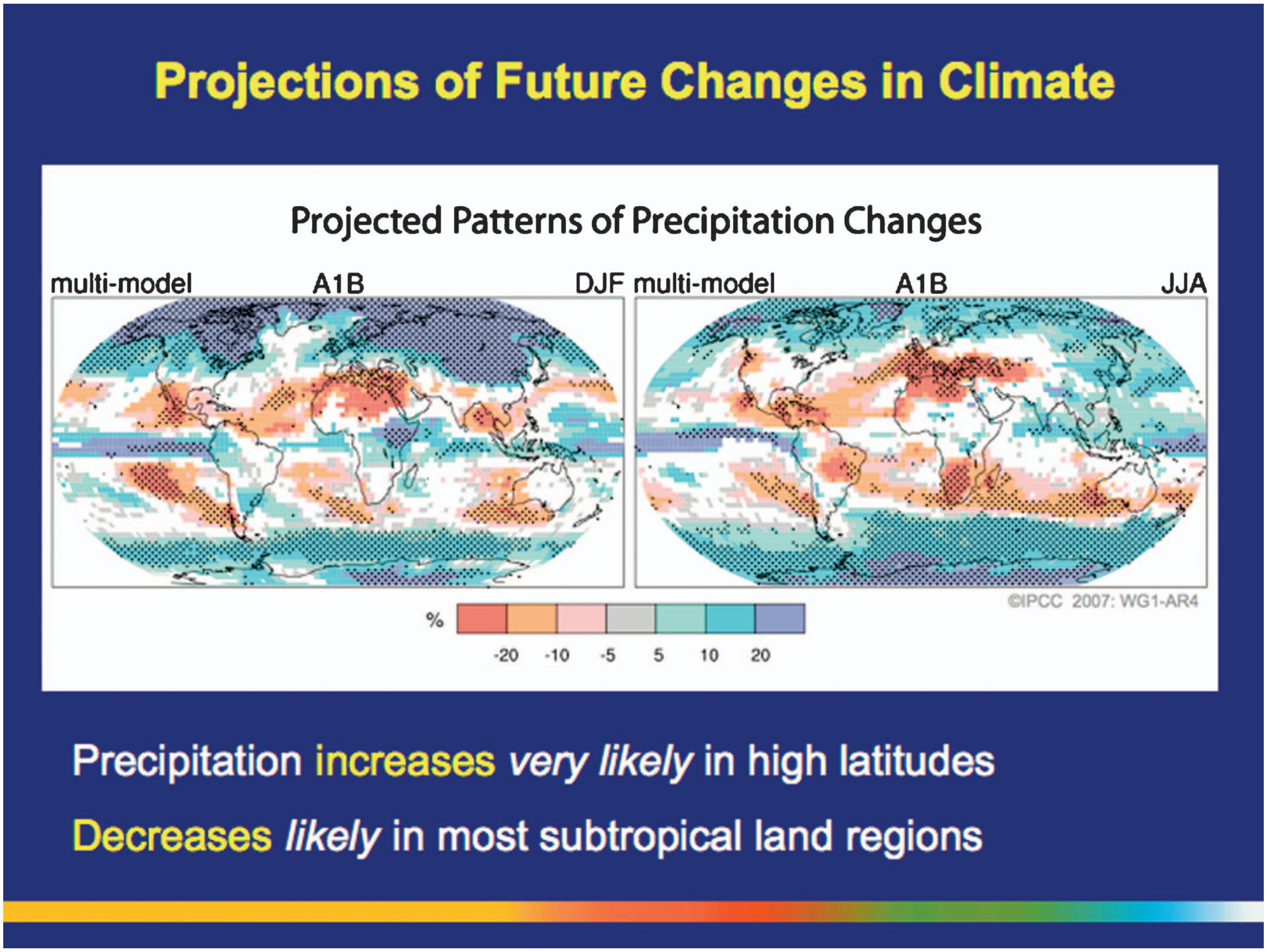

Fig. 3. (Color) Projected precipitation (R. K. Pachauri and B. Jallow, with permission, www.ipcc.ch)

mate variation and warned that average runoff and water availability would decrease in the Mediterranean and southern countries of Africa.

Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multimodel averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change.

"Agricultural production, including access to food, in many African countries and regions is projected to be severely compromised by climate variability and change. The area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semiarid and arid areas, are expected to decrease. This would further adversely affect food security and exacerbate malnutrition in the continent. In some countries, yields from rain-fed agriculture could be reduced by up to 50% by 2020.

Local food supplies are projected to be negatively affected by decreasing fisheries resources in large lakes due to rising water temperatures, which may be exacerbated by continued overfishing."

The 2001 IPCC Report warned that coastal settlements in the Gulf of Guinea, Senegal, Gambia, Egypt, and along the east–southern African coast would be adversely impacted by sea-level rise through inundation and coastal erosion. It should be noted, however, that climate change models for the central Africa region vary considerably in their predictions.

Twenty of the transboundary water supply agreements listed in the Transboundary Freshwater Dispute Database are located in the African continent. Based on the conclusions of the 2007 IPCC Assessment, but recognizing the caveat for central Africa, all water sharing agreements are at risk. Especially significant are those involving the Nile River. Most of these can be considered colonial-era agreements that are outdated. In 1998, all Nile riparian states except Eritrea began discussions about a regional partnership to better manage the Nile. This Nile Basin Initiative included the countries of Burundi, Sudan, Tanzania, Uganda, the Democratic Republic of Congo, Egypt, Ethiopia, Kenya, and Rwanda (The Nile 2003). Given the potential severe impacts from climate change, this initiative should place climate change high on the agenda as a new regional water sharing agreement is developed.

Asia

"Glacier melt in the Himalayas is projected to increase flooding, rock avalanches from destabilized slopes, and affect water resources within the next two to three decades. This will be followed by decreased river flows as the glaciers recede.

Freshwater availability in central, south, east, and southeast Asia particularly in large river basins is projected to decrease due to climate change which, along with population growth and increasing demand arising from higher standards of living, could adversely affect more than a billion people by the 2050s." The 2001 IPCC Report warned that extreme events would increase in temperate and tropical Asia, including floods, droughts, forest fires, and tropical cyclones. Runoff and water availability is expected to decrease in arid and semiarid Asia but increase in northern Asia. Sea-level rise and an increase in the intensity of tropical cyclones would displace tens of millions of people in low-lying coastal areas of temperate and tropical Asia and increased intensity of rainfall would increase flood risks in these areas.

"Coastal areas, especially heavily populated megadelta regions in south, east, and southeast Asia, will be at greatest risk due to increased flooding from the sea and in some megadeltas flooding from the rivers.

Endemic morbidity and mortality due to diarrhoeal disease primarily associated with floods and droughts are expected to rise in east, south, and southeast Asia due to projected changes in hydrological cycle associated with global warming. Increases in coastal water temperature would exacerbate the abundance and/or toxicity of cholera in South Asia."

Forty-one transboundary agreements primarily dedicated to shared water supply exist in the Asian continent. The 2007 IPCC Reports show the 15 water sharing agreements in western Asia (Middle East) at significant risk because of projected estimates of reduced yields in the future.

Although freshwater availability in central Asia is projected to decrease, data are inconclusive with regard to the region in and around the four water sharing agreements to which Kazakhstan is party.

Reduction in freshwater availability in south Asia will occur as a general rule but must be seasonally adjusted. Models suggest that the monsoon season, June–September, will remain stable but extremely dry periods may occur during other seasons. The agreements should be modified as necessary and should place more emphasis on stored water for the support need in the dry periods. The water sharing agreements between India and Bangladesh are at great risk and may cause increased tensions. Although reduced freshwater in the Ganges–Brahmaputra–Meghna basin may reduce freshwater flooding in southern Bangladesh, sea level rise is projected to more than offset this with salt water flooding.

The monsoon season in southeast Asia occurs during the period December–March, when the models predict a significant reduction in precipitation. Thus, the Mekong initiative faces high risks.

Northeast Asia will have less deviation in precipitation and the water sharing agreements for the Amur Basin, between China and Mongolia, face limited risk.

Australia and New Zealand

"As a result of reduced precipitation and increased evaporation, water security problems are projected to intensify by 2030 in southern and eastern Australia and, in New Zealand, in northland and some eastern regions." This is a change from the 2001 IPCC Report which warned of increases in the intensity of heavy rains and tropical cyclones.

Ongoing coastal development and population growth, in areas such as Cairns and southeast Queensland (Australia) and northland to the Bay of Plenty (New Zealand), are projected to exacerbate risks from sea-level rise and increases in the severity and frequency of storms and coastal flooding by 2050.

Production from agriculture and forestry by 2030 is projected to decline over much of southern and eastern Australia, and over parts of eastern New Zealand, due to increased drought and fire. However, in New Zealand, initial benefits to agriculture and forestry are projected in western and southern areas and close to major rivers due to a longer growing season, less frost, and increased rainfall.

Although no international water sharing agreements are relevant to Australia, the country's National Water Initiative will face significant risks of reduced freshwater availability. This will cause significant disruption to the program for permanent trades in water and its intended expansion. Water recovery efforts in the Murray–Darling Basin Water Agreement may be compromised (Australian Government 2006).

Europe

"Negative impacts will include increased risk of inland flash floods, and more frequent coastal flooding and increased erosion (due to storminess and sea level rise). Mountainous areas will face glacier retreat, reduced snow cover and winter tourism, and extensive species losses (in some areas up to 60% under high emission scenarios by 2080)." The 2001 Report warned that river flood hazards will increase across much of Europe and in coastal areas, risk of flooding, erosion and wetland loss would increase substantially with implications for human settlement, industry, tourism, agriculture, and coastal natural habitats.

"In southern Europe, climate change is projected to worsen conditions (high temperatures and drought) in a region already vulnerable to climate variability, and to reduce water availability, hydropower potential, summer tourism, and in general, crop productivity."

A number of international water supply or joint management agreements exist in the southern Europe region of high risk. Most agreements are quite river or lake specific except the 1968 treaty between Bulgaria and Turkey which calls for cooperation in the use of shared waters. Because climate change is expected to be especially significant (similar to northern Africa) in southern Europe riparian to the Mediterranean these treaties will probably require extensive modification or replacement.

"In central and eastern Europe, summer precipitation is projected to decrease, causing higher water stress. Health risks due to heat waves are projected to increase. Forest productivity is expected to decline and the frequency of peatland fires to increase."

A number of international water supply or joint management agreements, ranging from the Rhine River Basin in the west to the Vistula River in the east, are located in this region of medium risk. While most are very site specific treaties that involve navigation, water quality, or hydropower, a limited number involve joint use of transboundary, or frontier, waters. In these cases, whether the agreement can be modified to conform to the predicted climate changes or must be replaced depends on the administrative apparatus contained in the treaty (see Draper 2006). The 1958 agreement between Czechoslovakia and Poland may require two replacement treaties due to the recent separation of the Czech Republic and Slovakia. Models suggest that the periods of reduced precipitation may peak in the summer months and return to less drastic reductions in the late fall and winter. Emphasis on stored water may be required to meet demands in the summer months. This should be built into the water sharing agreements. The 1994 Convention on cooperation for the protection and sustainable use of the River Danube is at high risk, primarily because the lower basin will be affected in a manner similar to basins in the Mediterranean fringe. The precipitation forecasts for the upper basin are similar to other basins in central Europe.

"In northern Europe, climate change is initially projected to bring mixed effects, including some benefits such as reduced demand for heating, increased crop yields, and increased forest growth. However, as climate change continues, its negative impacts (including more frequent winter floods, endangered ecosystems, and increasing ground instability) are likely to outweigh its benefits."

Transboundary water sharing agreements in the northern fringes are at limited risk.

Latin America

"By midcentury, increases in temperature and associated decreases in soil water are projected to lead to gradual replacement of tropical forest by savanna in eastern Amazonia. Semiarid vegetation will tend to be replaced by arid-land vegetation.

In drier areas, climate change is expected to lead to salinization and desertification of agricultural land. Productivity of some important crops are projected to decrease and livestock productivity to decline, with adverse consequences for food security. In temperate zones soybean yields are projected to increase." The 2001 IPCC Report warned that floods and droughts would become more frequent with floods increasing sediment loads and degrading water quality in some areas.

. . . Sea-level rise is projected to cause increased risk of flooding in low-lying areas. Changes in precipitation patterns and the disappearance of glaciers are projected to significantly affect water availability for human consumption, agriculture, and energy generation. . . .

As with central Africa, it must be noted that climate change models for South America vary considerably in their predictions, especially for the winter months. That being said, of the two major transboundary basins in South America, only the La Plata has an agreement that is directly related to water supply. All may be at high risk due to a projected reduction of precipitation, at least in the summer and fall. The 1978 Treaty for Amazonian cooperation that may involve water supply will, however, be at high risk due to the expected aridity.

North America

"Moderate climate change in the early decades of the century is projected to increase aggregate yields of rainfed agriculture by 5–20%, but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or depend on highly utilized water resources.

Warming in western mountains is projected to cause decreased snowpack, more winter flooding, and reduced summer flows, exacerbating competition for over-allocated water resources." The 2001 Report warned that snowmelt-dominated watersheds in western North America will experience earlier spring peak flow reductions in summer flows and reduced lake levels and outflows of the Great Lakes–St. Lawrence under most scenarios.

> Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution. Population growth and the rising value of infrastructure in coastal areas increase vulnerability to climate variability and future climate change, with losses projected to increase if the intensity of tropical storms increases.

The 2001 IPCC Report warned that a sea-level rise 5 mm/year (0.2 in.) would result in enhanced coastal erosion, coastal flooding, loss of coastal wetlands, and increased risk from storm surges, particularly in Florida and much of the U.S. Atlantic coast.

As a general rule, the agreements at high risk are international transboundary agreements between the United States and Mexico, as well as interstate water sharing agreements (compacts) in the southwestern and midwestern tiers of states. Agreements between the United States and Canada will be at relative low risk as will be interstate compacts in the east. The effect of snowmelt will have an adverse effect along the continental divide, north from Arizona and New Mexico to Alaska (Brown 2007).

> Recent warming and changes in atmospheric circulation patterns over North America have resulted in reductions in the duration of the snow cover season, the amount of water stored in the snowpack, as well as a widespread trend toward earlier spring melt. These changes are particularly pronounced over western Canada . . . where spring melt has advanced at a rate of close to half-a-day per year over the period since 1955. Reduced storage of water in the snowpack and earlier melt translate to a lower fresh water pulse for recharge of soil moisture and reservoirs, and increased potential for evaporation loss. This trend, coupled with increasing demand for water, suggests increasing conflict in the use and management of snowmelt-derived water supplies.

The major risk in North America lies to those agreements that involve river basins whose rivers rely as a major contribution on snow melt. The 2007 IPCC Working Group II contribution reports that there is "high confidence" of "increased run-off and earlier spring discharge in many . . . snow-fed rivers" (WGII 2007). As an example, water users of the upper and lower Colorado River basins may find that, because of the lack of snow loads in the headwaters of the basins, the source water needed to support agriculture in the basins during the growing season is greatly reduced. The increase in evaporation will negatively affect the ability to store water for future use in surface reservoirs. Independent modeling has reported effects on shared waters in the western United States that supports this conclusion (Stewart et al. 2004).

> Spring snowmelt is the most important contribution of many rivers in western North America. If climate changes, this contribution may change. A shift in the timing of springtime snowmelt towards earlier in the year already is observed during 1948–2000 in many western rivers. . . . Streamflow timing changes for the 1995–2099 period are projected (to be) strongest in the Pacific Northwest, Sierra Nevada, and Rocky Mountains, where many rivers eventually run 30–40 days earlier.

The earlier spring streamflow timing will cause a significant economic disruption since peak demand for irrigated agriculture occurs in the summer. Each summer will be a continuing struggle for available water between farming and urban water supply. More importantly, as to the effectiveness of the transboundary water sharing agreements, significant disputes may arise because upstream parties may be unable to meet their obligations to downstream parties or downstream parties will not receive their expected allocation.

Concluding Thoughts

There is little dispute that climate change is occurring as this article is written. A consensus exists among scientists that climate change is accelerating because of human influence. There is, of course, a divergent view that explains the causes of climate change as a natural phenomenon (Horner 2007). The dispute, such as it is, changes nothing with respect to the challenges facing the water resources manager, whether he/she be a lawmaker, policymaker, regulator, scientist, engineer, farmer, or environmentalist. The challenge is the virtual certainty of a changing climate and how the change will dramatically alter how water as a scarce resource is allocated. Nowhere is this challenge greater than the allocation of shared waters between or among politically independent governments.

The effects of climate change will extend across political boundaries. Therefore, the parties to a water sharing agreement should recognize that the water sharing agreement may need to be adapted, even significantly adapted or replaced, as more accurate and precise predictability becomes available on those changes.

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