Climate Change and the Transformation of Global Water Resources

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Abstract

Over the coming decades, changes in climate and society will drive a major transformation of global water resources. But the intensity and type of risks to water resources will vary greatly from region-to-region. For example, it is likely that climate change will intensify water scarcity in specific "hot spot regions" such as southern Europe, northeast Brazil, and southern Africa. At other locations precipitation and water availability will increase, although also with negative side effects. In the case of Europe, precipitation is expected to increase during winter and this likely to lead to more frequent flooding during this season in the central and northern sections of the continent. Meanwhile, global warming has already quickened the pace of glacier-melting in the Alps, Himalayas, and elsewhere. As the melting continues, river runoff fed by these glaciers will at first increase. Later, though, glaciers will diminish along with runoff, and this will endanger water supplies downstream. Society needs to respond immediately to these risks, and this response should take place at all levels, from local to global. At the global level there are three main tasks to take on. First, we have to reduce the immediate risk to society by establishing comprehensive early warning systems for droughts and floods. Second, we have to extend our knowledge of transformations going on in the global water system by expanding the scope of remote earth observations, and by conducting new large-scale field experiments and surveys. Third, we must protect nature and society over the long run by strengthening the global governance of water. This means exploring new ways of managing water at the global level through novel international institutions and conventions. These tasks need to be given high priority because the all-encompassing changes taking place in the global water system justify an equally wide-ranging response from society.

Key words: Water resources; climate change; water availability.

1. Introduction

There is little doubt remaining in the scientific community that global climate is being modified by the greenhouse gases released by society into the atmosphere. Moreover, it is also very likely that changing patterns of rainfall and snowfall, and consistently warmer temperatures, will have wide-ranging impacts on global water resources including major changes in the flow patterns of rivers, alterations in the availability of water, and increases or decreases in the frequency of droughts and floods. But the nature and intensity of changes will not be the same everywhere. In some places there will be too much water (at least for people), and in others too little. Where annual precipitation tends to increase, as is likely in northern parts of Europe, flooding may become more frequent. Where it becomes drier, as expected in Southern Europe and many other parts of the world, more frequent droughts will be the problem. This paper examines how the impacts of climate change on water resources could play out differently in different parts of the world and how society can respond to this new challenge.

2. How does climate change affect water resources?

Ever liter of water flowing through the landscape in liquid form, or coursing through the atmosphere as vapor, makes up part of the great global cycle of freshwater. Climate change will disrupt this cycle and affect all aspects of water resources in Europe and in other parts of the world. Surface temperatures are increasing almost everywhere and this is stimulating higher evaporation rates from moist surfaces and larger transpiration losses from plants. ("Transpiration" refers to water conducted out through the pores of plants.) But other complicating factors may intervene to temper evaporation. For example, as the moisture content of the atmosphere increases, its extra water-holding capacity will eventually decline and this slows evaporation. Also cloudiness may increase in some areas and this will decrease solar radiation at the earth's surface and subsequently slow down the rates of evaporation and transpiration. When these and other factors are combined, the result is a large variation from location-to-location in how evaporation and transpiration will respond to climate change.

Where evaporation and transpiration increase, the increased moisture in the atmosphere will modify regional patterns of precipitation. Although the total amount of precipitation falling over the course of a year on ocean and land surfaces is expected to increase, other parts of the world are likely to experience strong decreases in their annual volume of rainfall and snowfall. Below we refer to these as "hot spot regions" of water scarcity. Here, the total volume of water available annually for human uses – household, industry or agriculture – will be reduced. Exactly how much depends on many factors. One is the intensity and type of climate change at different locations, for example, whether precipitation increases or decreases within a particular season. Another factor is the kind of water system responding to climate change: Different types of rivers will respond differently; a highly regulated river, already controlled by dams and reservoirs, is likely to be less vulnerable than a free-flowing river (Arnell, 2001).

All this underlines the fact that climate change will disrupt the global water cycle in many different and complicated ways which we need to anticipate and prepare for.

3. More water becoming available

If we sum up the various changes in the water cycle caused by climate change we can estimate, at least roughly, whether more or less water will be available around the world. The expected change in water availability has been calculated by global hydrology models that take into account the effect of different climate scenarios and project changes in river runoff and groundwater recharge. Most models and scenarios indicate increasing water availability over much, if not most, of the land surface of the earth. Results from different European modeling studies and scenarios show that precipitation may increase over the Atlantic and northern parts of Europe and substantially increase average annual water availability here (Werritty, 2001; Andréasson *et al.*, 2004). By the 2020s (relative to current climate) average water availability in Europe, north of 47°N, could increase by around 5 to 15%, and by the 2070s by 9 to 22% (Figure 1) (Alcamo *et al.*, 2007). Meanwhile in Europe south of 47°N, it could drop by up to 23% by the 2020s and 6 to 36% by the 2070s (for the same set of scenarios) (Alcamo *et al.*, 2007). It may be difficult, however, to recognize the influence of climate change on water availability up to the 2020s because water availability has a strong-year-year variability due to current climate variability. But the long term effects of climate change will become more discernible later in the century.

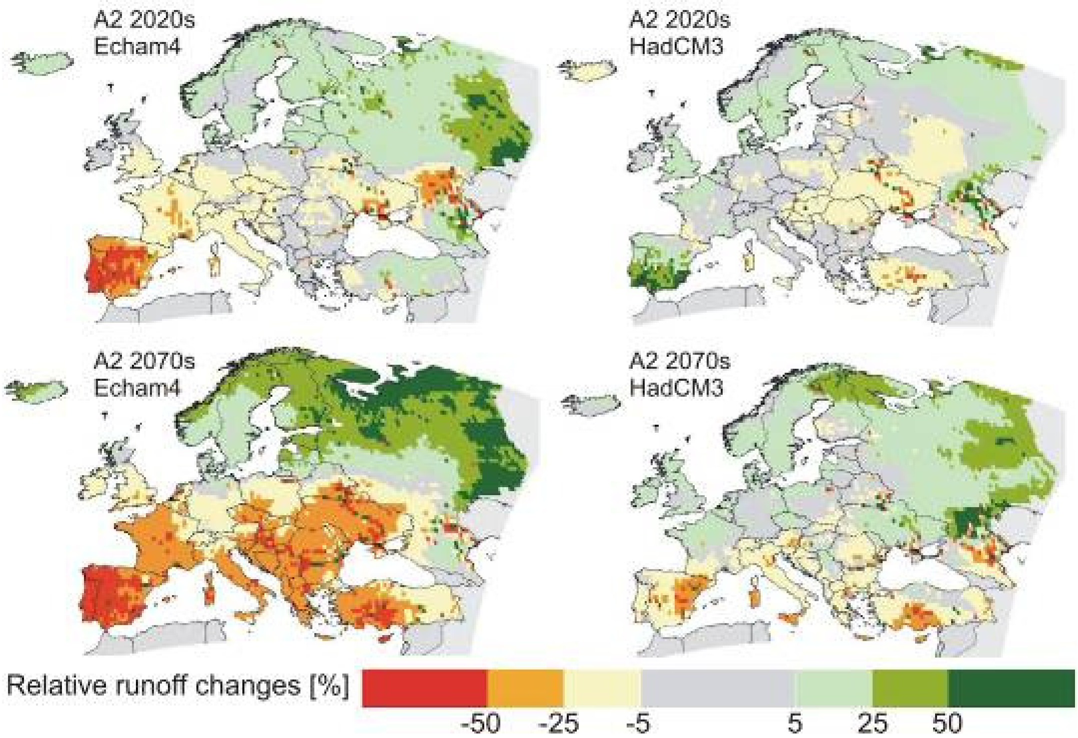

Figure 1. *Change in annual river runoff between a 1961-1990 baseline period and two future time periods (2020s and 2070s) for two different climate modeling results for the IPCC A2 scenario. Green indicates increasing runoff, yellow and red decreasing. Source: Alcamo et al., 2007.*

It is important to note that increased annual water availability will not necessarily translate into benefits to people. It is possible that increasing rainfall and higher river flows will occur during seasons that already have plentiful rains. For example, Arnell (2004) computed that an increase in annual runoff in South and East Asia may occur primarily during the already wet monsoon season and it will be difficult to store the "excess" volume of water for the dry season.

4. Hot spot regions of increasing water scarcity

While computer modeling results indicate that a large fraction of the earth's land area is becoming wetter (Figure 2), they also indicate the occurrence of some hot spot regions of increasing scarcity. These are territories where climate is already arid or semi-arid and where water availability will further substantially decline under climate change.

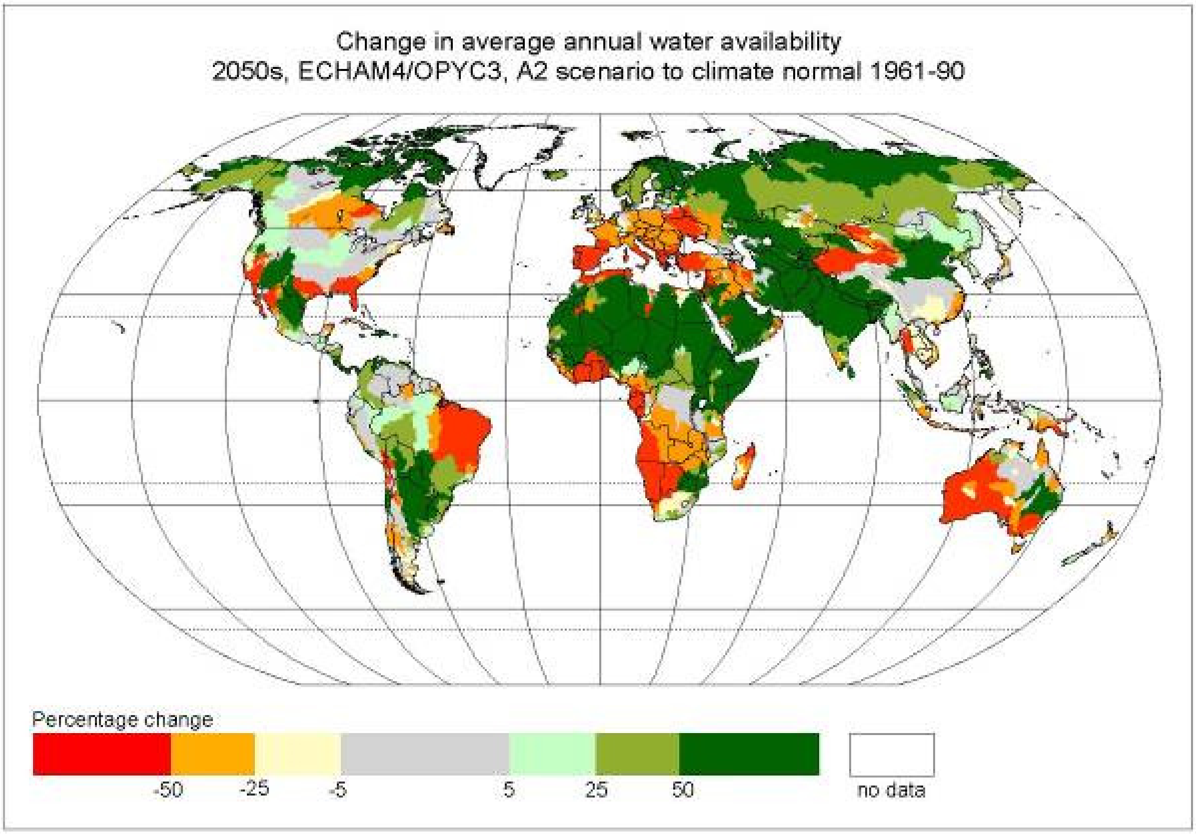

***Figure* 2.** *Change in average annual water availability between climate normal period (1961-90) and 2050s under A2 scenario. Source: Alcamo et al. 2007.*

One of these hot spot regions is Southern Europe (Menzel and Bürger, 2002; Etchevers *et al.*, 2002; Chang *et al.*, 2002; Iglesias *et al.*, 2005). Water availability in Europe, south of 47°N, could drop by up to 23% by the 2020s and 6 to 36% by the 2070s (Figure 1) (for a range of scenarios; Alcamo *et al.*, 2007). Less water will be available here for drinking, for manufacturing, for cooling electricity-generating turbines, and for aquatic ecosystems.

Other hot spot regions are shown in Figure 2. In these already dry areas annual water availability could decrease by more than 50% towards the end of the century, relative to "current climate" conditions. Included are territories with large poor populations such as Northeast Brazil, the southern part of Africa, and the Middle East. Here intensified water intensity will surely be a barrier to these peoples' hopes for a higher standard of living. Climate change will make it more difficult to provide basic household water services as well as adequate water supply for industry and agriculture. Other hot spot areas are the southwest of the United States and parts of Australia. Here the wealthier population will find it easier to adapt to climate change. Nevertheless, climate change will make it difficult for inhabitants to maintain their current high level of water consumption.

5. How will river flows change?

Not only annual water availability, but also seasonal patterns of precipitation and river runoff will be transformed. Rivers usually have seasonal flow patterns characteristic of their climate zone. For example, river runoff under a Mediterranean climate tends to be high during the winter when most of its annual rainfall occurs, whereas under a Montane climate it tends to be low during this season because moisture is stored as snow and not released as runoff until spring.

Under global warming, precipitation and runoff patterns are likely to experience seasonal changes. Studies in Europe have shown that winter flows will increase and summer flows decrease in the Rhine (Middelkoop and Kwadijk, 2001), Slovakian rivers (Szolgay *et al.*, 2004), the Volga and in various rivers in central and eastern Europe (Oltchev *et al.*, 2002). A decline in summer precipitation may decrease average summer flows by as much as 50% in central Europe (Eckhardt and Ulbrich, 2003), and by as much as 80% in some rivers in southern Europe (Santos *et al.*, 2002).

6. Disappearing glaciers and downstream flow

A good example of the complex ways in which climate change is affecting the global water system is the case of melting glaciers and river flow. This is also an example of how river flow will not only be affected by "local" changes in precipitation and temperature, but also by more subtle changes going on far upstream. A main source of water for many rivers with their origin in the Alps and other high mountains is melt water from glaciers lodged in alpine valleys. These glaciers accumulate moisture during the winter by storing snowfall and give up this moisture mostly as melt water when temperatures rise in spring and summer. But this stable seasonal pattern is being disrupted by global warming which is causing many glaciers to melt at a faster pace than they accumulate snow and ice during winter.

The faster melting of glaciers will at first increase the late spring and early summer flows of rivers they feed. Hence, over the coming years and decades it should be expected that the typical spring and summer surge of milk-colored glacial water rushing down from the highlands will become even more intense. But gradually, after several decades, the glaciers will shrink so much that they will no longer substantially feed downstream rivers. For example, average summer flows of many European glacier-fed rivers could drop by 50% (Hock *et al.*, 2005; Zierl and Bugmann, 2005).

The glaciers of the Himalayas, and the rivers they feed, are a special case of climate impacts. All together, Himalayan glaciers store 12,000 km^3 of water, more than three times the total volume of water withdrawn each year for all human water uses. Melt water from these glaciers provides much of the flow of the great rivers that drain South Asia, including the Indus and the Ganges-Brahmaputra. Hundreds of millions of people depend on this water for their water supply and economic activity – the Ganges basin alone has around 500 million inhabitants. For this reason it is especially noteworthy that Himalayan glaciers are receding faster on average than elsewhere and may disappear by 2035 at current rates of warming. (Cruz *et al.*, 2007). Although South Asia's rivers are not likely to entirely disappear because the monsoon rains refresh them each year, they may become more seasonal because their source of spring and summer discharge is rapidly diminishing.

7. The impacts of sea level rise on water supply

While changing temperature and precipitation patterns are modifying glaciers, river runoff and water availability, the global water system will be pressured from another direction – the sea. As the atmosphere heats up, the upper layers of the ocean will become warmer. Since water expands when heated, the volume of ocean water will also increase, raising global average sea levels. (In Scandinavia and some other locations, continents are slowly rising which compensates somewhat for the increase in the volume of seawater.) Adding to this effect will be the melting of mountain glaciers and perhaps parts of the Greenland and other ice caps. During the 21st century, the sum of these effects could lead to a global average sea level rise of 19 to 58 cm (for a range of climate change scenarios).

Sea level rise will have at least two noteworthy impacts on coastal water resources. First, it will increase the risk of saltwater intrusion into aquifers lying along the coast, and so increase the risk of saltwater contamination of the water supply of communities that rely on this groundwater. At greatest risk will be low lying coastal areas with shallow aquifers. Second, sea level rise will thrust the ocean's saltwater further upstream into river estuaries, and in this way threaten the intake pipes where cities and municipalities take in freshwater for their water supplies. There is a distinct possibility that that many cities located on estuaries will have to implement early warning systems for anticipating salt contamination of their intake pipes, or in extreme cases will have to move their intake pipes further upstream or out of the estuary entirely.

8. Changing outflow to estuaries

While rising oceans will push saltwater further upstream in river estuaries, other changes will be occurring in the downstream direction. As changing climate alters the volume of water running off the land, this will also change the volume of freshwater flowing into estuaries and out into the oceans. Where freshwater outflow increases, it will make estuaries less salty and will compensate somewhat for the saltwater thrust upstream by sea level rise. Recent estimates (Alcamo *et al.*, 2006) showed that 15 to 18 of the world's largest estuaries might have substantially higher inflow of freshwater over the coming decades because of climate change. For the other estuaries, however, freshwater inflows may decrease and allow the saltwater of the ocean to push even further inland. Regardless of whether freshwater inflows increase or decrease, the magnitude of changes are expected to be large, ranging from 14 to 37% relative to their current levels (for a range of scenarios) (Alcamo *et al.*, 2006). These changes will undoubtedly alter the salinity levels and flow patterns in estuaries and these changes are certain to have a significant, but still uncertain, impact on the aquatic ecosystems of these estuaries.

9. Responding to climate change: Acting locally and regionally

The latest report of the Intergovernmental Panel on Climate Change made it clear that there are already signs of climate change impacts including the receding of glaciers, the occurrence of heat waves, and far-ranging changes in the growth characteristics of plants, (IPCC, 2007). It is also clear that further and more intense climate impacts should be expected, even if greenhouse gas emissions are radically reduced, because of the lag time between past greenhouse gas emissions and their effect on climate change. Hence, it is necessary and wise to begin adapting to climate change. The good news is that we have many reasonable adaptation options to select from.

As we review our options, an important point to keep in mind is that adaptation will have to take place at all levels of society, from the household scale up through to the local, regional and, finally, to the national and global levels. Options at the local to regional scale are particularly attractive because society already manages its water resources at this scale. Indeed, municipal water authorities and river basin water managers have built up a wealth of experience in how to manage water under the threat of floods and droughts and this experience will be valuable in adapting to climate change. The European Environment Agency has drawn from this experience and compiled a good summary of adaptation measures relevant especially to the local to regional scale (Footitt and Hedger, 2007). These measures are summarized in the following paragraphs.

Protecting Against Floods

Technical flood protection – For centuries dikes, dams and other structures have protected inhabitants of lowlands from flooding and it is likely they will also be an important way to cope with more frequent high river flows stemming from climate change. Many European regions are already continuously repairing river or coastal dikes and improving drainage systems to protect against recurring river and coastal floods. Now many nations are building their dikes thicker and higher as a hedge against the additional threat from climate change.

Natural retention of flood water – As the damage caused by floods increases around the world, many communities and regions are considering investing in costly dams, dikes and other technical measures to avoid a repetition of this damage. Because of the high costs associated with technical measures, another approach has been gaining in popularity, namely to put aside parts of the river flood plain that can be flooded under high water conditions and serve as a temporary storage basin for flood flows. Many countries, including Denmark, Germany, the Netherlands, and Sweden, are already setting aside riparian areas (side channels and wetlands) for this purpose. These are mainly recreational, farming, or undeveloped areas that can be inundated without great risk to human populations and their structures.

Restrictions of settlement/building development in risk areas – It is understood that under increasing precipitation and other conditions some areas will be at increased risk of flooding. For these areas, some countries are adopting long-term land use policies to prohibit the expansion of settlements that would be at risk from future flooding. In the

Netherlands, national law requires that new building projects that restrict the infiltration or storage of water must provide some compensation in other parts of the flood plain. Other examples are Austria which has developed “hazard zone plans” and France which has produced “flood risk maps” for their territories.

Standards for building development – In high-risk flood plains some countries are giving special attention to strengthening building standards to maximize the flood-resistance of structures. A few cities in Sweden are taking into account climate change in estimating potential floods and as a result are changing building codes to restrict the location of buildings. In some cases they also require higher minimum floor levels. Also the capacities of sewer systems in Sweden are being made larger so that they can carry the greater flows that will be produced by increasing precipitation.

Improving forecasting and information – An effective form of adaptation is to develop early-warning systems that communicate flood forecasts and emergency information to the public. Several river basins in Europe have flood early warning systems that combine meteorological forecasts with knowledge about the hydrology of rivers and topography to forecast the occurrence of floods some days in advance. An example is the FEWS-Rhine (Flood Early Warning System for the River Rhine) operated by Germany, the Netherlands, and Switzerland. While these systems provide a useful purpose, it may be even more useful to design these early warning systems on the national to global scale as proposed below.

Improving insurance schemes and information -- To compensate for the inevitable damage caused by floods it is possible to improve the type and coverage of insurance. In Belgium, recent legislation requires flood damages to be included in household “fire” insurance policies. Insurance for flood damage is possible in Germany. On average, France spends around 250 million Euro each year to reimburse damage caused by floods.

Drought/low flow protection

Technical measures to increase supply – An age-old hedge against droughts is storing water in reservoirs, tanks and sometimes in aquifers for use during dry conditions. As changing climate reduces precipitation in some regions, this approach will again become relevant. Currently the Netherlands is investigating the possibility of storing freshwater in Lake Ussemeer and Greece is examining the feasibility of large scale water storage in aquifers.

Increasing efficiency of water use – An effective adaptation measure is to reduce exposure to drought by decreasing as much as possible the reliance of the population on large water withdrawals. This can be done by increasing the efficiency of water use, or in other words, obtaining the same service from water (drinking water, irrigation or other) but with a smaller volume of water withdrawals. One example comes from the municipal sector where large losses occur between the time that water is withdrawn from its source to the time it is used in a household for drinking or other purposes. Although it is unrealistic to completely eliminate losses from leaky pipes and poorly functioning pumps to zero, proper maintenance can significantly reduce these losses.

For example the city of Zurich has reduced losses in its distribution system from around 10% to 5% over a ten year period through a program of leakage control (EEA, 2003).

Economic instruments – Water use can also be reduced by levies on water services or increasing the sale price of water. Water pricing is already wide spread in some parts of the world, especially in Europe. In France, for example, 85% of the costs of water are recovered from households and industry through metering and various tariffs. European governments have been hesitant to monitor and realistically price irrigation water use because low water prices are a kind of subsidy of domestic agriculture. France has found a compromise solution by requiring farmers to meter their water withdrawals when their abstraction rate is above a particular threshold (EC, 2007a). In principle, tariffs for all sectors can be made higher during drought periods to discourage water usage, but this practice is still rare in Europe and elsewhere. Although water pricing makes sense in Europe and other wealthy regions, a note of caution is needed for developing countries where basic water services are still not available to over a billion people. Here the price of water needs to be kept low enough for poor people so that everyone can have access to clean and affordable water.

Restriction of water uses – As another way of coping with water scarcity under climate change, local or regional authorities can be given the mandate to reallocate water during emergency drought situations. For example, local authorities in the Guadalquivir River Basin in Spain have used the authority granted to them under a "Drought Management Plan" to reallocate available water resources during droughts from irrigation water users to urban and industrial users (Ecologic, 2007).

Landscape planning measures to improve water balance – Land cover has a very large impact on the water balance of a watershed. Rainfall tends to pool on the surfaces of areas with compacted and barren soils and evaporates quickly after rainfall events. Vegetated surfaces tend to have an upper layer of decomposing organic matter (humus) which can better absorb precipitation and allow it to percolate to groundwater where it can slowly be retrieved. In the Netherlands, local authorities are required to carry out an assessment of the impact of all larger infrastructure projects on losses of infiltration or storage of water and must compensate for any projected losses.

Improving forecasting, monitoring, information – While it is now relatively easy to make short-term forecasts of weather events leading to flooding, the forecasting of drought periods requires forecasts many months in advance of the event. New knowledge of the climate system is beginning to make these medium-term forecasts more feasible. The question, at what scale should these forecasts be part of an early warning system? Should such a system be designed for the local to regional scale, or is it more appropriate for the national to global scale? Below it is recommended to implement these systems on the larger scale.

10. National to global responses to climate impacts on water resources

Since water management is already organized mostly by municipalities and river basins, it is very sensible to adopt measures locally and regionally to cope with climate change. Nevertheless there are also arguments for taking action at the *national* to *global levels*.

One argument is that the impacts of climate change will manifest themselves throughout the entire world and many measures for adapting to these impacts are applicable to many places around the world and within many parts of a country. An example of adaption measures applicable equally well around the world are early warning systems for climate-related extreme events. Another argument for national to global action is that some climate impacts transcend the river basin scale and have international or global aspects. Improving water use efficiency, is an example of an effective strategy for coping with climate-related water scarcity, which can be promoted not only locally or regionally, but also nationally and globally.

At the national and global levels there are three main tasks to take on. First, we have to reduce the immediate risk to society by establishing comprehensive early warning systems for droughts and floods. Second, we have to extend our knowledge of transformations going on in the global water system by expanding the scope of remote earth observations, and by conducting new large-scale field experiments and surveys. Third, we must protect nature and society over the long run by strengthening the global governance of water. This means exploring new ways of managing water at the global level through novel international institutions and conventions.

1. Reducing Immediate Risk to Society.

We mentioned above that the immediate threats to society posed by floods and droughts could be addressed by setting up “early warning systems” which would alert the public to an impending event and would recommend or require actions to be taken by authorities or the public to minimize danger to the public. While these systems are now being implemented on the municipal and river basin level, this is an adaptation measure, as noted above, that is applicable to virtually all parts of the world. Therefore it is worthwhile to consider setting up these systems on the national, continental or even global scale. Early warning systems consist of three main elements: a modeling system by which local scientists/experts make forecasts of flood or drought events, a procedure by which authorities decide on issuing an alert to the public, and a set of actions that can be taken in an emergency (for example, curtailment of water use or evacuation of the population). Such an early warning system requires close cooperation between scientists, decision makers and those responsible for communication networks.

There are already some examples of national-scale early warning systems. France has inaugurated a national early warning center for flooding covering 22 river basins. Spain has a national “global hydrologic indicators system” (river inflows, reservoir levels) for anticipating significant droughts and to better prepare for them.

First examples of early warning systems on the continental-scale are being tried out in Europe. A European Flood Alert System (EFAS) is currently in the last stages of development and is intended to provide forecasts 3 to 10 days in advance of high water events throughout Europe. EFAS will run by the European Commission’s Joint Research Center at Ispra in direct cooperation with river basin authorities (EC, 2007b). Meanwhile, the European Commission has proposed to set up a “European Drought Observatory” and early warning system by 2012 (EC, 2007c). This would be an apparatus to combine meteorological forecasts, hydrologic data, and other information to make medium-term forecasts of droughts in Europe and allow authorities to prepare possible emergency measures.

2. Extending Our Knowledge of the Global Water System

To cope with climate change we also need a sharper global view of the intensity and location of climate change impacts on the global water system. It is particularly important task to identify "hot spot" areas, as noted above, of rapid change or particular sensitivity. Three of the many options available for extending our knowledge of the global water system are global monitoring, large field experiments and new modeling and assessment tools.

(1) Global monitoring. The past decades have seen enormous progress in the use of satellites and aircraft to collect data about the global environment. But there is an urgent need to extend global monitoring to include planet-wide data on ecological, biogeochemical and anthropogenic variables (*e.g.* spatial variation of water quality, state of aquatic ecosystems, and locations of human appropriation of water resources). Collecting these data will certainly pose technical challenges, but the scientific community has already shown that satellite sensors can meet these challenges.

(2) Large Field Experiments. While remote earth observations are ideal for giving us an overview of changes in the water system, intensive field experiments can provide better understanding about processes and feedbacks in the system. These include big field programs such as the "African Monsoon Multidisciplinary Analyses" (AMMA) and the flow manipulation experiments, conducted on the Colorado, Snowy, and other rivers, in which experimental flows are released from dams in order to study their downstream ecological effects. Not only the natural sciences, but also social science surveys are needed on scales up to the planetary scale to provide new knowledge about the spatial variability and variety of human vulnerability to changes in the water system. This knowledge would help researchers match locations of expected rapid change with particularly vulnerable populations.

(3) New Modeling and Assessment Tools. Collecting new data is important but these data must also be analyzed by novel types of analytical tools. A new generation of global- and continental-scale water models is required for comprehending and anticipating future changes in the global water system. To be useful for addressing policy-relevant questions, these models must be able to integrate a very wide range of global scale information about the socioeconomic system, land use, climate, hydrology and aquatic ecosystems.

3. Global Governance of Water

As compared to global monitoring, field experiments, and other such actions, a more direct intervention on the global level would be to expand global governance of water. "Water governance" is defined by the United Nations Development Programme as "the political, economic and social processes and institutions by which governments, civil society and the private sector make decisions about how best to use, develop and manage water resources." The first steps towards global water governance were already taken back in 1921 with the adoption of the "Convention and Statute on the Regime of Navigable Waterways of International Concern" which prohibits states from impeding the navigation of important international waterways passing through their territory. The principle of global governance of water was more recently confirmed in the form of the Ramsar Convention (1971) ("Convention on Wetlands of International Importance Especially as Waterfowl Habitat") which established the fundamental right of the international community to intervene even if a particular water-related issue does not involve international waters.

If we accept the precedents for intervening in water issues on the global level, how can global intervention help us to cope with the new threats of climate impacts on the global water system? One possibility would be to adopt an international convention specifying international guidelines for "environmental flows" of rivers, i.e. the flow regimes of rivers that are theoretically required for maintaining or re-establishing viable aquatic ecosystems. Establishing international guidelines for environmental flows would be an important response to climate change because, as noted above, these changes are expected to alter the flow patterns of many rivers and thereby strongly effect aquatic ecosystems. Another example would be to promote water-saving behavior on the global level by adopting an international convention that specifies norms for the water use efficiency of internationally-traded products. Mandating international water efficiency standards would reduce the wastefulness of current water use and reduce the exposure of people and industry to increasing water scarcity related to climate change. These are just two of many different possibilities for managing water on the global level that should be considered as options for adapting to climate change.

11. Global water resources: From many changes to many responses

To sum up, climate change will transform global water resources in many different ways. Warmer temperatures have already hastened the tempo of melting of glaciers and begun to alter river flow patterns. Higher precipitation is likely to lead to more water availability over many areas, but the benefits may not be transferable from one season to the next. Arid and semi-arid "hot spots" will become still drier and more water scarce. Rivers will dry up and become seasonal. Meanwhile, rising sea level will push saltwater inland, and more runoff will push it again seaward. We have many options for coping with these changes, including extending measures that are already part of existing water management at the local to regional level. Yet the threat to water resources by climate change is global, so we should also consider global responses. These could include (i) reducing the immediate risk to society by establishing comprehensive early warning systems for droughts and flood; (ii) extending our knowledge of changes going on in the global water system by expanding remote earth observations and large-scale field experiments, and (iii) by protecting nature and society over the long run by strengthening the global governance of water. These actions need to be given high priority because the all-encompassing changes taking place in the global water system justify an equally wide-ranging response from society.

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