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Hydrology and Water Resources

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EXECUTIVE SUMMARY

- There are apparent trends in streamflow volume—both increases and decreases—in many regions. These trends cannot all be definitively attributed to changes in regional temperature or precipitation. However, widespread accelerated glacier retreat and shifts in streamflow timing in many areas from spring to winter are more likely to be associated with climate change.
- The effect of climate change on streamflow and groundwater recharge varies regionally and between scenarios, largely following projected changes in precipitation. In some parts of the world, the direction of change is consistent between scenarios, although the magnitude is not. In other parts of the world, the direction of change is uncertain.
- Peak streamflow is likely to move from spring to winter in many areas where snowfall currently is an important component of the water balance.
- Glacier retreat is likely to continue, and many small glaciers may disappear.
- Water quality is likely generally to be degraded by higher water temperature, but this may be offset regionally by increased flows. Lower flows will enhance degradation of water quality.
- Flood magnitude and frequency are likely to increase in most regions, and low flows are likely to decrease in many regions.
- Demand for water generally is increasing as a result of population growth and economic development, but it is falling in some countries. Climate change is unlikely to have a large effect on municipal and industrial demands but may substantially affect irrigation withdrawals.
- The impact of climate change on water resources depends not only on changes in the volume, timing, and quality of streamflow and recharge but also on system characteristics, changing pressures on the system, how the management of the system evolves, and what adaptations to climate change are implemented. Nonclimatic changes may have a greater impact on water resources than climate change.
- Unmanaged systems are likely to be most vulnerable to climate change.
- Climate change challenges existing water resources management practices by adding additional uncertainty. Integrated water resources management will enhance the potential for adaptation to change.
- Adaptive capacity (specifically, the ability to implement integrated water resources management), however, is distributed very unevenly across the world.

4.1. Introduction and Scope

This chapter assesses our understanding of the implications of climate change for the hydrological cycle, water resources, and their management. Since the beginnings of concern over the possible consequences of global warming, it has been widely recognized that changes in the cycling of water between land, sea, and air could have very significant impacts across many sectors of the economy, society, and the environment. The characteristics of many terrestrial ecosystems, for example, are heavily influenced by water availability and, in the case of instream ecosystems and wetlands, by the quantity and quality of water in rivers and aquifers. Water is fundamental to human life and many activities—most obviously agriculture but also industry, power generation, transportation, and waste management—and the availability of clean water often is a constraint on economic development. Consequently, there have been a great many studies into the potential effects of climate change on hydrology (focusing on cycling of water) and water resources (focusing on human and environmental use of water). The majority of these studies have concentrated on possible changes in the water balance; they have looked, for example, at changes in streamflow through the year. A smaller number of studies have looked at the impacts of these changes for water resources—such as the reliability of a water supply reservoir or the risk of flooding—and even fewer explicitly have considered possible adaptation strategies. This chapter summarizes key findings of research that has been conducted and published, but it concentrates on assessing opportunities and constraints on adaptation to climate change within the water sector. This assessment is based not only on the few studies that have looked explicitly at climate change but also on considerable experience within different parts of the water sector in adapting to changing circumstances in general.

This chapter first summarizes the state of knowledge of climate change impacts on hydrology and water resources (Section 4.2), before assessing effects on the hydrological cycle and water balance on the land (Section 4.3). Section 4.4 examines potential changes in water use resulting from climate change, and Section 4.5 assesses published work on the impacts of climate change for some water resource management systems. Section 4.6 explores the potential for adaptation within the water sector. The final two sections (Sections 4.7 and 4.8) consider several integrative issues as well as science and information requirements. The implications of climate change on freshwater ecosystems are reviewed in Chapter 5, although it is important to emphasize here that water management is increasingly concerned with reconciling human and environmental demands on the water resource. The hydrological system also affects climate, of course. This is covered in the Working Group I contribution to the Third Assessment Report (TAR); the present chapter concentrates on the impact of climate on hydrology and water resources.

At the outset, it is important to emphasize that climate change is just one of many pressures facing the hydrological system and water resources. Changing land-use and land-management practices (such as the use of agrochemicals) are altering the hydrological system, often leading to deterioration in the resource baseline. Changing demands generally are increasing pressures on available resources, although per capita demand is falling in some countries. The objectives and procedures of water management are changing too: In many countries, there is an increasing move toward "sustainable" water management and increasing concern for the needs of the water environment. For example, the Dublin Statement, agreed at the International Conference on Water and the Environment in 1992, urges sustainable use of water resources, aimed at ensuring that neither the quantity nor the quality of available resources are degraded. Key water resources stresses now and over the next few decades (Falkenmark, 1999) relate to access to safe drinking water, water for growing food, overexploitation of water resources and consequent environmental degradation, and deterioriation in water quality. The magnitude and significance of these stresses varies between countries. The late 1990s saw the development of several global initiatives to tackle water-related problems: The UN Commission on Sustainable Development published the "Comprehensive Assessment of the Freshwater Resources of the World" (WMO, 1997), and the World Water Council asked the World Commission for Water to produce a vision for a "water-secure world" (Cosgrove and Rijbersman, 2000). A series of periodical reports on global water issues was initiated (Gleick, 1998). The impacts of climate change, and adaptation to climate change, must be considered in the context of these other pressures and changes in the water sector.

4.2 State of Knowledge of Climate Change Impacts on Hydrology and Water Resources: Progress since the Second Assessment Report

4.2.1 Introduction

Over the past decade—and increasingly since the publication of the Second Assessment Report (SAR) (Arnell *et al*., 1996; Kaczmarek, 1996)—there have been many studies into climate change effects on hydrology and water resources (see the online bibliography described by Chalecki and Gleick, 1999), some coordinated into national programs of research (as in the U.S. National Assessment) and some undertaken on behalf of water management agencies. There are still many gaps and unknowns, however. The bulk of this chapter assesses current understanding of the impacts of climate change on water resources and implications for adaptation. This section highlights significant developments in three key areas since the SAR: methodological advances, increasing recognition of the effect of climate variability, and early attempts at adaptation to climate change.

4.2.2 Estimating the Impacts of Climate Change

The impacts of climate change on hydrology usually are estimated by defining scenarios for changes in climatic inputs to a hydrologicalmodel from the output of general circulation models

(GCMs). The three key developments here are constructing scenarios that are suitable for hydrological impact assessments, developing and using realistic hydrological models, and understanding better the linkages and feedbacks between climate and hydrological systems.

The heart of the scenario "problem" lies in the scale mismatch between global climate models (data generally provided on a monthly time step at a spatial resolution of several tens of thousands of square kilometers) and catchment hydrological models (which require data on at least daily scales and at a resolution of perhaps a few square kilometers). A variety of "downscaling" techniques have been developed (Wilby and Wigley, 1997) and used in hydrological studies. These techniques range from simple interpolation of climate model output (as used in the U.S. National Assessment; Felzer and Heard, 1999), through the use of empirical/statistical relationships between catchment and regional climate (e.g., Crane and Hewitson, 1998; Wilby *et al*., 1998, 1999), to the use of nested regional climate models (e.g., Christensen and Christensen, 1998); all, however, depend on the quality of simulation of the driving global model, and the relative costs and benefits of each approach have yet to be ascertained. Studies also have looked at techniques for generating stochastically climate data at the catchment scale (Wilby *et al.*, 1998, 1999). In principle, it is possible to explore the effects of changing temporal patterns with stochastic climate data, but in practice the credibility of such assessments will be strongly influenced by the ability of the stochastic model to simulate present temporal patterns realistically.

Considerable effort has been expended on developing improved hydrological models for estimating the effects of climate change. Improved models have been developed to simulate water quantity and quality, with a focus on realistic representation of the physical processes involved. These models often have been developed to be of general applicability, with no locally calibrated parameters, and are increasingly using remotely sensed data as input. Although different hydrological models can give different values of streamflow for a given input (as shown, for example, by Boorman and Sefton, 1997; Arnell, 1999a), the greatest uncertainties in the effects of climate on streamflow arise from uncertainties in climate change scenarios, as long as a conceptually sound hydrological model is used. In estimating impacts on groundwater recharge, water quality, or flooding, however, translation of climate into response is less well understood, and additional uncertainty is introduced. In this area, there have been some reductions in uncertainty since the SAR as models have been improved and more studies conducted (see Sections 4.3.8 and 4.3.10). The actual impacts on water resources—such as water supply, power generation, navigation, and so forth—depend not only on the estimated hydrological change but also on changes in demand for the resource and assumed responses of water resources managers. Since the SAR, there have been a few studies that have summarized potential response strategies and assessed how water managers might respond in practice (see Section 4.6).

There also have been considerable advances since the SAR in the understanding of relationships between hydrological processes at the land surface and processes within the atmosphere above. These advances have come about largely through major field measurement and modeling projects in different geographical environments [including the First ISLSCP Field Experiment (FIFE), LAMBADA, HAPEX-Sahel, and NOPEX; see www.gewex.com], coordinated research programs (such as those through the International Geosphere-Biosphere Programme (IGBP; see www.igbp.se) and large-scale coupled hydrology-climate modeling projects [including GEWEX Continental-Scale International Project (GCIP), Baltic Sea Experiment (BALTEX), and GEWEX Asian Monsoon Experiment (GAME); see www.gewex.com/projects.html]. The ultimate aim of such studies often is to lead to improved assessments of the hydrological effects of climate change through the use of coupled climate-hydrology models; thus far, however, the benefits to impact assessments have been indirect, through improvements to the parameterizations of climate models. A few studies have used coupled climate-hydrology models to forecast streamflow (e.g., Miller and Kim, 1996), and some have begun to use them to estimate effects of changing climate on streamflow (e.g., Miller and Kim, 2000).

4.2.3. Increased Awareness of the Effect of Climatic Variability on Hydrology and Water Resources

Since the SAR, many studies have explored linkages between recognizable patterns of climatic variability—particularly El Niño and the North Atlantic Oscillation—and hydrological behavior, in an attempt to explain variations in hydrological characteristics over time. These studies in North America (McCabe, 1996; Piechota *et al.*, 1997; Vogel *et al*., 1997; Olsen *et al.*, 1999), South America (Marengo, 1995; Compagnucci and Vargas, 1998), Australasia (Chiew *et al*., 1998), Europe (e.g., Shorthouse and Arnell, 1997), and southern Africa (Shulze, 1997) have emphasized variability not just from year to year but also from decade to decade, although patterns of variability vary considerably from region to region. Most studies focus on the past few decades with recorded hydrological data, but an increasing number of studies have reconstructed considerably longer records from various proxy data sources (e.g., Isdale *et al*., 1998; Cleaveland, 2000). Such research is extremely valuable because it helps in interpretation of observed hydrological changes over time (particularly attribution of change to global warming), provides a context for assessment of future change, and opens up possibilities for seasonal flow prediction (e.g., Piechota *et al.*, 1998) hence more efficient adaptation to climatic variability. It also emphasizes that the hydrological "baseline" cannot be assumed to be constant, even in the absence of climate change.

4.2.4. Adaptation to Climate Change in the Water Sector

Water management is based on minimization of risk and adaptation to changing circumstances (usually taking the form of altered demands). A wide range of adaptation techniques has been developed and applied in the water sector over decades. One widely used classification distinguishes between increasing capacity (e.g., building reservoirs or structural flood defenses), changing operating rules for existing structures and systems, managing demand, and changing institutional practices. The first two often are termed “supply-side” strategies, whereas the latter two are “demand-side.” Over the past few years, there has been a considerable increase in interest in demand-side techniques. International agencies such as the World Bank (World Bank, 1993) and initiatives such as the Global Water Partnership are promoting new ways of managing and pricing water resources to manage resources more effectively (Kindler, 2000).

This work is going on largely independently of climate change, but changes in water management practices will have a very significant impact on how climate change affects the water sector. Water managers in some countries are beginning to consider climate change explicitly, although the methodologies for doing so are not yet well defined and vary between and within countries depending on the institutional arrangements for long-term water resources planning. In the UK, for example, water supply companies were required by regulators in 1997 to “consider” climate change in estimating their future resource, hence investment, projections (Subak, 2000). In the United States, the American Water Works Association urged water agencies to explore the vulnerability of their systems to plausible climate changes (AWWA, 1997).

Clearly, however, the ability of water management agencies to alter management practices in general or to incorporate climate change varies considerably between countries. This issue is discussed further in Section 4.6.

4.3. Effects on the Hydrological Cycle

4.3.1. Introduction

This section summarizes the potential effects of climate change on the components of the water balance and their variability over time.

4.3.2. Precipitation

Precipitation is the main driver of variability in the water balance over space and time, and changes in precipitation have very important implications for hydrology and water resources. Hydrological variability over time in a catchment is influenced by variations in precipitation over daily, seasonal, annual, and decadal time scales. Flood frequency is affected by changes in the year-to-year variability in precipitation and by changes in short-term rainfall properties (such as storm rainfall intensity). The frequency of low or drought flows is affected primarily by changes in the seasonal distribution of precipitation, year-to-year variability, and the occurrence of prolonged droughts.

TAR WGI Section 2.5 summarizes studies into trends in precipitation. There are different trends in different parts of the world, with a general increase in Northern Hemisphere mid- and high latitudes (particularly in autumn and winter) and a decrease in the tropics and subtropics in both hemispheres. There is evidence that the frequency of extreme rainfall has increased in the United States (Karl and Knight, 1998) and in the UK (Osborn *et al*., 2000); in both countries, a greater proportion of precipitation is falling in large events than in earlier decades.

Current climate models simulate a climate change-induced increase in annual precipitation in high and mid-latitudes and most equatorial regions but a general decrease in the subtropics (Carter and Hulme, 1999), although across large parts of the world the changes associated with global warming are small compared to those resulting from natural multi-decadal variability, even by the 2080s. Changes in seasonal precipitation are even more spatially variable and depend on changes in the climatology of a region. In general, the largest percentage precipitation changes *over land* are found in high latitudes, some equatorial regions, and southeast Asia, although there are large differences between climate models.

Until recently, very few projections of possible changes in year-to-year variability as simulated by climate models have been published, reflecting both the (until recently) short model runs available and the recognition that climate models do not necessarily reproduce observed patterns of climatic variability. Recent developments, however, include the increasing ability of some global climate models to reproduce features such as El Niño (e.g., Meehl and Washington, 1996) and open up the possibility that it may be feasible to estimate changes in year-to-year variability. Recent scenarios for the UK, derived from HadCM2 experiments, indicate an increase in the relative variability of seasonal and annual rainfall totals resulting from global warming (Hulme and Jenkins, 1998).

Potential changes in intense rainfall frequency are difficult to infer from global climate models, largely because of coarse spatial resolution. However, there are indications (e.g., Hennessy *et al*., 1997; McGuffie *et al*., 1999) that the frequency of heavy rainfall events generally is likely to increase with global warming. Confidence in this assertion depends on the confidence with which global climate models are held. More generally, uncertainty in GCM projections of precipitation largely determines the uncertainty in estimated impacts on hydrological systems and water resources.

Increasing temperatures mean that a smaller proportion of precipitation may fall as snow. In areas where snowfall currently is marginal, snow may cease to occur—with consequent, very significant, implications (discussed below) for hydrological regimes. This projection is considerably less uncertain than possible changes in the magnitude of precipitation.

4.3.3. Evaporation

Evaporation from the land surface includes evaporation from open water, soil, shallow groundwater, and water stored on vegetation, along with transpiration through plants. The rate of evaporation from the land surface is driven essentially by meteorological controls, mediated by the characteristics of vegetation and soils, and constrained by the amount of water available. Climate change has the potential to affect all of these factors—in a combined way that is not yet clearly understood—with different components of evaporation affected differently.

The primary meteorological controls on evaporation from a well-watered surface (often known as potential evaporation) are the amount of energy available (characterized by net radiation), the moisture content of the air (humidity—a function of water vapor content and air temperature), and the rate of movement of air across the surface (a function of windspeed). Increasing temperature generally results in an increase in potential evaporation, largely because the water-holding capacity of air is increased. Changes in other meteorological controls may exaggerate or offset the rise in temperature, and it is possible that increased water vapor content and lower net radiation could lead to lower evaporative demands. The relative importance of different meteorological controls, however, varies geographically. In dry regions, for example, potential evaporation is driven by energy and is not constrained by atmospheric moisture contents, so changes in humidity are relatively unimportant. In humid regions, however, atmospheric moisture content is a major limitation to evaporation, so changes in humidity have a very large effect on the rate of evaporation.

Several studies have assessed the effect of changes in meteorological controls on evaporation (e.g., Chattopadhyary and Hulme, 1997), using models of the evaporation process, and the effect of climate change has been shown to depend on baseline climate (and the relative importance of the different controls) and the amount of change. Chattopadhyary and Hulme (1997) calculated increases in potential evaporation across India from GCM simulations of climate; they found that projected increases in potential evaporation were related largely to increases in the vapor pressure deficit resulting from higher temperature. It is important to emphasize, however, that different evaporation calculation equations give different estimates of absolute evaporation rates and sensitivity to change. Therefore, it can be very difficult to compare results from different studies. Equations that do not consider explicitly *all* meteorological controls may give very misleading estimates of change.

Vegetation cover, type, and properties play a very important role in evaporation. Interception of precipitation is very much influenced by vegetation type (as indexed by the canopy storage capacity), and different vegetation types have different rates of transpiration. Moreover, different vegetation types produce different amounts of turblence above the canopy; the greater the turbulence, the greater the evaporation. Achange in catchment vegetation—directly or indirectly as a result of climate change—therefore may affect the catchment water balance (there is a huge hydrological literature on the effects of changing catchment vegetation). Several studies have assessed changes in biome type under climate change (e.g., Friend *et al*., 1997), but the hydrological effects of such changes—and, indeed, changes in agricultural land use—have not yet been explored.

Although transpiration from plants through their stomata is driven by energy, atmospheric moisture, and turbulence, plants exert a degree of control over transpiration, particularly when water is limiting. Stomatal conductance in many plants falls as the vapor pressure deficit close to the leaf increases, temperature rises, or less water becomes available to the roots—and transpiration therefore falls. Superimposed on this short-term variation in stomatal conductance is the effect of atmospheric carbon dioxide (CO_2) concentrations. Increased CO_2 concentrations reduce stomatal conductance in C_3 plants (which include virtually all woody plants and temperate grasses and crops), although experimental studies show that the effects vary considerably between species and depend on nutrient and water status. Plant water-use efficiency (WUE, or water use per unit of biomass) therefore may increase substantially (Morison, 1987), implying a reduction in transpiration. However, higher CO_2 concentrations also may be associated with increased plant growth, compensating for increased WUE, and plants also may acclimatize to higher CO_2 concentrations. There have been considerably fewer studies into total plant water use than into stomatal conductance, and most empirical evidence to date is at the plant scale; it is difficult to generalize to the catchment or regional scale (Field *et al*., 1995; Gifford *et al*., 1996; Amthor, 1999). Free-air CO_2 enrichment (FACE) experiments, however, have allowed extrapolation at least to the 20-m plot scale. Experiments with cotton, for example (Hunsaker *et al*., 1994), showed no detectable change in water use per unit land area when CO_2 concentrations were increased to 550 ppmv; the 40% increase in biomass offset increased WUE. Experiments with wheat, however, indicated that increased growth did not offset increased WUE, and evaporation declined by approximately 7% (although still less than implied by the change in stomatal conductance; Kimball *et al*., 1999). Some model studies (e.g., Field *et al*., 1995, for forest; Bunce *et al*., 1997, for alfalfa and grass; Cao and Woodward, 1998, at the global scale) suggest that the net direct effect of increased CO_2 concentrations at the catchment scale will be small (Korner, 1996), but others (e.g., Pollard and Thompson, 1995; Dickinson *et al*., 1997; Sellers *et al*., 1997; Raupach, 1998, as discussed by Kimball *et al*., 1999) indicate that stomata have more control on regional evaporation. There clearly is a large degree of uncertainty over the effects of CO_2 enrichment on catchment-scale evaporation, but it is apparent that reductions in stomatal conductance do not necessarily translate into reductions in catchment-scale evaporation.

The *actual* rate of evaporation is constrained by water availability. A reduction in summer soil water, for example, could lead to a reduction in the rate of evaporation from a catchment despite an increase in evaporative demands. Arnell (1996) estimated for a sample of UK catchments that the rate of actual evaporation would increase by a smaller percentage than the atmospheric demand for evaporation, with the greatest difference in the "driest" catchments, where water limitations are greatest.

4.3.4. Soil Moisture

The amount of water stored in the soil is fundamentally important to agriculture and is an influence on the rate of actual evaporation, groundwater recharge, and generation of runoff. Soil moisture contents are directly simulated by global climate models, albeit over a very coarse spatial resolution, and outputs from these models give an indication of possible directions of change. Gregory *et al.* (1997), for example, show with the HadCM2 climate model that a rise in greenhouse gas (GHG) concentrations is associated with reduced soil moisture in Northern Hemisphere mid-latitude summers. This was the result of higher winter and spring evaporation, caused by higher temperatures and reduced snow cover, and lower rainfall inputs during summer.

The local effects of climate change on soil moisture, however, will vary not only with the degree of climate change but also with soil characteristics. The water-holding capacity of soil will affect possible changes in soil moisture deficits; the lower the capacity, the greater the sensitivity to climate change. Climate change also may affect soil characteristics, perhaps through changes in waterlogging or cracking, which in turn may affect soil moisture storage properties. Infiltration capacity and water-holding capacity of many soils are influenced by the frequency and intensity of freezing. Boix-Fayos *et al*. (1998), for example, show that infiltration and water-holding capacity of soils on limestone are greater with increased frost activity and infer that increased temperatures could lead to increased surface or shallow runoff. Komescu *et al*. (1998) assess the implications of climate change for soil moisture availability in southeast Turkey, finding substantial reductions in availability during summer.

4.3.5. Groundwater Recharge and Resources

Groundwater is the major source of water across much of the world, particularly in rural areas in arid and semi-arid regions, but there has been very little research on the potential effects of climate change. This section therefore can be regarded as presenting a series of hypotheses.

Aquifers generally are replenished by effective rainfall, rivers, and lakes. This water may reach the aquifer rapidly, through macro-pores or fissures, or more slowly by infiltrating through soils and permeable rocks overlying the aquifer. A change in the amount of effective rainfall will alter recharge, but so will a change in the duration of the recharge season. Increased winter rainfall—as projected under most scenarios for mid-latitudes—generally is likely to result in increased groundwater recharge. However, higher evaporation may mean that soil deficits persist for longer and commence earlier, offsetting an increase in total effective rainfall. Various types of aquifer will be recharged differently. The main types are unconfined and confined aquifers. An unconfined aquifer is recharged directly by local rainfall, rivers, and lakes, and the rate of recharge will be influenced by the permeability of overlying rocks and soils. Some examples of the effect of climate change on recharge into unconfined aquifers have been described in France, Kenya, Tanzania, Texas, New York, and Caribbean islands. Bouraoui *et al.* (1999) simulated substantial reductions in groundwater recharge near Grenoble, France, almost entirely as a result of increases in evaporation during the recharge season. Macro-pore and fissure recharge is most common in porous and aggregated forest soils and less common in poorly structured soils. It also occurs where the underlying geology is highly fractured or is characterized by numerous sinkholes. Such recharge can be very important in some semi-arid areas (e.g., the Wajir region of Kenya; Mailu, 1993). In principle, "rapid" recharge can occur whenever it rains, so where recharge is dominated by this process it will be affected more by changes in rainfall amount than by the seasonal cycle of soil moisture variability. Sandstrom (1995) modeled recharge to an aquifer in central Tanzania and showed that a 15% reduction in rainfall—with no change in temperature—resulted in a 40–50% reduction in recharge; he infers that small changes in rainfall could lead to large changes in recharge and hence groundwater resources. Loaiciga *et al*. (1998) explored the effect of a range of climate change scenarios on groundwater levels in the Edwards Balcones Fault Zone aquifer in Texas, a heavily exploited aquifer largely fed by streamflow seepage. They show that, under six of the seven GCM-based scenarios used, groundwater levels and springflows would reduce substantially as a result of lower streamflow. However, they use $2xCO_2$ scenarios that represent changes in temperature that are considerably greater than those projected even by the 2080s under current scenarios (Carter and Hulme, 1999), so the study considerably overstates the effect of climate change in the next few decades.

Shallow unconfined aquifers along floodplains, which are most common in semi-arid and arid environments, are recharged by seasonal streamflows and can be depleted directly by evaporation. Changes in recharge therefore will be determined by changes in the duration of flow of these streams—which may locally increase or decrease—and the permeability of the overlying beds, but increased evaporative demands would tend to lead to lower groundwater storage. In semi-arid areas of Kenya, flood aquifers have been improved by construction of subsurface weirs across the river valleys, forming subsurface dams from which water is tapped by shallow wells. The thick layer of sands substantially reduces the impact of evaporation. The wells have become perennial water supply sources even during the prolonged droughts (Mailu, 1988, 1992).

Sea-level rise will cause saline intrusion into coastal aquifers, with the amount of intrusion depending on local groundwater gradients. Shallow coastal aquifers are at greatest risk (on Long Island, New York, for example). Groundwater in low-lying islands therefore is very sensitive to change. In the atolls of the Pacific Ocean, water supply is sensitive to precipitation patterns and changes in storm tracks (Salinger *et al.*, 1995). A reduction in precipitation coupled with sea-level rise would not only cause a diminution of the harvestable volume of water; it also would reduce the size of the narrow freshwater lense (Amadore *et al*, 1996). For many small island states, such as some Caribbean islands, seawater intrusion into freshwater aquifers has been observed as a result of overpumping of aquifers. Any sea-level rise would worsen the situation.

It will be noted from the foregoing that unconfined aquifers are sensitive to local climate change, abstraction, and seawater intrusion. However, quantification of recharge is complicated by the characteristics of the aquifers themselves as well as overlying rocks and soils.

A confined aquifer, on the other hand, is characterized by an overlying bed that is impermeable, and local rainfall does not influence the aquifer. It is normally recharged from lakes, rivers, and rainfall that may occur at distances ranging from a few kilometers to thousands of kilometers. Recharge rates also vary from a few days to decades. The Bahariya Oasis and other groundwater aquifers in the Egyptian Desert, for example, are recharged at the Nubian Sandstone outcrops in Sudan; such aquifers may not be seriously affected by seasonal or interannual rainfall or temperature of the local area.

Attempts have been made to calculate the rate of recharge by using carbon-14 isotopes and other modeling techniques. This has been possible for aquifers that are recharged from short distances and after short durations. However, recharge that takes place from long distances and after decades or centuries has been problematic to calculate with accuracy, making estimation of the impacts of climate change difficult. The medium through which recharge takes place often is poorly known and very heterogeneous, again challenging recharge modeling. In general, there is a need to intensify research on modeling techniques, aquifer characteristics, recharge rates, and seawater intrusion, as well as monitoring of groundwater abstractions. This research will provide a sound basis for assessment of the impacts of climate change and sea-level rise on recharge and groundwater resources.

4.3.6. River Flows

By far the greatest number of hydrological studies into the effects of climate change have concentrated on potential changes on streamflow and runoff. The distinction between "streamflow" and "runoff" can be vague, but in general terms streamflow is water within a river channel, usually expressed as a rate of flow past a point—typically in $m^3 s^{-1}$—whereas runoff is the amount of precipitation that does not evaporate, usually expressed as an equivalent depth of water across the area of the catchment. A simple link between the two is that runoff can be regarded as streamflow divided by catchment area, although in dry areas this does not necessarily hold because runoff generated in one part of the catchment may infiltrate before reaching a channel and becoming streamflow. Over short durations, the amount of water leaving a catchment outlet usually is expressed as streamflow; over durations of a month or more, it usually is expressed as runoff. In some countries, "runoff" implies surface runoff only (or, more precisely, rapid response to an input of precipitation) and does not include the contribution of discharge from groundwater to flow, but this is a narrow definition of the term.

This section first considers recent trends in streamflow/runoff and then summarizes research into the potential effects of future climate change.

4.3.6.1. Trends in Observed Streamflow

Since the SAR, there have been many notable hydrological events—including floods and droughts—and therefore many studies into possible trends in hydrological data. Table 4-1 summarizes some of these studies and their main results.

In general, the patterns found are consistent with those identified for precipitation: Runoff tends to increase where precipitation has increased and decrease where it has fallen over the past few years. Flows have increased in recent years in many parts of the United States, for example, with the greatest increases in low flows (Lins and Slack, 1999). Variations in flow from year to year have been found to be much more strongly related to precipitation changes than to temperature changes (e.g., Krasovskaia, 1995; Risbey and Entekhabi, 1996). There are some more subtle patterns, however. In large parts of eastern Europe, European Russia, central Canada (Westmacott and Burn, 1997), and California (Dettinger and Cayan, 1995), a major—and unprecedented—shift in streamflow from spring to winter has been associated not only with a change in precipitation totals but more particularly with a rise in temperature: Precipitation has fallen as rain, rather than snow, and therefore has reached rivers more rapidly than before. In cold regions, such as northern Siberia and northern Canada, a recent increase in temperature has had little effect on flow timing because precipitation continues to fall as snow (Shiklomanov, 1994; Shiklomanov *et al*., 2000).

However, it is very difficult to identify trends in hydrological data, for several reasons. Records tend to be short, and many data sets come from catchments with a long history of human intervention. Variability over time in hydrological behavior is very high, particularly in drier environments, and detection of any signal is difficult. Variability arising from low-frequency climatic rhythms is increasingly recognized (Section 4.2), and researchers looking for trends need to correct for these patterns. Finally, land-use and other changes are continuing in many catchments, with effects that may outweigh any climatic trends. Changnon and Demissie (1996), for example, show that human-induced changes mask the effects of climatic variability in a sample of midwest U.S. catchments. Even if a trend is identified, it may be difficult to attribute it to global warming because of other changes that are continuing in a catchment. A widespread lack of data, particularly from many developing

***Table 4-1**: Recent studies into trends in river flows.*

Study Area	Data Set	Key Conclusions	Reference(s)
Global	– 161 gauges in 108 major world rivers, data to 1990	– Reducing trend in Sahel region but weak increasing trend in western Europe and North America; increasing relative variability from year to year in several arid and semi-arid regions	– Yoshino (1999)
Russia			
– European Russia and western Siberia	– 80 major basins, records from 60 to 110 years	– Increase in winter, summer, and autumn runoff since mid-1970s; decrease in spring flows	– Georgiyevsky *et al.* (1995, 1996, 1997); Shiklomanov and Georgiyevsky (2001)
– European former Soviet Union	– 196 small basins, records up to 60 years	– Increase in winter, summer, and autumn runoff since mid-1970s; decrease in spring flows	– Georgiyevsky *et al*. (1996)
Baltic Region			
– Scandinavia		– Increase in winter, summer and autumn runoff since mid-1970s; decrease in spring flows	– Bergstrom and Carlsson (1993)
– Baltic states		– Increase in winter, summer and autumn runoff since mid-1970s; decrease in spring flows	– Tarend (1998)
Cold Regions			
– Yenesei, Siberia	– Major river basin	– Little change in runoff or timing	– Shiklomanov (1994)
– Mackenzie, Canada	– Major river basin	– Little change in runoff or timing	– Shiklomanov *et al.* (2000)
North America			
– United States	– 206 catchments	– 26 catchments with significant trends: half increasing and half decreasing	– Lins and Slack (1999)
– California	– Major river basins	– Increasing concentration of streamflow in winter as a result of reduction in snow	– Dettinger and Cayan (1995); Gleick and Chalecki (1999)
– Mississippi basin	– Flood flows in major basins	– Large and significant increases in flood magnitudes at many gauges	– Olsen *et al*. (1999)
– West-central Canada	– Churchill-Nelson river basin	– Snowmelt peaks earlier; decreasing runoff in south of region, increase in north	– Westmacott and Burn (1997)
South America			
– Colombia	– Major river basins	– Decrease since 1970s	– Marengo (1995)
– Northwest Amazon	– Major river basins	– Increase since 1970s	– Marengo *et al*. (1998)
– SE South America	– Major river basins	– Increase since 1960s	– Genta *et al*. (1998)
– Andes	– Major river basins	– Increase north of 40°S, decrease to the south	– Waylen *et al*. (2000)
Europe			
– UK	– Flood flows in many basins	– No clear statistical trend	– Robson *et al*. (1998)
Africa			
– Sahelian region	– Major river basins	– Decrease since 1970s	– Sircoulon (1990)
Asia			
– Xinjiang region, China	– Major river basins	– Spring runoff increase since 1980 from glacier melt	– Ye *et al*. (1999)
Australasia			
– Australia	– Major basins	– Decrease since mid-1970s	– Thomas and Bates (1997)

countries, and consistent data analysis makes it impossible to obtain a representative picture of recent patterns and trends in hydrological behavior. Monitoring stations are continuing to be closed in many countries. Reconstructions of long records, stretching back centuries, are needed to understand the characteristics of natural decadal-scale variability in streamflow.

4.3.6.2. Effects of Climate Change on River Flows

By far the majority of studies into the effects of climate change on river flows have used GCMs to define changes in climate that are applied to observed climate input data to create perturbed data series. These perturbed data are then fed through a hydrological model and the resulting changes in river flows assessed. Since the SAR, there have been several global-scale assessments and a large number of catchment-scale studies. Confidence in these results is largely a function of confidence in climate change scenarios *at the catchment scale*, although Boorman and Sefton (1997) show that the use of a physically unrealistic hydrological model could lead to misleading results.

Arnell (1999b) used a macro-scale hydrological model to simulate streamflow across the world at a spatial resolution of 0.5°x0.5°,

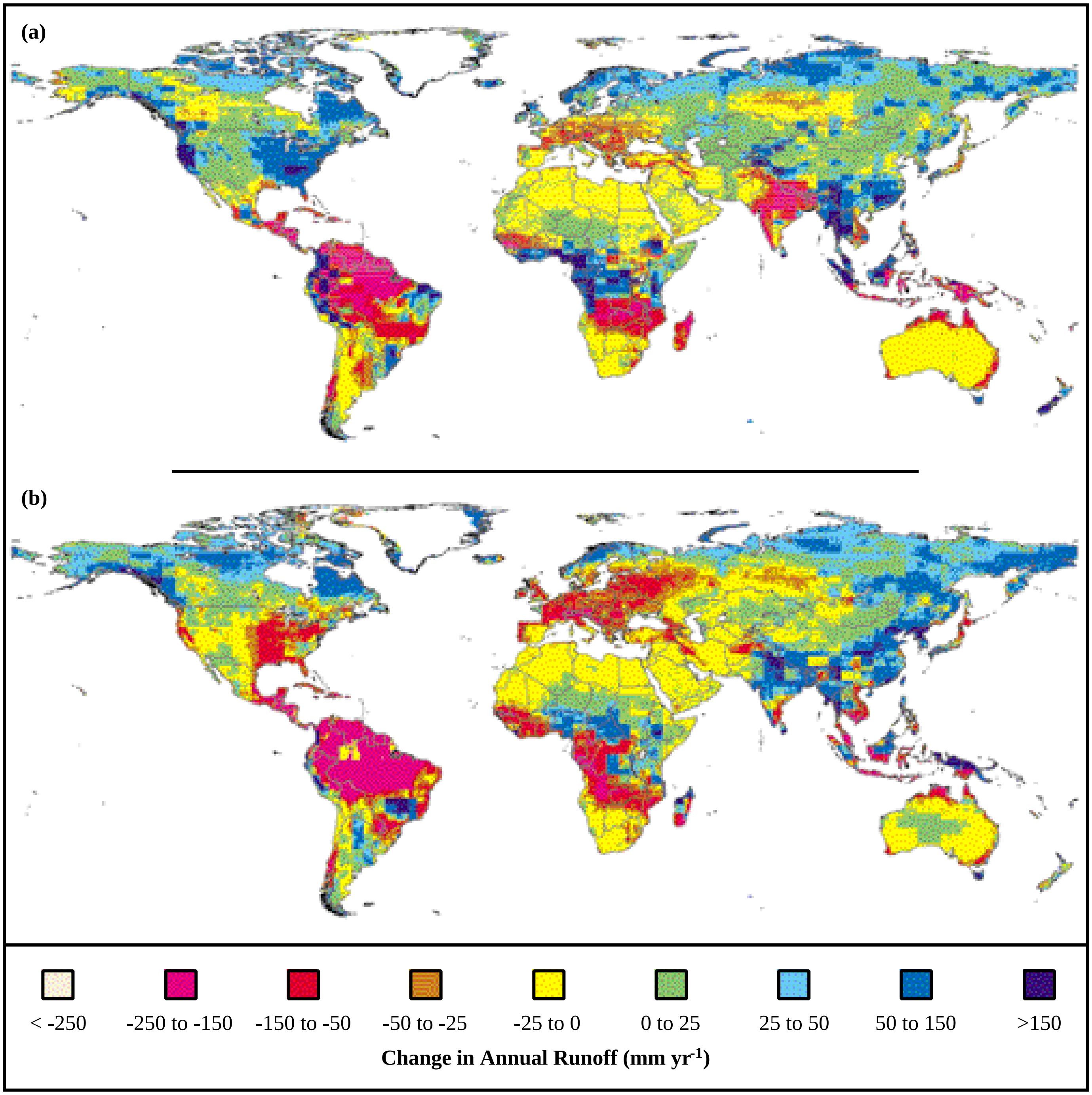

Figure 4-1: Change in average annual runoff by 2050 under HadCM2 ensemble mean (a) and HadCM3 (b) (Arnell, 1999b).

under the 1961–1990 baseline climate and under several scenarios derived from HadCM2 and HadCM3 experiments. Figure 4-1 shows the absolute change in annual runoff by the 2050s under the HadCM2 and HadCM3 scenarios: Both have an increase in effective CO_2 concentrations of 1% yr^{-1}. The patterns of change are broadly similar to the change in annual precipitation—increases in high latitudes and many equatorial regions but decreases in mid-latitudes and some subtropical regions—but the general increase in evaporation means that some areas that see an increase in precipitation will experience a reduction in runoff. Alcamo *et al*. (1997) also simulated the effects of different climate change scenarios on global river flows, showing broadly similar patterns to those in Figure 4-1.

Rather than assess each individual study, this section simply tabulates catchment-scale studies published since the SAR and draws some general conclusions. As in the SAR, the use of different scenarios hinders quantitative spatial comparisons. Table 4-2 summarizes the studies published since the SAR, by continent. All of the studies used a hydrological model to estimate the effects of climate scenarios, and all used scenarios based on GCM output. The table does not include sensitivity studies (showing the effects of, for example, increasing precipitation by 10%) or explore the hydrological implications of past climates. Although such studies provide extremely valuable insights into the sensitivity of hydrological systems to changes in climate, they are not assessments of the potential effects of future global warming.

It is clear from Table 4-2 that there are clear spatial variations in the numbers and types of studies undertaken to date; relatively few studies have been published in Africa, Latin America, and southeast Asia. A general conclusion, consistent across many studies, is that the effects of a given climate change scenario vary with catchment physical and land-cover properties and that small headwater streams may be particularly sensitive to change—as shown in northwestern Ontario, for example, by Schindler *et al*. (1996).

4.3.6.2.1. Cold and cool temperate climates

These areas are characterized by precipitation during winter falling as snow and include mountainous and low-lying regions. A major proportion of annual streamflow is formed by snow melting in spring. These areas include large parts of North America, northern and eastern Europe, most of Russia, northern China, and much of central Asia. The most important climate change effect in these regions is a change in the timing of streamflow through the year. A smaller proportion of precipitation during winter falls as snow, so there is proportionately more runoff in winter and, as there is less snow to melt, less runoff during spring. Increased temperatures, in effect, reduce the size of the natural reservoir storing water during winter. In very cold climates (such as in Siberia and northern Russia), there is little change in the timing of streamflow because winter precipitation continues to fall as snow with higher temperatures.

Table 4-2*: Catchment-scale studies since the Second Assessment Report addressing the effect of climate change on hydrological regimes.*

Region/Scope	Reference(s)
Africa	
– Ethiopia	Hailemariam (1999)
– Nile Basin	Conway and Hulme (1996); Strzepek *et al*. (1996)
– South Africa	Schulze (1997)
– Southern Africa	Hulme (1996)
Asia	
– China	Ying and Zhang (1996); Ying *et al*. (1997); Liu (1998); Shen and Liang (1998); Kang *et al*. (1999)
– Himalaya	Mirza and Dixit (1996); Singh and Kumar (1997); Singh (1998)
– Japan	Hanaki *et al*. (1998)
– Philippines	Jose *et al*. (1996); Jose and Cruz (1999)
– Yemen	Alderwish and Al-Eryani (1999)
Australasia	
– Australia	Bates *et al*. (1996); Schreider *et al*. (1996); Viney and Sivapalan (1996)
– New Zealand	Fowler (1999)
Europe	
– Albania	Bruci and Bicaj (1998)
– Austria	Behr (1998)
– Belgium	Gellens and Roulin (1998); Gellens *et al*. (1998)
– Continent	Arnell (1999a)
– Czech Republic	Hladny *et al*. (1996); Dvorak *et al*. (1997); Buchtele *et al*. (1998)
– Danube basin	Starosolszky and Gauzer (1998)
– Estonia	Jaagus (1998); Jarvet (1998); Roosare (1998)
– Finland	Lepisto and Kivinen (1996); Vehviläinen and Huttunen (1997)
– France	Mandelkern *et al* (1998)
– Germany	Daamen *et al*. (1998)
– Greece	Panagoulia and Dimou (1996)
– Hungary	Mika *et al*. (1997)
– Latvia	Butina *et al*. (1998); Jansons and Butina (1998)
– Nordic region	Saelthun *et al*. (1998)
– Poland	Kaczmarek et al. (1996, 1997)
– Rhine basin	Grabs (1997)
– Romania	Stanescu *et al*. (1998)
– Russia	Georgiyevsky *et al*., (1995, 1996, 1997); Kuchment (1998); Shiklomanov (1998)
– Slovakia	Hlaveova and Eunderlik (1998); Petrovic (1998)

Table 4-2 (continued)

Region/Scope	**Reference**
Europe (continued)	
– Spain	Avila *et al.* (1996); Ayala-Carcedo (1996)
– Sweden	Xu (1998); Bergstrom *et al*. (2001)
– Switzerland	Seidel *et al*. (1998)
– UK	Arnell (1996); Holt and Jones (1996); Arnell and Reynard (1996, 2000); Sefton and Boorman (1997); Roberts (1998); Pilling and Jones (1999)
Latin America	
– Continent	Yates (1997); Braga and Molion (1999)
– Panama	Espinosa *et al*. (1997)
North America	
– USA	Bobba *et al*. (1997); Hanratty and Stefan (1998); Chao and Wood (1999); Hamlet and Lettenmaier (1999); Lettenmaier *et al*. (1999); Leung and Wigmosta (1999); Miller *et al*. (1999); Najjar (1999); Wolock and McCabe (1999); Miller and Kim (2000); Stonefelt *et al*. (2000)
– Mexico	Mendoza *et al*. (1997)

The largest effects are in the most "marginal" snow-dominated regime areas.

The effects of climate change on the magnitude of annual runoff and flows through the year are much less consistent than the effect on streamflow timing because they depend not on the temperature increase but on the change in precipitation. In general, precipitation increases in high-latitude areas under most scenarios, but in lower latitudes precipitation may decrease. Kazcmarek *et al*. (1997), for example, show a decrease in annual runoff in Poland under a Geophysical Fluid Dynamics Laboratory (GFDL)-based scenario (by around 20% by the 2050s) but an increase under a Goddard Institute for Space Studies (GISS) scenario (by as much as 20%); in both cases, the season of maximum flow shifts from spring to winter.

Similar patterns are found for rivers in mountainous regions or draining from mountains. The Rhine and Danube, for example, would both see a reduction in spring flows and an increase in winter runoff (Grabs, 1997; Starosolszky and Gauzer, 1998), as would rivers draining east and west from the Rocky Mountains in North America.

4.3.6.2.2. Mild temperate climates

Hydrological regimes in these regions are dominated by the seasonal cycles of rainfall and evaporation; snowfall and snowmelt are not important. Here, climate change tends to affect the magnitude of flows in different seasons—by an amount that depends on the change in rainfall—and may lead to an exaggerated seasonal cycle, but it generally does not affect the timing of flows through the year. In the UK, for example, most scenarios result in an increase in winter runoff and, particularly in the south, a decrease in summer runoff (Arnell and Reynard, 1996); similar patterns are found across most of western Europe under most scenarios (Arnell, 1999a). Low flows tend to occur during summer, and changes in low-flow frequency are closely related to changes in the balance between summer rainfall and summer evaporation. Across most mid-latitude temperate regions, summer rainfall would decline with global warming, leading to a reduction in low flows.

The detailed effect of a given change in climate, however, depends to a large extent on the geological characteristics of the catchment. Studies in the UK (Arnell and Reynard, 1996) and Belgium (Gellens and Roulin, 1998) have indicated that in catchments with considerable groundwater, changes in summer flows are largely a function of the change not in summer rainfall but in rainfall during the winter recharge season.

4.3.6.2.3. Arid and semi-arid regions

River flows in arid and semi-arid regions are very sensitive to changes in rainfall: A given percentage change in rainfall can produce a considerably larger percentage change in runoff. There have been relatively few studies in such regions since the SAR, but work has been done in southern Africa (Schulze, 1997), Australia (Bates *et al*., 1996), northern China (Ying *and* Huang, 1996), and southern Russia (Georgiyevsky *et al*., 1996; Shiklomanov, 1998).

4.3.6.2.4. Humid tropical regions

Runoff regimes in these regions are very much influenced by the timing and duration of the rainy season or seasons. Climate change therefore may affect river flows not only through a change in the magnitude of rainfall but also through possible changes in the onset or duration of rainy seasons (such as those caused by monsoon).

4.3.7. Lakes

Lakes are particularly vulnerable to changes in climate parameters. Variations in air temperature, precipitation, and other meteorological components directly cause changes in evaporation, water balance, lake level, ice events, hydrochemical and hydrobiological regimes, and the entire lake ecosystem. Under some climatic conditions, lakes may disappear entirely. There are many different types of lakes, classified according to lake formation and origin, the amount of water exchange, hydrochemistry, and so forth.

An important distinction is drawn between closed (endorheic) lakes, with no outflow, and exorheic lakes, which are drained by outflowing rivers. Endorheic lakes are very dependent on the balance of inflows and evaporation and are very sensitive to change in either (whether driven by climate change, climatic variability, or human interventions). This also means that they are very important indicators of climate change and can provide records of past hydroclimatic variability over a large area (e.g., Kilkus, 1998; Obolkin and Potemkin, 1998). Small endorheic lakes are most vulnerable to a change in climate; there are indications that even relatively small changes in inputs can produce large fluctuations in water level (and salinity) in small closed lakes in western North America (Laird *et al*., 1996).

The largest endorheic lakes in the world are the Caspian and Aral Seas, Lake Balkash, Lake Chad, Lake Titicaca, and the Great Salt Lake. Some of the largest east African lakes, including Lakes Tanganyika and Malawi, also can be regarded as practically endorheic. Changes in inflows to such lakes can have very substantial effects: The Aral Sea, for example, has been significantly reduced by increased abstractions of irrigation water upstream, the Great Salt Lake in the United States has increased in size in recent years as a result of increased precipitation in its catchment, and Qinghai Lake in China has shrunk following a fall in catchment precipitation. Many endorheic lake systems include significant internal thresholds, beyond which change may be very different. Lake Balkash, for example, currently consists of a saline part and a fresh part, connected by a narrow strait. Several rivers discharge into the fresh part, preventing salinization of the entire lake. Areduction in freshwater inflows, however, would change the lake regime and possibly lead to salinization of the freshwater part; this would effectively destroy the major source of water for a large area.

Exorheic lakes also may be sensitive to changes in the amount of inflow and the volume of evaporation. Evidence from Lake Victoria (east Africa), for example, indicates that lake levels may be increased for several years following a short-duration increase in precipitation and inflows. There also may be significant thresholds involving rapid shifts from open to closed lake conditions. Progressive southward expansion of Lake Winnipeg under postglacial isostatic tilting was suppressed by a warm dry climate in the mid-Holocene, when the north basin of the lake became closed (endorheic) and the south basin was dry (Lewis *et al*., 1998). A trend of progressively moister climates within the past 5,000 years caused a return from closed to open (overflowing) lake conditions in the north basin and rapid flooding of the south basin about 1,000 years later. Other examples include Lake Manitoba, which was dry during the warm mid-Holocene (Teller and Last, 1982). Computations of sustainable lake area under equilibrium water balance (after Bengtsson and Malm, 1997) indicate that a return to dry conditions comparable to the mid-Holocene climate could cause this 24,400-km^2 lake draining a vast area from the Rocky Mountains east almost to Lake Superior to become endorheic again (Lewis *et al*., 1998).

Climate change also is likely to have an effect on lake water quality, through changes in water temperature and the extent and duration of ice cover. These effects are considered in Section 4.3.10.

4.3.8. Changes in Flood Frequency

Although a change in flood risk is frequently cited as one of the potential effects of climate change, relatively few studies since the early 1990s (e.g., Nash and Gleick, 1993; Jeton *et al.*, 1996) have looked explicitly at possible changes in high flows. This largely reflects difficulties in defining credible scenarios for change in the large rainfall (or snowmelt) events that trigger flooding. Global climate models currently cannot simulate with accuracy short-duration, high-intensity, localized heavy rainfall, and a change in mean monthly rainfall may not be representative of a change in short-duration rainfall.

A few studies, however, have tried to estimate possible changes in flood frequencies, largely by assuming that changes in monthly rainfall also apply to "flood-producing" rainfall. In addition, some have looked at the possible additional effects of changes in rainfall intensity. Reynard *et al.* (1998), for example, estimated the change in the magnitude of different return period floods in the Thames and Severn catchments, assuming first that all rainfall amounts change by the same proportion and then that only "heavy" rainfall increases. Table 4-3 summarizes the changes in flood magnitudes in the Thames and Severn by

Table 4-3*: Percentage change in magnitude of peak floods in Severn and Thames catchments by the 2050s (Reynard et al., 1998).*

	Return Period				
Catchment	2-Year	5-Year	10-Year	20-Year	50-Year
Thames					
– GGx-x[a]	10	12	13	14	15
– GGx-s[b]	12	13	14	15	16
Severn					
– GGx-x[a]	13	15	16	17	20
– GGx-s[b]	15	17	18	19	21

[a] GGx-x = HadCM2 ensemble mean scenario with proportional change in rainfall.
[b] GGx-s = HadCM2 ensemble mean scenario with change in storm rainfall only.

the 2050s: Flood risk increases because winter rainfall increases, and in these relatively large catchments it is the total volume of rainfall over several days, not the peak intensity of rainfall, that is important. Schreider *et al.* (1996) in Australia assessed change in flood risk by assuming that all rainfall amounts change by the same proportion. They found an increase in flood magnitudes under their wettest scenarios—even though annual runoff totals did not increase—but a decline in flood frequency under their driest scenarios.

Panagoulia and Dimou (1997) examined possible changes in flood frequency in the Acheloos basin in central Greece. Floods in this catchment derive from snowmelt, and an increase in winter precipitation—as indicated under the scenarios used—results in more frequent flood events of longer duration. The frequency and duration of small floods was most affected. Saelthun *et al.* (1998) explored the effect of fixed increases in temperature and precipitation in 25 catchments in the Nordic region. They show that higher temperatures and higher precipitation increases flood magnitudes in parts of the region where floods tended to be generated from heavy rainfall in autumn but decrease flood magnitudes where floods are generated by spring snowmelt. In some cases, the peak flood season shifts from spring to autumn. This conclusion also is likely to apply in other environments where snow and rain floods both occur.

Mirza *et al*.(1998) investigated the effects of changes in precipitation resulting from global warming on future flooding in Bangladesh. Standardized precipitation change scenarios from four GCMs were used for the analysis. The most extreme scenario showed that for a 2°C rise in global mean temperature, the average flood discharge for the Ganges, Brahmaputra, and Meghna could be as much as 15, 6, and 19% higher, respectively.

4.3.9. Changes in Hydrological Drought Frequency

Droughts are considerably more difficult to define in quantitative terms than floods. Droughts may be expressed in terms of rainfall deficits, soil moisture deficits, lack of flow in a river, low groundwater levels, or low reservoir levels; different definitions are used in different sectors. A "hydrological" drought occurs when river or groundwater levels are low, and a "water resources" drought occurs when low river, groundwater, or reservoir levels impact water use. Low river flows in summer may not necessarily create a water resources drought, for example, if reservoirs are full after winter; conversely, a short-lived summer flood may not end a water resources drought caused by a prolonged lack of reservoir inflows. Water resources droughts therefore depend not only on the climatic and hydrological inputs but critically on the characteristics of the water resource system and how droughts are managed. This section focuses on hydrological drought, particularly on low river flows. Different studies have used different indices of low river flows, including the magnitude of minimum flows, the frequency at which flows fall below some threshold, the duration of flow below a threshold, and the cumulative difference between actual flows and some defined threshold.

At the global scale, Arnell (1999b) explored the change in the minimum annual total runoff with a return period of 10 years under several scenarios, based on HadCM2 and HadCM3 GCMs. He shows that the pattern of this measure of "low flow" (which is relatively crude) changes in a similar way to average annual runoff (as shown in Figure 4-1) but that the percentage changes tend to be larger. Arnell (1999a) mapped a different index of low flow across Europe—the average summed difference between streamflow and the flow exceeded 95% of the time, while flows are below this threshold—under four scenarios. The results suggest a reduction in the magnitude of low flows under most scenarios across much of western Europe, as a result of lower flows during summer, but an amelioration of low flows in the east because of increased winter flows. In these regions, however, the season of lowest flows tends to shift from the current winter low-flow season toward summer.

Döll *et al.* (1999) also modeled global runoff at a spatial resolution of 0.5°x0.5°, not only for average climatic conditions but also for typical dry years. The annual runoff exceeded in 9 years out of 10 (the 10-year return period "drought" runoff) was derived for each of more than 1,000 river basins covering the whole globe. Then the impact of climate change on these runoff values was computed by scaling observed temperature and precipitation in the 1-in-10 dry years with climate scenarios of two different GCMs (Chapter 3), ECHAM4/OPYC3 and GFDL-R15. Climate variability was assumed to remain constant. For the same GHG emission scenario, IS92a, the two GCMs compute quite different temperature and more so precipitation changes. With the GFDL scenario, runoff in 2025 and 2075 is simulated to be higher in most river basins than with the ECHAM scenario. The 1-in-10 dry year runoff is computed to decrease between the present time (1961–1990 climate) and 2075 by more than 10% on 19% (ECHAM) or 13% (GFDL) of the global land area (Table 4-4) and to increase by more than 50% on 22% (ECHAM) or 49% (GFDL) of the global land area. These results underline the high sensitivity of computed future runoff changes to GCM calculations.

***Table 4-4**: Computed change of 1-in-10 dry year runoff under emission scenario IS92a between the present time (1961–90) and 2075: Influence of climate scenarios computed by two GCMs (Döll et al., 1999).*

Change in Runoff between Present and 2075 (%, decrease negative)	**Fraction of Global Land Area, where Runoff will have Changed (%), using Climate Scenarios of** MPI	GFDL
Increase by more than 200%	8.4	14.4
+50 to +200	13.4	34.9
+10 to + 50	39.5	24.0
-10 to +10	19.9	14.0
-50 to -10	12.1	10.1
Decrease by more than 50%	6.7	2.5

There have been several other studies into changes in low flow indicators at the catchment scale. Gellens and Roulin (1998), for example, simulated changes in low flows in several Belgian catchments under a range of GCM-based scenarios. They show how the same scenario could produce rather different changes in different catchments, depending largely on the catchment geological conditions. Catchments with large amounts of groundwater storage tend to have higher summer flows under the climate change scenarios considered because additional winter rainfall tends to lead to greater groundwater recharge (the extra rainfall offsets the shorter recharge season). Low flows in catchments with little storage tend to be reduced because these catchments do not feel the benefits of increased winter recharge. Arnell and Reynard (1996) found similar results in the UK. The effect of climate change on low flow magnitudes and frequency therefore can be considered to be very significantly affected by catchment geology (and, indeed, storage capacity in general). Dvorak *et al*. (1997) also showed how changes in low flow measures tend to be proportionately greater than changes in annual, seasonal, or monthly flows.

4.3.10. Water Quality

Water in rivers, aquifers, and lakes naturally contains many dissolved materials, depending on atmospheric inputs, geological conditions, and climate. These materials define the water's chemical characteristics. Its biological characteristics are defined by the flora and fauna within the water body, and temperature, sediment load, and color are important physical characteristics. Water "quality" is a function of chemical, physical, and biological characteristics but is a value-laden term because it implies quality in relation to some standard. Different uses of water have different standards. Pollution can be broadly defined as deterioration of some aspect of the chemical, physical, or biological characteristics of water (its "quality") to such an extent that it impacts some use of that water or ecosystems within the water. Major water pollutants include organic material, which causes oxygen deficiency in water bodies; nutrients, which cause excessive growth of algae in lakes and coastal areas—known as eutrophication (leading to algal blooms, which may be toxic and consume large amounts of oxygen when decaying); and toxic heavy metals and organic compounds. The severity of water pollution is governed by the intensity of pollutants and the assimilation capacity of receiving water bodies—which depends on the physical, chemical, and biological characteristics of streamflow—but not all pollutants can be degraded, however.

Chemical river water quality is a function of the chemical load applied to the river, water temperature, and the volume of flow. The load is determined by catchment geological and land-use characteristics, as well as by human activities in the catchment: Agriculture, industry, and public water use also may result in the input of "polluting" substances. Agricultural inputs are most likely to be affected by climate change because a changing climate might alter agricultural practices. A changing climate also may alter chemical processes in the soil, including chemical weathering (White and Blum, 1995). Avila *et al.* (1996) simulated a substantial increase in base cation weathering rates in Spain when temperature and precipitation increased (although if precipitation were reduced, the effects of the higher temperature were offset). This, in turn, resulted in an increase in concentrations of base cations such as calcium, sodium, and potassium and an increase in streamwater alkalinity. Warmer, drier conditions, for example, promote mineralization of organic nitrogen (Murdoch *et al*., 2000) and thus increase the potential supply to the river or groundwater. Load also is influenced by the processes by which water reaches the river channel. Nitrates, for example, frequently are flushed into rivers in intense storms following prolonged dry periods.

River water temperature depends not only on atmospheric temperature but also on wind and solar radiation (Orlob *et al*., 1996). River water temperature will increase by a slightly lesser amount than air temperature (Pilgrim *et al*., 1998), with the smallest increases in catchments with large contributions from groundwater. Biological and chemical processes in river water are dependent on water temperature: Higher temperatures alone would lead to increases in concentrations of some chemical species but decreases in others. Dissolved oxygen concentrations are lower in warmer water, and higher temperatures also would encourage the growth of algal blooms, which consume oxygen on decomposition.

Streamwater quality, however, also will be affected by streamflow volumes, affecting both concentrations and total loads. Carmichael *et al*. (1996), for example, show how higher temperatures and lower summer flows could combine in the Nitra River, Slovakia, to produce substantial reductions in dissolved oxygen concentrations. Research in Finland (Frisk *et al*., 1997; Kallio *et al*., 1997) indicates that changes in stream water quality, in terms of eutrophication and nutrient transport, are very dependent on changes in streamflow. For a given level of inputs, a reduction in streamflow might lead to increases in peak concentrations of certain chemical compounds. Cruise *et al.* (1999) simulated increased concentrations of nitrate in the southeast United States, for example, but the total amount transported from a catchment might decrease. Hanratty and Stefan (1998) simulated reductions in nitrate and phosphate loads in a small Minnesota catchment, largely as a result of reductions in runoff. Alexander *et al.* (1996) suggest that nutrient loadings to receiving coastal zones would vary primarily with streamflow volume. Increased streamflow draining toward the Atlantic coast of the United States under many scenarios, for example, would lead to increased nutrient loadings. An increased frequency of heavy rainfall would adversely affect water quality by increasing pollutant loads flushed into rivers and possibly by causing overflows of sewers and waste storage facilities. Polluting material also may be washed into rivers and lakes following inundation of waste sites and other facilities located on floodplains.

Water temperature in lakes responds to climate change in more complicated ways because thermal stratification is formed in summer, as well as in colder regions in winter. Meyer *et al*. (1999) evaluated the effect of climate change on thermal stratification by simulation for hypothetical lakes. They show that lakes in subtropic zones (about latitude 30 to 45°) and in subpolar zones (latitude 65 to 80°) are subject to greater relative changes in thermal stratification patterns than mid-latitude or equatorial lakes and that deep lakes are more sensitive than shallow lakes in the subtropic zones. Hostetler and Small (1999) simulated potential impacts on hypothetical shallow and deep lakes across North America, showing widespread increases in lake water temperature slightly below the increase in air temperature in the scenarios used. The greatest increases were in lakes that were simulated to experience substantial reductions in the duration of ice cover; the boundary of ice-free conditions shifted northward by 10° of latitude or more (1,000 km). Fang and Stefan (1997) show by simulation that winter stratification in cold regions would be weakened and the anoxic zone would disappear. Observations during droughts in the boreal region of northwestern Ontario show that lower inflows and higher temperatures produce a deepening of the thermocline (Schindler *et al.*, 1996).

The consequences of these direct changes to water quality of polluted water bodies may be profound, as summarized by Varis and Somlyody (1996) for lakes. Increases in temperature would deteriorate water quality in most polluted water bodies by increasing oxygen-consuming biological activities and decreasing the saturation concentration of dissolved oxygen. Hassan *et al.* (1998a,b) employed a downscaled climate model combined with GCM output to predict future stratification for Suwa Lake, Japan, on a daily basis, as well as for the prolonged summer stratification period. They predict increased growth of phytoplankton and reduced dissolved oxygen concentrations at different depths in the lake. Analysis of past observations in Lake Biwa in Japan (Fushimi, 1999) suggests that dissolved oxygen concentrations also tend to reduce when air (and lake water) temperature is higher.

Water quality in many rivers, lakes, and aquifers, however, is heavily dependent on direct and indirect human activities. Land-use and agricultural practices have a very significant effect on water quality, as do management actions to control point and nonpoint source pollution and treat wastewaters discharged into the environment. In such water bodies, future water quality will be very dependent on future human activities, including water management policies, and the direct effect of climate change may be very small in relative terms (Hanratty and Stefan, 1998). Considerable effort is being expended in developed and developing countries to improve water quality (Sections 4.5 and 4.6), and these efforts will have very significant implications for the impact of climate change on water quality.

Confidence in estimates of change in water quality is determined partly by climate change scenarios (and their effects on streamflow), but additional uncertainty is added by current lack of detailed understanding of some of the process interactions involved.

4.3.11. Glaciers and Small Ice Caps

Valley glaciers and small ice caps represent storages of water over long time scales. Many rivers are supported by glacier melt, which maintains flows through the summer season. The state of a glacier is characterized by the relationship between the rate of accumulation of ice (from winter snowfall) and the rate of ablation or melt. Most, but not all, valley glaciers and small ice caps have been in general retreat since the end of the Little Ice Age, between 100 and 300 years ago—for example, in Switzerland (Greene *et al*., 1999), Alaska (Rabus and Echelmeyer, 1998), the Canadian Rockies (Schindler, 2001), east Africa (Kaser and Noggler, 1991), South America (Ames and Hastenrath, 1996; see also Chapter 14), the arid region of northwest China (Liu *et al*., 1999), and tropical areas as a whole (Kaser, 1999). Temperature appears to be the primary control (Greene *et al*., 1999), and rates of retreat generally are accelerating (Haeberli *et al*., 1999). The World Glacier Monitoring Service (see http://www.geo.unizh.ch/wgms) monitors glacier mass balances and publishes annual reports on glacier fluctuations.

The effect of future climate change on valley glaciers and small ice caps depends on the extent to which higher temperatures are offset by increased winter accumulation. At the global scale, Gregory and Oerlemans (1998) simulate a general decline in valley glacier mass (and consequent rise in sea level), indicating that the effects of higher temperatures generally are more significant than those of additional winter accumulation. Model studies of individual glaciers have shown general retreat with global warming. Wallinga and van de Wal (1998) and Haerberli and Beniston (1998), for example, both simulated retreat in Alpine glaciers with higher temperatures and changes in winter accumulation. Davidovich and Ananicheva’s (1996) simulation results show retreat of Alaskan glaciers but also a substantial increase in mass exchange (and therefore rate of movement) as a result of increased winter accumulation.

Oerlemans *et al.* (1998) simulated the mass balance of 12 valley glaciers and small ice sheets distributed across the world. They found that most scenarios result in retreat (again showing that temperature changes are more important than precipitation changes) but showed that it was very difficult to generalize results because the rate of change depends very much on glacier hypsometry (i.e., variation in altitude across the glacier). Their simulations also show that, in the absence of a change in precipitation, a rise in temperature of 0.4°C per decade would virtually eliminate all of their study glaciers by 2100, but a rise of 0.1°C per decade would “only” lead to a reduction in glacier volume of 10–20%.

Tropical glaciers are particularly exposed to global warming. Kaser *et al.* (1996) show that the equilibrium line altitude (ELA)—the line separating the accumulation zone from the ablation zone—of a tropical glacier is relatively more sensitive to changes in air temperature than that of a mid-latitude glacier. This is because of the lack of seasonality in tropical temperatures and the fact that ablation is significant year-round. To illustrate, a 1°C rise in temperature during half of the year only will have a direct impact on total ablation, annual mass balance, and ELA of a tropical glacier. In the case of a mid-latitude glacier, this increase may occur during winter when temperatures may be well below freezing over much (if not all) of the glacier. As a result, there may be no significant change in ablation or position of the ELA, even though the annual temperature will have increased.

Glacier retreat has implications for downstream river flows. In rivers fed by glaciers, summer flows are supported by glacier melt (with the glacier contribution depending on the size of the glacier relative to basin area, as well as the rate of annual melt). If the glacier is in equilibrium, the amount of precipitation stored in winter is matched by melt during summer. However, as the glacier melts as a result of global warming, flows would be expected to increase during summer—as water is released from long-term storage—which may compensate for a reduction in precipitation. As the glacier gets smaller and the volume of melt reduces, summer flows will no longer be supported and will decline to below present levels. The duration of the period of increased flows will depend on glacier size and the rate at which the glacier melts; the smaller the glacier, the shorter lived the increase in flows and the sooner the onset of the reduction in summer flows.

4.3.12. River Channel Form and Stability

Patterns of river channel erosion and sedimentation are determined largely by variations in streamflow over time—in particular, the frequency of floods. There is considerable literature on past changes in streamflow—caused by human influences or natural climatic variability—and associated river channel changes (Rumsby and Mackin, 1994) but very little on possible future channel changes. This largely reflects a lack of numerical models to simulate erosion and sedimentation processes; assessments of possible future channel changes that have been made have been inferred from past changes. In northern England, for example, Rumsby and Mackin (1994) show that periods with large numbers of large floods are characterized by channel incision, whereas periods with few floods were characterized by lateral reworking and sediment transfer. Increased flooding in the future therefore could be associated with increased channel erosion.

The density of the drainage network reflects the signature of climate on topography. Moglen *et al.* (1998) show that drainage density is sensitive to climate change but also that the direction of change in density depends not only on climate change but also on the current climate regime.

Hanratty and Stefan (1998) simulated streamflow and sediment yield in a small catchment in Minnesota. The scenario they used produced a reduction in sediment yield, largely as a result of reduced soil erosion, but their confidence in the model results was low. In fact, the lack of physically based models of river channel form and sediment transport means that the confidence in estimates of the effect of climate change on river channels is low in general.

4.3.13. Climate Change and Climatic Variability

Even in the absence of a human-induced climate change, hydrological behavior will vary not only from year to year but also from decade to decade (see Section 4.2). Hulme *et al*. (1999) simulated streamflow across Europe under four climate change scenarios for the 2050s (based on four different simulations from the HadCM2 climate model) and seven scenarios representing different 30-year climates extracted from a long run of the HadCM2 model with no GHG forcing. They show that natural multi-decadal (30-year) variability in average annual runoff is high across most of Europe and that this natural variability in runoff in mid-latitude Europe is greater than the simulated signal of climate change. In northern and southern Europe, the magnitude of climate change by the 2050s is greater than the magnitude of natural variability. However, the spatial patterns of climate change and climatic variability are very different, with a much more coherent (usually north-south) pattern in the climate change signal. Nevertheless, the results indicate that, for individual catchments in certain areas, the magnitude of climate change effects on some indicators of streamflow may be smaller than natural climatic variability for several decades, whereas in other areas, the climate change signal will be larger than past experience.

4.4. Effects on Water Withdrawals

4.4.1. Introduction

The consequences of climate change for water resources depend not only on possible changes in the resource base—as indicated in Section 4.3—but also on changes in the *demand*, both human and environmental, for that resource. This section assesses the potential effects of climate change on water withdrawals and use, placing these effects in the context of the many nonclimatic influences that are driving demand.

It must be noted that "demand" in its economic sense means willingness to pay for a particular service or commodity and is a function of many variables—particularly price, income (for households), output (for industries or agriculture), family composition, education levels, and so forth. The usefulness of the demand function is found in the ability to predict the effects of changes in causal variables and in measurement of the demanding party's "willingness to pay" as a measure of gross benefits to the demanding party of various quantities. This willingness to pay is measured as the area under the demand function in the price-quantity plane. The quantities *actually* purchased (the quantities of water withdrawn or used) over time are the result of the interaction of factors affecting demand as defined above and conditions of supply (or availability). Thus, for example, the fact that the quantity purchased over time increases could be the result of falling costs of supply (a shift in the supply curve) rather than an increase in demand (shift in the demand curve). In this section, the term "demand" often is used as a synonym for "requirements;" this reflects usage of the term in large parts of the water sector.

Demands can be classified along two dimensions: instream or offstream, and consumptive or nonconsumptive. Instream demands use water within the river channel (or lake) and do not involve withdrawal. Examples include ecosystem uses, navigation, hydropower generation, recreation, and use of the water course for waste assimilation. Offstream demands extract water from the river channel, lake, or aquifer. They include domestic, industrial, and agricultural demands, as well as extractions for industrial and power station cooling. These demands can be consumptive or nonconsumptive. Consumptive demands “use” the water so it cannot be entirely returned to the river; nonconsumptive demands return the water to the river, although it may be returned to a different catchment or at a different quality. The primary consumptive demands are for irrigation and some types of industrial cooling (where the water is evaporated to the atmosphere rather than returned to the river).

4.4.2. World Water Use

Figure 4-2 shows estimated total water withdrawals, by sector, from 1900 to 1998 (Shiklomanov, 1998; Shiklomanov *et al*., 2000). Agricultural use—primarily for irrigation—is by far the largest proportion, accounting in 1995 for 67% of all withdrawals and 79% of all water consumed. Municipal, or domestic, use represents only about 9% of withdrawals. There are large differences, of course, between continents, with the greatest absolute volume of irrgation withdrawals in Asia.

Over the past few years there have been many projections of future water withdrawals; virtually all have overestimated the actual rate of increase (Shiklomanov, 1998). Figure 4-2 also shows projected total global water withdrawals estimates made for the UN Comprehensive Assessment of the Freshwater Resources of the World (Raskin *et al*., 1997). The central projection represents a “Conventional Development Scenario” (CDS), with “best-guess” estimates of future population growth, economic development, and water-use intensity. The upper and lower lines represent high and low cases, where the assumed rates of growth are altered. Under the core CDS, global water withdrawals would increase by about 35% over 1995 values by 2025, with low and high estimates of 23 and 49%, respectively. The greatest rates of growth are projected to be in Africa and the Middle East, with the lowest growth in developed economies. These projections are very dependent not only on the assumed rate of population growth but also on the different assumed rates of water usage. They do not take potential climate change into account.

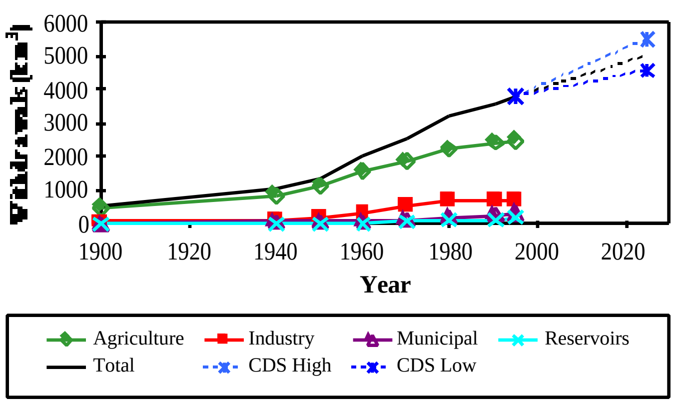

Figure 4-2: Global water withdrawals, 1900–1995, with projected future total withdrawals to 2025 [data from Shiklomanov *et al*., 2000 (after Raskin *et al*., 1997)].

The amount of municipal water withdrawals is dependent on the number of urban dwellers, the level of development (related to the availability of a piped distribution network and sewage systems, amongst other things), income levels, and price where actually applied to water. Per capita withdrawals in many developed countries are falling, and this may more than offset an increasing population: Total municipal withdrawals in the United States, for example, are falling largely as a result of increasing prices, conservation education provided by water utilities, and increasing use of water-efficient appliances. However, municipal withdrawals in developing countries can be expected to increase with living standards; under the CDS, per capita withdrawals in these countries are projected to rise toward those in more economically developed countries. Rapid urbanization in developing countries is expected to lead to very substantial increases in total municipal water withdrawals.

The industrial sector currently accounts for approximately 20% of current withdrawals. This water is used primarily either in processing (food processing or heavy industry) or for cooling; the relative proportions vary between countries. Future industrial water use is expected to rise substantially as industrial development continues, but the increase probably will be less than the increase in industrial production as water is used with greater efficiency (using less per unit of production, for example, or relocating power generation plants to coastal areas to use seawater for cooling). Under the CDS, total industrial water use increases; this increase is concentrated largely in Asia and Latin America (Raskin *et al*., 1997).

The amount of water used for agriculture is dependent primarily on the level of irrigation development, the pricing of water, and the reliability of supply. Future irrigation uses are a function of the rate of expansion of irrigated land, irrigation efficiency, and pricing practices. Efficiency is projected to improve—partly as a result of changes in the cost of water and partly as a result of technological developments—but this may be more than offset by increases in the area under irrigation. The amount of increase, however, is very uncertain; it depends on, among other things, assumed rates of population growth (increasing demand) and assumed changes in world agricultural markets. Previous estimates of future water use have tended to overestimate the rate of increase because the rate of expansion of irrigated land has been overestimated (Shiklomanov, 1998). The expanded use of pricing to reflect water scarcity is being strongly promoted by international organizations and will affect the quantities used. However, many regions that historically have been dependent on rainfall are using *supplemental irrigation*—a factor that will increase irrigation use.

Estimates of future water withdrawals are notoriously uncertain, largely reflecting uncertainties in the future rate of population and economic growth. There is an analogy here with GHG emissions scenarios. Also important, however, are possible changes in the way water is priced. Much agricultural water, for example, currently is heavily subsidized, and a shift toward a more "economic" price for water is likely to have a very significant effect on use. The World Bank and other economic development agencies are pushing for major reforms in the way water is priced and sold, as well as the use of water markets as an efficient way of reallocating existing supplies and motivating efficiency.

4.4.3. Sensitivity of Demand to Climate Change

Climate change is another potential influence on the demand for water. Municipal demand is related to climate to a certain extent. Shiklomanov (1998) notes different rates of use in different climate zones, although in making comparisons between cities it is difficult to account for variation in nonclimatic controls. The sensitivity of municipal demand to climate change is likely to be very dependent on the uses to which the water is put. The most sensitive areas are increased personal washing and—more importantly in some cultures—increased use of water in the garden and particularly on the lawn. Studies in the UK (Herrington, 1996) suggest that a rise in temperature of about 1.1°C by 2025 would lead to an increase in average per capita domestic demand of approximately 5%—in addition to nonclimatic trends—but would result in a larger percentage increase in peak demands (demands for garden watering may be highly concentrated). Boland (1997) estimated the effects of climate change on municipal demand in Washington, D.C., under a range of different water conservation policies. Table 4-5 summarizes percentage change in summer water use under the range of scenarios considered. Boland (1997) concludes that the effect of climate change is "small" relative to economic development and the effect of different water conservation policies.

***Table 4-5**: Percentage change in average summer water use from 1990 by 2030: Washington, D.C. (Boland, 1997).*[a]

	Policy 1[b]	Policy 2[c]	Policy 3[d]
No change in climate	+100	+61	+45
Additional Change over Baseline Climate			
GISS A scenario	+8	+8	+8
GISS B scenario	-13	-13	-13
GFDL scenario	+15	+15	+15
Max Planck scenario	+17	+16	+17
Hadley Centre scenario	+19	+19	+19

[a] See original paper for scenario definitions.
[b] Policy 1 = 1990 measures.
[c] Policy 2 = Policy 1 plus increased recycling, public education, and altered plumbing regulations.
[d] Policy 3 = Policy 2 plus 50% real increase in water tariffs.

Industrial use for processing purposes is insensitive to climate change; it is conditioned by technologies and modes of use. Demands for cooling water, however, may be affected by climate change. Increased water temperatures will reduce the efficiency of cooling, perhaps necessitating increased abstraction (or, of course, changes in cooling technologies to make them more efficient).

Agricultural demand, particularly for irrigation water, is considerably more sensitive to climate change. There are two potential effects. First, a change in field-level climate may alter the need for and timing of irrigation: Increased dryness may lead to increased demands, but demands could be reduced if soil moisture content rises at critical times of the year. Döll and Siebert (1999) applied a global irrigation water-use model with a spatial resolution of 0.5°x0.5° to assess the impact of climate change on net irrigation requirements per unit irrigated area, with a climate change scenario based on the ECHAM4 GCM. Figure 4-3 shows the relative change of net irrigation requirements between the present time (1961–1990) and 2025 in all areas equipped for irrigation in 1995. Under this scenario—and similarly under the corresponding HadCM3 scenario—net irrigation requirements per unit irrigated area generally would decrease across much of the Middle East and northern Africa as a result of increased precipitation, whereas most irrigated areas in India would require more water. The extra irrigation requirements per unit area in most parts of China would be small; the HadCM3 scenario leads to a greater increase in northern China. Other climate models would give different indications of regional changes in irrigation requirements. On the global scale, increases and decreases in net irrigation requirements largely cancel, and there is less difference between different climate models; under two scenarios considered by Döll and Siebert (2001), global net irrigation requirements would increase, relative to the situation without climate change, by 3.5–5% by 2025 and 6–8% by 2075. Actual changes in withdrawals would be dependent on changes in the efficiency of irrigation water use.

The second potential effect of climate change on irrigation demand is through increasing atmospheric CO_2 concentrations (Chapter 5). Higher CO_2 concentrations lower plant stomatal conductance, hence increase WUE; but as indicated in Section 4.3.3, this may be offset to a large extent by increased plant growth.

Hatch *et al*.(1999) assessed irrigation water requirements in Georgia, USA, using a climate change scenario derived from HadCM2. This scenario produced increased rainfall in most seasons, which, together with a shorter growing season and the assumed effect of CO_2 enrichment, resulted in a *decrease* in irrigation demand, ranging from just 1% by 2030 for soybean

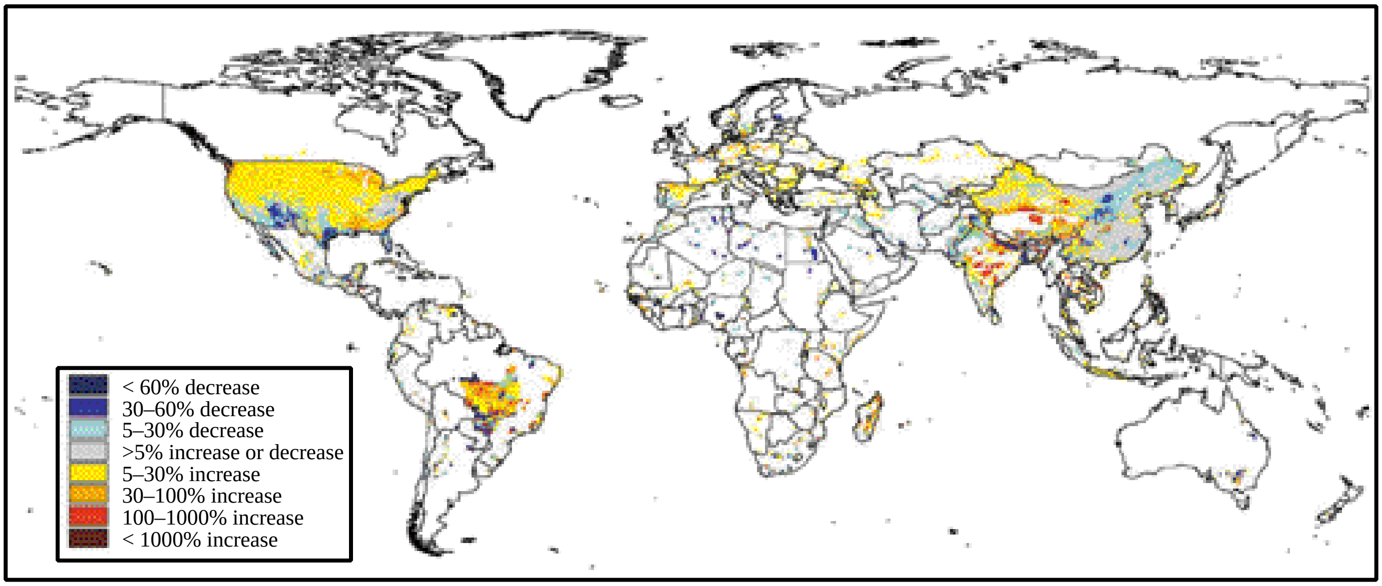

Figure 4-3: Relative change of annual net irrigation requirement between present time (1961–1990) and 2025 as a result of climate change (MPI climate scenario; areas equipped for irrigation in 1995 shown) (Döll and Siebert, 2001).

to as much as 20% by 2030 for corn. Along the Gulf Coast of the United States, however, the same scenario implies an increase in irrigation demands (Ritschard *et al*., 1999). Strzepek *et al*. (1999) also simulated decreases in irrigation requirements across the U.S. cornbelt under two of three scenarios (with the decrease depending on assumed irrigation use efficiency) but an increase under the third scenario. These three studies together indicate considerable uncertainty in estimated future irrigation withdrawals.

4.5. Impacts on Water Resources and Hazards

4.5.1. Introduction

The preceding sections have assessed the potential effect of climate change on river flows, groundwater recharge and other biophysical components of the water resource base, and demands for that resource. The consequences, or impacts, of such changes on risk or resource reliability depend not only on the biophysical changes in streamflow, recharge, sea-level rise, and water quality but also on the characteristics of the water management system. This section considers what possible changes in hydrology and demand will mean for water supply, flood risk, power generation, navigation, pollution control, recreation, habitats, and ecosystems services *in the absence of planned adaptation to climate change*. In practice, of course, the *actual* impacts of climate change will be rather different because water managers will make incremental or autonomous adaptations to change—albeit on the basis of imperfect knowledge—and the impact of change will be a function of adaptation costs and residual impacts. However, very few studies have incorporated deliberate adaptation strategies (Alexandrov, 1998, is one), and studies that do not consider adaptation provide a base case for assessing the magnitude of the climate change "problem." More significant, some studies have not accounted for nonclimatic changes in the way water resources are managed or systems are operated and have applied the future climate to the present management system. This is unrealistic, but the extent of adaptation by many water managers is uncertain. It is important to assess the effect of climate change by, say, the 2050s in the context of the water management system that would exist by then in the absence of climate change—considering, for example, changes in demand or legislative requirements.

The sensitivity of a water resource system to climate change is a function of several physical features and, importantly, societal characteristics. Physical features that are associated with maximum sensitivity include:

- A current hydrological and climatic regime that is marginal for agriculture and livestock
- Highly seasonal hydrology as a result of either seasonal precipitation or dependence on snowmelt
- High rates of sedimentation of reservoir storage
- Topography and land-use patterns that promote soil erosion and flash flooding conditions
- Lack of variety in climatic conditions across the territory of the national state, leading to inability to relocate activities in response to climate change.

Societal characteristics that maximize susceptibility to climate change include:

- Poverty and low income levels, which prevent long-term planning and provisioning at the household level
- Lack of water control infrastructures
- Lack of maintenance and deterioration of existing infrastructure
- Lack of human capital skills for system planning and management

- Lack of appropriate, empowered institutions
- Absence of appropriate land-use planning
- High population densities and other factors that inhibit population mobility
- Increasing demand for water because of rapid population growth
- Conservative attitudes toward risk [unwillingness to live with some risks as a tradeoff against more goods and services (risk aversion)]
- Lack of formal links among the various parties involved in water management.

This section first considers the global-scale implications of climate change on broad measures of water resources then assesses in more detail potential impacts on defined systems.

4.5.2. Impacts of Climate Change on Water Resources: A Global Perspective

There are several indicators of water resource stress, including the amount of water available per person and the ratio of volume of water withdrawn to volume of water potentially available. When withdrawals are greater than 20% of total renewable resources, water stress often is a limiting factor on development (Falkenmark and Lindh, 1976); withdrawals of 40% or more represents high stress. Similarly, water stress may be a problem if a country or region has less than 1,700 m^3 yr^{-1} of water per capita (Falkenmark and Lindh, 1976). Simple numerical indices, however, give only partial indications of water resources pressures in a country or region because the consequences of "water stress" depend on how the water is managed.

At the global scale, assessments of water stress usually are made by country because that is the unit at which water-use data generally are available. In 1990, approximately one-third of the world's population lived in countries using more than 20% of their water resources, and by 2025 about 60% of a larger total would be living in such stressed countries, in the absence of climate change (WMO, 1997), largely because population growth. Arnell (1999b, 2000) estimates the effect of a number of climate change scenarios on national water resource availability and compares this with estimated future demands for water (increasing following the CDS outlined in Section 4.4). Table 4-6 shows the numbers of people living in countries using more than 20% of their water resources in 2025 and 2050 and in which the amount of resources decreases by more than 10% as a result of climate change. There is considerable variability between scenarios, essentially reflecting how resources change in populous countries, but by the 2020s the table indicates that about 0.5 billion people could see increased water resources stress as a result of climate change. Significant geographic variations are hidden in Table 4-6. Under most of the scenarios considered, climate change increases stresses in many countries in southern and western Africa and the Middle East, whereas it ameliorates stresses in parts of Asia. Alcamo *et al.* (1997) found broadly similar results.

Figure 4-4 shows water resources per capita in 1990 and 2050 for a set of countries, as listed in Table 14-3 of the WGII contribution to the SAR, showing resources per capita in 2050 without climate change (long line) and under eight climate change scenarios (short lines) (Arnell, 2000). There are some differences with the earlier table because of the use of updated data sets, but similar conclusions can be drawn. Climate change tends to have a small effect relative to population growth, and the range of magnitudes of effect between scenarios also is little changed; the effects are still uncertain. For most of the example countries, climate change may result in either an increase or a decrease, although for some the climate change signal is more consistent (reductions in South Africa, Cyprus, and Turkey, for example, and increases in China). Note that these figures represent national averages, and different parts of each country may be differently affected.

Table 4-7 gives an indication of the potential effect of stabilizing GHG concentrations on the total number of people living in water-stressed countries adversely affected by climate change (Arnell *et al*., 2001). The results are conditional on the climate model used and the stabilization scenario, but this study—using just the HadCM2 climate model—suggests that by the 2050s the "weaker" stabilization target has little effect on the total number of impacted people, and although the "stronger" target reduces the impact of climate change, it does not eliminate it. The changes by the 2020s are very much affected by climatic variability between the various GCM runs.

4.5.3. Catchment and System Case Studies

Although there have been many assessments of the effect of climate change on river flows and (to a much lesser extent)

***Table 4-6**: Number of people living in water-stressed countries that are adversely affected by climate change, under a "business-as-usual" emissions scenario (IS92a) (Arnell, 2000).*

	Total Population (millions)	Population in Water-Stressed Countries[a] (millions)	Number of People (millions) in Water-Stressed Countries with Increase in Water Scarcity							
			HadCM2	HadCM3	ECHAM4	CGCM1	CSIRO	CCSR	GFDL	NCAR
2025	8055	5022	338–623	545	488	494	746	784	403	428
2050	9505	5915	2209–3195	1454	662	814	1291	1439	—	—

[a] Water-stressed countries use more than 20% of their available resources.

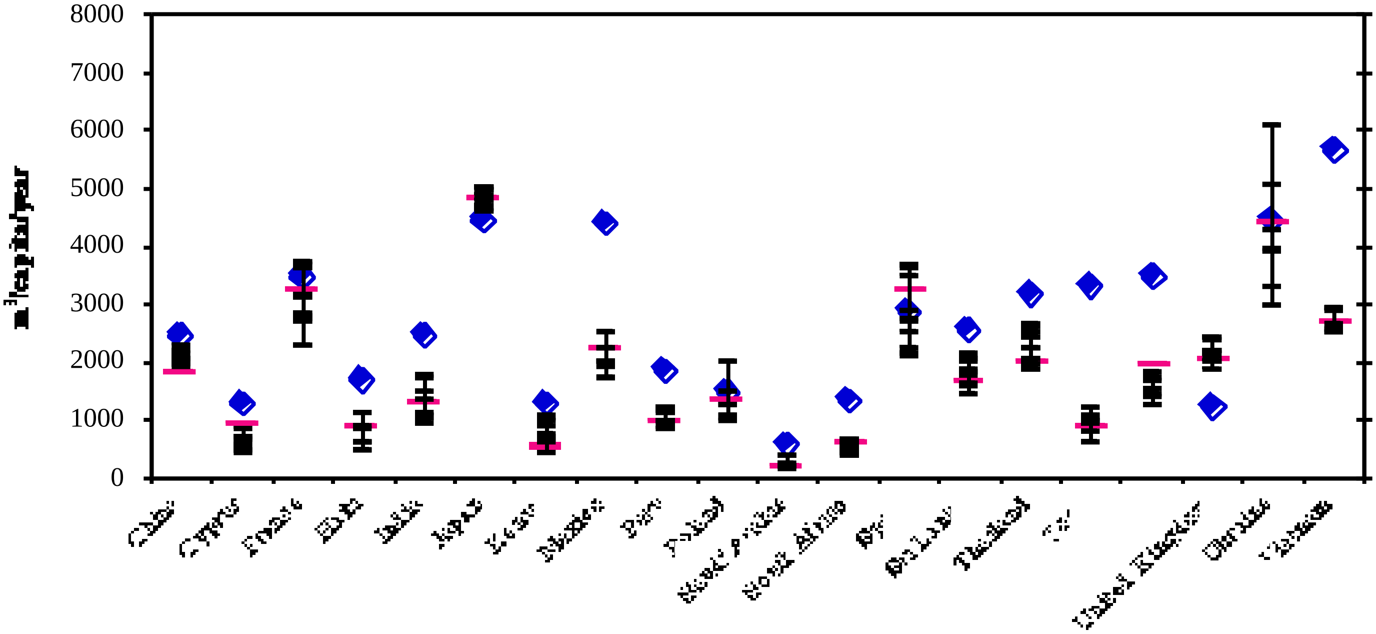

Figure 4-4: National water resources per capita (m³ yr⁻¹), in 1990 and 2050 under several climate change scenarios, for some countries (Arnell, 2000). Blue diamonds represent 1990; long pink bars 2050 with no climate change; and short black bars 2050 under different climate change scenarios.

groundwater recharge, there have been few published quantitative studies into impacts on real water resource systems. Table 4-8 lists studies published in particular aspects of the water sector. Rather than summarize a large number of studies—which use different scenarios and different methodologies—this section gives a description of a few particularly comprehensive studies.

Perhaps the most comprehensive set of studies conducted to date was published by Lettenmaier *et al*. (1999). This study looked at potential climate change impacts on six dimensions of water resource (power generation, municipal water supply, recreation, flood defense, navigation, and environmental flow regulation) in six major U.S. basins, using realistic models of the water system operation and scenarios for possible future nonclimatic changes in demands and objectives (not all the six dimensions were assessed in each basin). Table 4-9 summarizes the results, showing changes in a range of indicators (which varied between basins) by 2050 under three climate change scenarios and a varying number of operational and demand scenarios. The results clearly show considerable variability between scenarios and catchments; they also show that climate change might produce water resources benefits. The results also indicate that, in most sectors and basins, the impacts of different demand and operational assumptions by 2050 are greater than, or of similar magnitude to, the potential impacts of climate change.

Kaczmarek *et al*. (1996) assessed the impact of climate change on the water supply system in the Warta River basin in Poland, looking at two climate change scenarios in the context of increasing demand for water (particularly from irrigation). In the absence of climate change, they show that there would be supply problems in part of the system by 2050, simply because of the increase in demand. Under one of the scenarios, inflows to supply reservoirs would increase sufficiently to prevent supply problems; under the other scenario, the risk of shortage would increase substantially (the probability of an annual deficit of 10% would increase from 4 to ~25%, for example). Kaczmarek *et al*. (1996) also looked at the feasibility of one adaptation option—transferring water from one reservoir to another—and showed how it could lessen the likelihood of shortage.

Table 4-7*: Effect of stabilization of CO_2 concentrations on numbers of people living in water-stressed countries adversely affected by climate change (Arnell et al., 2001). Climate change under each emissions scenario is simulated with HadCM2 general circulation model; other climate models could give different indications of the effect of stabilization.*

	Total Population (millions)	Population in Water-Stressed Countries (millions)	Number of People (millions) in Water-Stressed Countries with Increase in Water Scarcity		
			IS92a	S750	S550
2025	8055	5022	338–623	242	175
2050	9505	5915	2209–3195	2108	1705

***Table 4-8**: Studies of impact of climate change on water resources and hazards (published since the SAR).*

Impact	Catchment/Region	Reference
Public water supply		
– Water supply systems	Four U.S. basins	Lettenmaier *et al*. (1999)
– Supply reservoirs	Czech Republic	Dvorak *et al*. (1997)
– Supply reservoir	Philippines	Jose *et al*. (1996)
– Supply reservoir	Yangtze basin, China	Shen and Liang (1998)
– Supply reservoirs	UK, Iran	Adeloye *et al*. (1998)
– Supply system	Poland	Kaczmarek *et al*. (1996)
– Groundwater supply	Texas, USA	Loaiciga *et al*. (1998)
– Water supply system	New York City, USA	Blake *et al*. (2000)
– Supply system	Rhine River	Grabs (1997)
Irrigation		
– Impacts on crop yields	New York, Indiana, and Oklahoma, USA	Tung and Haith (1998)
– Impacts on crop yields	Southern European Russia	Georgiyevsky *et al*. (1996)
– Rice irrigation	Senegal River basin, West Africa	Venema *et al*. (1997)
– Irrigated agriculture	Columbia River, USA/Canada	Cohen *et al*. (2000)
– Irrigated cropland	Georgia, USA	Hatch *et al*. (1999)
– Irrigated cropland	USA	Strzepek *et al*. (1999)
Power generation		
– Hydropower (reservoir)	Southeast USA	Robinson (1997)
– Hydropower (reservoir)	Nordic region	Saelthun *et al*. (1998)
– Hydropower (lake)	Great Lakes	Chao and Wood (1999)
– Hydropower (lake)	Four U.S. basins	Lettenmaier *et al*. (1999)
– Hydropower (reservoir)	Columbia River, USA/Canada	Cohen *et al*. (2000)
– Hydropower (reservoir)	Tana River, Kenya	Mutua (1998)
Navigation		
– River navigation	Rhine River	Grabs (1997)
– River navigation	Three U.S. basins	Lettenmaier *et al*. (1999)
– River navigation	Columbia River, USA/Canada	Cohen *et al*. (2000)
– Lake navigation	Great Lakes	Chao and Wood (1999)
Flood risk		
– Riverine flood risk	Rhine basin	Grabs (1997)
– Riverine flood risk	Eastern Australia	Minnery and Smith (1996)
– Riverine flood risk	Columbia River, USA/Canada	Cohen *et al*. (2000)
– Riverine flood risk	Five U.S. basins	Lettenmaier *et al*. (1999)

The River Rhine is a very important transport route within Europe. Grabs (1997) considered the effect of two climate change scenarios on navigation opportunities, having translated climate into streamflow by using a catchment water balance model. Table 4-10 summarizes the results: Under one of the scenarios, there would be little obvious effect on navigation opportunities, but under the other movement could be curtailed, particularly by the middle of the 21st century.

The vast majority of the impact assessments in Table 4-8 describe the effects of climate change on the reliability of an existing system. Very few explore the costs of these impacts, primarily because of difficulties in deciding the basis for calculation. Are the costs of climate change equal to the cost of continuing to provide the current standard of service? Are the costs of services foregone (in terms of extra flood damages or reduced use of water), or are they incurred in providing services at a new economically-optimum level? In other words, estimates of the cost of climate change must consider explicitly the measures used to adapt to that change, and the economic costs of climate change will depend on the adaptation strategies adopted. Carmichael *et al.* (1996) present one of the few studies that has tried to cost the implications of climate change. They investigated the treatment costs necessary to maintain a given water quality standard (expressed in terms of dissolved oxygen content) in a river in Slovakia and calculated the least costly treatment under the present hydrological regime and under one scenario for the 2020s. They showed that costs would be little

Table 4-8 (continued)

Impact	Catchment/Region	Reference
Pollution control and water quality management		
– Wastewater treatment	Slovakia	Carmichael *et al*. (1996)
Low flows and instream needs		
– Fishery impacts	Columbia River, USA/Canada	Cohen *et al*. (2000)
– Environmental low flows	Midwest USA	Eheart *et al*. (1999)
General overview		
– Review	UK	Arnell (1998)
– Review	USA	Gleick (2000)
– Review	Canada	Bruce *et al*. (2000)
– Review	Central Great Plains, USA	Ojima *et al*. (1999)
– Review	Mexico	Mendoza *et al*. (1997)
– Review	Estonia	Jarvet (1998)
– Review	South Asia	Mirza (1999)
– Review	Kenya	Awuor (1998)

different if the aim were to meet a 4 ppm dissolved oxygen target under average summer conditions but would rise by a factor of about 14 (at current prices) if the aim were to meet the same target under low-flow conditions, even taking a least-cost approach.

Aggregated estimates of the cost of impacts of climate change on water resources have been prepared for Spain, the UK, and the United States. Ayala-Carcedo and Iglesias-Lopez (2000) estimate that the reduction in water supplies under one scenario would cost nearly US$17 billion (2000 values) between 2000 and 2060, or about US$280 million yr^{-1} in terms of increased expenditure to maintain supplies and lost agricultural production. A study in the UK estimated the costs of climate change for water supply and flood protection (ERM, 2000). Table 4-11 shows the costs (converted to US$) involved in making up shortfalls of 5, 10, and 20% in the supply or demand across Britain, under several different types of approaches (see Section 4.6.2). The study assumes that the same change in water availability occurred across all of Britain—which probably overstates the costs because many parts of Britain are projected to have increased runoff—and estimated costs on the basis of standardized costs per unit of water. The study does not consider the feasibility of each of the potential adaptations. The cost of demand management measures increases substantially for large reductions in demand because more expensive technologies are needed. Note that a 5% reduction in demand represents just more than half the water of a 5% increase in supply; reducing domestic demand by 20% has a similar effect to increasing supply by 10%. The ERM study assumes that annual riverine flood damages would increase, because of increased flooding, by about US$80–170 million yr^{-1} over the next 30 years (compared to a current figure of about US$450 million), and the average annual cost of building structural works to prevent this extra flooding would be about US$40 million.

There have been two sets of estimates of the aggregate cost of climate change for water resources in the United States, using different approaches. Hurd *et al.* (1999) examined four river basins under nine climate change scenarios (defining fixed changes in temperature and precipitation) and extrapolated to the United States as a whole. Their study uses detailed economic and hydrological modeling and suggests that the largest costs would arise through maintaining water quality at 1995 standards—US$5.68 billion yr^{-1} (1994 US$) by 2060 with a temperature increase of 2.5°C and a 7% increase in precipitation—and through lost hydropower production (US$2.75 billion yr^{-1} by 2060, under the same scenario). Costs of maintaining public water supplies would be small, and although loss of irrigation water would impact agricultural users, changed cropping and irrigation patterns would mean that the economic losses to agriculture would be less than US$0.94 billion yr^{-1} by 2060. However, this study extrapolates from the four study catchments to the entire United States by assuming that the same climate change would apply across the whole country.

Frederick and Schwarz (1999) take a different approach, looking at 18 major water resource regions and 99 assessment subregions, with two climate change scenarios for the 2030s based on climate model simulations. Water scarcity indices were developed for each assessment subregion, comparing scarcities under "desired streamflow conditions" and "critical streamflow conditions" on the demand side with "mean streamflows" and "dry-condition streamflows" on the supply side. These indices played a key role in determining the costs of meeting various streamflow targets. A supply-demand balance in each region is achieved through supply- and demand-side measures, each of which has an assumed unit cost. Three strategies were defined for each region: "environmental," focusing on protecting the environment; "efficient," maintaining supplies to users; and "institutional," placing limits on

***Table 4-9**: Impact of climate change scenarios by 2050 on various water resource indices in six U.S. basins (Lettenmaier et al., 1999).*[a]

	Savannah	Apalachicola-Chattanooga-Flint (ACF)	Missouri	Columbia	Tacoma	Boston Water Supply
Energy production						
– GFDL	+26%	+5%	-8%	-5%		
– Hadley Centre	+3%	-10%	-13%	-4%		
– MPI	-5%	-1%	-33%	-12%		
– Demand/operational	-3%	-5 to +3%	not calculated	-10 to -15%		
Municipal and industrial supply						
– GFDL			-9%	-5%	0	0
– Hadley Centre			-5%	-1%	0	0
– MPI			-15%	-14%	0	-5%
– Demand/Operational			not calculated	0	-15%	-3 to -40%
Flood risk						
– GFDL	+70%	+32%	+4%		+40%	
– Hadley Centre	+50%	-3%	+10%		+40%	
– MPI	+16%	-10%	+12%		+35%	
Navigation						
– GFDL		+3%	-8%	-2%		
– Hadley Centre		-2%	-10%	-5%		
– MPI		-1%	-10%	+5%		
– Demand/operational		-2 to -17%	not calculated	-4%		
Instream flow requirements						
– GFDL	0			-4%	-1%	
– Hadley Centre	-1%			-5%	-6%	
– MPI	-3%			-10%	-8%	
– Demand/operational	-1 to -3%			0 to +12%	-8 to -9%	
Recreation						
– GFDL	+7%	+22%	0	-10%		
– Hadley Centre	+5%	-5%	0	-8%		
– MPI	+3%	+4%	0	-12%		
– Demand/operational	+18%	-25 to +28%	not calculated	-9 to +3%		

[a] See original paper for detailed summary of scenarios used.

changes in environmental indicators and the area of irrigation. The total national cost of climate change was determined under each strategy by aggregating least-cost measures in each subregion. Table 4-12 summarizes the estimated national costs under the three strategies and two scenarios. The costs are considerably greater under the drier CGCM1 scenario than under the wetter HadCM2 scenario (which, in fact, implies a benefit), and they vary with management strategy. Costs under the drier scenario are considerably higher than those estimated by Hurd *et al*. (1999), reflecting partly the different approaches used and partly the spatial variability in the effect of climate change considered by Frederick and Schwarz (1999).

4.5.4. Impacts of Climate Change on Water Resources: An Overview

This section explores the global-scale implications of climate change for water resources stress and summarizes a few studies into climate change impacts on several real-world water management systems. However, few published studies consider impacts in quantitative terms on real-world systems; most published studies infer changes in water resources from changes in streamflow.

It is very difficult to draw quantitative conclusions about the impacts of climate change, for several reasons. Different studies

***Table 4-10**: Effect of climate change on navigation opportunities on River Rhine (Grabs, 1997).*

	Average Annual Number of Days when Large Boat-Trains can Move (flows between 2000 and 5500 $m^3 sec^{-1}$) UKHI	CCC
1990	168	
2020	164	170
2050	156	170
2100	148	166

have used different methodologies and different scenarios, but, most important, different systems respond very differently to climate change. It is possible, however, to make some qualitative generalizations:

- In systems with large reservoir capacity, changes in resource reliability may be proportionately smaller than changes in river flows.
- The potential impacts of climate change must be considered in the context of other changes that affect water management. Few studies have explicitly compared climate change with other pressures, but in many environments it is likely that over a time horizon of less than 20 years, climate change impacts will be very small relative to other pressures. This will depend on the system.
- The implications of climate change are likely to be greatest in systems that currently are highly stressed.

By far the majority of studies of the impact of climate change on water resources have concentrated on human aspects of the water environment. Only a very few (e.g., Eheart *et al*., 1999; Meyer *et al*., 1999) have considered impacts on the aquatic environment. Some of these studies are considered in Chapter 5, but it must be remembered that water resources systems in many parts of the world increasingly are being managed to maintain instream and wetland ecosystems. This either increases effective water demand or decreases water availability.

Confidence in estimated quantitative impacts of climate change on water resources generally is low, reflecting initial confidence in climate change scenarios and low confidence in estimates of future pressures on water resources (as a result of factors such as changes in demand or legislative requirements). However, techniques for estimating the impacts of a given scenario are now well established.

4.6. Adaptation Options and Management Implications

4.6.1. Introduction

The preceding sections have assessed the possible effects of climate change on the water resource base and on the demand for water, as well as the potential impacts on water users. Most published studies have looked at impacts in the absence of planned adaptation to climate change, and the few studies that have tried to cost impacts have had to make assumptions about adaptation. This section assesses opportunities in the water sector for adapting to climate change and explores any constraints which may exist.

Water management has always adapted to change (especially following extreme events or in response to increased demand), and climate change is just one of the pressures facing water managers. Other pressures include increasing demands for water resources or protection against hazard, changing water management objectives (which recently have included increasing

***Table 4-11**: Estimated national average annual costs (US$ million) of impacts of climate change on water resources and riverine flooding, UK, over next 30 years (ERM, 2000).*

	5% reduction in supply by 2030	**10% reduction in supply by 2030**	**20% reduction in supply by 2030**
Volume of water (Ml day^{-1})	757	1514	3028
Supply-side			
– Reservoirs	3.3–25	6–50	12–100
– Conjunctive use schemes	140–1200	280–2430	570–4900
– Bulk transfers	0.5–90	1–175	2–360
– Desalination	4–12	10–24	19–48
	5% reduction in municipal demand by 2030	**10% reduction in municipal demand by 2030**	**20% reduction in municipal demand by 2030**
Volume of water (Ml day^{-1})	420	835	1670
Demand management measures	0.5	1	9

***Table 4-12**: National average annual cost of maintaining water supply-demand balance in the USA (Frederick and Schwarz, 1999). Values in 1994 US$ billion.*

Management Strategy	**HadCM2**	**CGCM1**
"Efficient"	-4.7	105
"Environmental"	-4.7	251
"Institutional"	not calculated	171

recognition of the importance of meeting environmental needs as well as those of offstream demands), changing water management technologies, and altered legislative environments.

It is important to distinguish between development of adaptive options for meeting changing demands and resources and assessment of the abilities of a given water management agency (interpreted broadly) actually to adapt to climate change. Over the years, a wide range of adaptive techniques has been developed, largely in response to the need to meet increased demands. Broad distinctions can be drawn among "supply-side" adaptive techniques (changing structures, operating rules, and institutional arrangements) and "demand-side" techniques (which change the demand for water or protection against risk and include institutional changes as well). Examples of supply-side adaptations include increasing flood defenses, building weirs and locks to manage water levels for navigation, and modifying or extending infrastructure to collect and distribute water to consumers. Demand-side techniques include water demand management (such as encouraging water-efficient irrigation and water pricing initiatives), changing water allocations (Miller *et al*., 1997), and nonstructural flood management measures (such as land-use controls). Distinctions also can be drawn between anticipatory and reactive actions. The former are taken in advance of some change, the latter in response to a change. Reactive actions include short-term operational adaptations, such as temporary exploitation of new sources, and longer term measures. Amajor flood or drought, for example, often triggers a change in water management. However, although many adaptive options do exist, knowledge of these options and the expertise of officials to execute them may be limited in some situations.

The optimum extent of adaptation can be characterized in terms of the benefits and costs of adaptation. The extremes of adaptation are "no adaptation" and "adaptation sufficient to eliminate all effects" (which usually is not physically possible). The optimum level of adaptation minimizes the combined costs of adaptation and residual negative effects, with the most cost-effective steps taken first.

Water managers long have had access to many techniques for assessing options and implementing adaptive strategies. However, the techniques used have changed over time and vary between countries, and they are very much influenced by institutional arrangements in place in a country. Factors that affect adaptive capacity in a country include institutional capacity, wealth, management philosophy (particularly management attitudes toward supply-side versus demand-side strategies, as well as "sustainable" management), planning time scale, and organizational arrangements (adaptation will be harder, for example, when there are many different "managers" involved or where water managers do not have sound professional guidance).

This section looks first at water management options, then at management techniques. It contends that water managers generally are aware of technical and institutional options—although for many reasons may not have access to all of them—and that climate change challenges management techniques for assessing and selecting options, rather than the technical and institutional options themselves.

4.6.2. Water Management Options

Table 4-13 summarizes some supply- and demand-side adaptive options, by water-use sector. Each option has a set of economic, environmental, and political advantages and disadvantages.

Most of these strategies are being adopted or considered in many countries in the face of increasing demands for water resources or protection against risk. In the UK, for example, water supply companies currently are pursuing the "twin track" of demand management and supply management in response to potential increases in demand for water (although there is a conflict between different parts of the water management system over the relative speeds with which the two tracks should be followed). These management strategies also are potentially feasible in the face of climate change. Nowhere, however, are water management actions being taken explicitly and solely to cope with climate change, although in an increasing number of countries climate change is being considered in assessing future resource management. In the UK, for example, climate change is one of the factors that must be considered by water supply companies in assessing their future resource requirements—although companies are highly unlikely to have new resources justified at present on climate change alone.

The continuing debate in water management (Easter *et al*., 1998) is between the practicalities and costs of supply-side versus demand-side options, and this debate is being pursued indepedently of climate change. The tide is moving toward the use of demand-side options because they are regarded as being more environmentally sustainable, cost-effective, and flexible (Frederick, 1986; World Bank, 1993; Young *et al*., 1994; Anderson and Hill, 1997). "Smart" combinations of supply-side and demand-side approaches are needed, although in many cases new supply-side infrastructure may be necessary. This is particularly the case in developing countries, where the challenge often is not to curb demand but to meet minimum human health-driven standards.

There do appear, however, to be numerous "no regret" policies that warrant immediate attention. In this context, a "no regret" policy is one that would generate net social benefits regardless

Table 4-13: *Supply-side and demand-side adaptive options: some examples.*

Supply-Side		**Demand-Side**	
Option	*Comments*	*Option*	*Comments*
Municipal water supply			
– Increase reservoir capacity	– Expensive; potential environmantal impact	– Incentives to use less (e.g., through pricing)	– Possibly limited opportunity; needs institutional framework
– Extract more from rivers or groundwater	– Potential environmental impact	– Legally enforceable water use standards (e.g., for appliances)	– Potential political impact; usually cost-inefficient
– Alter system operating rules	– Possibly limited opportunity	– Increase use of grey water	– Potentially expensive
– Inter-basin transfer	– Expensive; potential environmental impact	– Reduce leakage	– Potentially expensive to reduce to very low levels, especially in old systems
– Desalination	– Expensive (high energy use)		
– Seasonal forecasting	– Increasingly feasible	– Development of non-water-based sanitation systems	– Possibly too technically advanced for wide application
Irrigation			
– Increase irrigation source capacity	– Expensive; potential environmental impact	– Increase irrigation-use efficiency	– By technology or through increasing prices
		– Increase drought-toleration	– Genetic engineering is controversial
		– Change crop patterns	– Move to crops that need less or no irrigation
Industrial and power station cooling			
– Increase source capacity	– Expensive	– Increase water-use efficiency and water recycling	– Possibly expensive to upgrade
– Use of low-grade water	– Increasingly used		
Hydropower generation			
– Increase reservoir capacity	– Expensive; potential environmental impact	– Increase efficiency of turbines; encourage energy efficiency	– Possibly expensive to upgrade
– Seasonal forecasting	– May not be feasible		
Navigation			
– Build weirs and locks	– Expensive; potential environmental impact	– Alter ship size and frequency	– Smaller ships (more trips, thus increased costs and emissions)
– Increased dredging	– Potential environmental impact		
Pollution control			
– Enhance treatment works	– Potentially expensive	– Reduce volume of effluents to treat (e.g., by charging discharges)	
		– Catchment management to reduce polluting runoff	– Requires management of diffuse sources of pollution
Flood management			
– Increase flood protection (levees, reservoirs)	– Expensive; potential environmental impact	– Improve flood warning and dissemination	– Technical limitations in flash-flood areas, and unknown effectiveness
– Catchment source control to reduce peak discharges	– Most effective for small floods	– Curb floodplain development	– Potential major political problems

of whether there was climate change. Examples include elimination of subsidies to agriculture and floodplain occupancy and explicit recognition of environmental values in project design and evaluation. The effect of successful demand-side policies is to reduce the need for supply augmentation, although they may not prevent such needs entirely if changes are large. Such policy changes represent the minimum package of "anticipatory policy changes" in response to climate change.

4.6.3. Implications of Climate Change for Water Management Policy

Climate change exaggerates current pressures in water management—adding to the debate on sound management strategies—and adds a new component. This new component relates to uncertainty in climate change: How can water management efficiently adapt to climate change, given that the magnitude (or possibly even the direction) of change is not known? Conventionally, water resource managers assume that the future resource base will be the same as that of the past and therefore that estimates of indices such as average reservoir yield or probable maximum flood that are based on past data will apply in the future. There are two issues: assessing alternatives in the face of uncertainty and making decisions on the basis of this assessment.

Techniques for assessing alternatives include scenario analysis and risk analysis. Scenario analysis is central to climate change impact assessment, but it is not widely used in water resource assessment (although there are some very important exceptions, such as at the federal level in the United States). Scenario analysis, as in climate change impact assessment, tends to involve simulation of the effects of different scenarios, although in water resources assessment these tend to be different demand and operational scenarios rather than different climate scenarios. Stakhiv (1998) argues that if water managers already adopt a scenario-based approach, as at the federal level in the United States (Lins and Stakhiv, 1998), climate change therefore does not cause any additional *conceptual* challenges to water management: Climate change can be regarded simply as an extra type of scenario. However, the uncertain nature of climate change and the potential for nonlinearities in impact mean not only that the range of scenarios conventionally considered may be too narrow but also that a larger number of scenarios must be evaluated. In practice, scenario-based approaches are used in few water management agencies, and adoption of scenario analysis would challenge conventional water management practices in many countries.

Risk analysis involves assessment of the risk of certain thresholds being crossed under different possible futures (Major, 1998). It generally involves stochastic simulation of hydrological data to develop a sampling distribution of possible futures. In principle, climate change can be incorporated into risk analysis by changing the underlying population from which data are generated according to climate change scenarios. Matalas (1997) discusses the role of stochastic simulation in the context of climate change and argues that given the wide range in futures that often is simulated by assuming a stationary climate, the operational assumption of stationarity may remain appropriate in the face of climate change in some regions. However, it is possible that climate change could generate futures outside those produced under stationarity, and it cannot be assumed that climate change can be ignored in all circumstances.

The second main issue is that of decisionmaking under uncertainty. This issue was widely investigated during the 1960s and 1970s, largely in the context of uncertainties about demands or the precise distribution of floods and droughts over the short and medium terms. Climate change has revived interest in decisionmaking under uncertainty, and several analyses of different techniques have been published (e.g., Fisher and Rubio, 1997; Frederick, 1997; Hobbs, 1997; Hobbs *et al.,* 1997; Luo and Caselton, 1997; Chao *et al*., 1999). There still is considerable debate. Hobbs (1997), for example, concludes that Bayesian approaches involving allocation of probabilities to specific outcomes are more suitable than Dempster-Shafer reasoning (which requires the analyst to assign probabilities to ranges—perhaps overlapping—of outcomes), but Luo and Caselton (1997) conclude the reverse. Particularly significant is the issue of assigning probabilities to alternative possible futures. Hobbs *et al*. (1997) note unease among water planners in assigning subjective probabilities to different futures.

Planners of water resource and flood protection schemes conventionally cope with uncertainty by adding a safety factor to design estimates. This safety factor usually is defined arbitrarily.

***Table 4-14**: Headroom "score" characterizing effect of climate change on resource zone yield: an approach used in UK (UKWIR, 1998).*

Range in Resource Zone Yield between Four Defined Scenarios[a]	Case 1: Two Scenarios Above and Two Below Mean	Case 2: Three Scenarios Below and One Above Mean	Case 3: Three Scenarios Above and One Below Mean
<15%	2	3	1
15–25%	4	6	2
25–35%	6	9	3
>35%	8	10	4

[a]As percentage of "best estimate" of yield.

As part of a review of water resource design practices in the UK, a more formal approach to calculation of this safety factor, or "headroom," has been developed (UKWIR, 1998). This procedure identifies eight sources of supply-side uncertainty and three sources of demand-side uncertainty, each of which is given a score. The total score is summed and converted into a percentage value for the headroom allowance (with a maximum of 20%). Climate change is included as one of the supply-side uncertainties; its score depends on the range of estimates of supply-yield under four defined climate change scenarios (Table 4-14). Although this approach has many arbitrary elements, it does represent a systematic approach to the treatment of climate change uncertainties in water resources assessment.

Different aspects of the water sector have different planning horizons and infrastructure lifetimes. The parts of the water sector with long horizons and lifetimes need to take a different approach to climate change than parts with shorter lead times; one assessment and decision methodology will not be suitable for all managers.

4.6.4. Factors Affecting Adaptive Capacity

From the beginning of human attempts to shape the water environment to human benefit, water management has dealt with the variability of the native supply of water and the variability of demands for the use of water (Stakhiv, 1998). Great strides have been made in dealing with even extreme water regimes—particulary droughts—through interventions on the supply and demand sides (e.g., Stern and Easterling, 1999). Drought management planning is playing an increasing role in many water management agencies, lowering their susceptibility to drought impacts. Thus, in some ways the prospects of a change in the resource base—perhaps characterized by lower mean supplies and higher variability—represent only a sharpening of traditional challenges to water management. There are three important differences, however. First, future climate change is highly uncertain at spatial and temporal scales that are relevant to water management: All we know is that the future may not necessarily be like the recent past. Second, as noted above, the potential pervasiveness of these changes across large regions presents challenges that preclude some traditional steps of adaptation and requires innovative approaches that go beyond experience to date. Third, climate-induced effects may be nonlinear, carrying potential for surprises beyond those incorporated in traditional water management.

The ability to adapt to climate variability and climate change is affected by a range of institutional, technological, and cultural features at the international, national, regional, and local levels, in addition to specific dimensions of the change being experienced. Among the most important features are the following:

1) The capacity of water-related institutions, consisting of water agencies' authority to act, skilled personnel, the capability and authority to consider a wide range of alternatives (including but not limited to supply-side and demand-side interventions) in adapting to changed conditions, the capability and authority to use multi-objective planning and evaluation procedures in the assessment of policy alternatives, procedures for conflict resolution, and incentives to undertake serious *ex post* analysis of policies and projects to learn what has really worked (OECD, 1985). For example, O'Connor *et al.* (1999) found in the Susquehanna River Basin, USA, that experienced full-time water managers are more likely to consider future scenarios in their planning than part-time managers.
2) The legal framework for water administration that always constrains, for better and for worse, the options that are open to water management. Naturally, laws change as needs change, but the changes are slow and greatly lag changing needs. In many countries, the legal framework for water management is moving toward increasing environmental protection (e.g., the European Union's habitats directive). Such a direction poses further constraints on options to address climate change, but if the move reflects an increasing concern with *sustainable* water management (however defined), opportunities for considering adaptation to climate change are increased.
3) The wealth of nations in terms of natural resources and ecosystems, human-made capital (especially in the form of water control systems), and human capital (including trained personnel) that determines what nations can "afford to commit" to adaptation. This should include the ability and willingness to transfer wealth among population groups and regions within a country and among nations. This is the major constraint on adaptation to climate change in poorer countries.
4) The state of technology and the framework for the dissemination (or monopolization) of technology, especially in the fields of bioengineering of drought- and salt-resistant varieties of plants and techniques for the desalination of seawater.
5) Mobility of human populations to change residential and work locations in response to severe climate events or climate change. This is a major factor in coastal and island areas. Mobility is severely hampered by population pressures, especially in tropical island settings.
6) The *speed* of climate change is crucial in determining the capabilities of societies to adapt and change water management practices. Speed of change and the *cumulative extent* of change affect the impacts on society in nonlinear fashions (Howe *et al.*, 1990; National Research Council, 1992).
7) The complexity of management arrangements also may be a factor in response. In principle, the fewer agencies involved in water management, the easier it will be to implement an adaptation strategy (although the structure within the agencies will be very important). If there are many stakeholders to involve—perhaps with conflicting requirements, management goals, and perceptions and each with some management control over part of the water system—it may be more difficult

to adapt to changing circumstances. There is evidence that in some mature infrastructure systems, there may be substantial oportunities for increasing the resilience of water resource systems through institutional changes as well (Hansler and Major, 1999).

8) The ability of water managers to assess current resources and project future resources. This requires continuing collection of data and the ability to use scenarios with hydrological models to estimate possible future conditions.

Whether adaptation takes place or not may be heavily influenced by the occurrence of extreme events. Such events often are catalysts for change in management and may serve two roles. First, they may expose failings in the current water management system. Second, they may raise the perception among decision makers of the possibility of climate change—even if they cannot be attributed directly to climate change.

Recent experience with extreme events (e.g., the Chinese floods of 1998, the Rhine floods of 1996 and 1997, the eastern European floods of 1997 and 1998, and the Mozambique floods of 2000) shows that many societies are extremely exposed to loss and damage during extreme events, especially floods. At first, it may appear that this implies that existing adaptive techniques, as widely used by water managers, are not working as expected to minimize risk and loss (some loss will always be inevitable because no flood protection scheme can provide complete protection): Adaptation is not working. However, there is extensive evidence that social vulnerability to extreme events is serious and increasing (Munasinghe and Clark, 1995; Hewitt, 1997; Tobin and Montz, 1997; Haughton, 1998; La Red, 1999; Mileti, 1999) and that this exposure to hazards has been significantly increased by public and private development with insufficient regard for known hazards (Hewitt, 1997; Marsden, 1997; Pulwarty and Riebsame, 1997). In the United States there was more damage from hurricanes between 1990 and 1995 than there was between 1970 and 1990, after adjustments for inflation (Pielke, 1997), even though both periods had low hurricane frequency (Landsea *et al*., 1996). Changnon *et al*. (1997) analyzed the dramatic increase in dollar losses of insured property in the United States, which reached US$840 billion in the 1990–1994 period, and conclude that changes in weather and climate were not primary causes. Detailed meteorological analyses came to the same conclusion for flooding losses (Changnon, 1998; Karl and Knight, 1998).

Thus, societies' failure to adapt to extreme events *in the broadest sense* (i.e., by "allowing" risk-prone development) appears to have been largely responsible for increased damages, and that failure has not improved with time (Changnon and Changnon, 1998; Pielke and Landsea, 1998; Kunkel *et al*. 1999). It also appears that political decisions may have produced maladaptive results (Wiener, 1996; Hewitt, 1997; Mileti, 1999). In the United States, insurance has been a leading instrument for hazard awareness and post-event recovery. After 30 years of promotion, education, and subsidized premiums, only 20% of residents in floodplains were insured by the late 1990s (LeCompte and Gahagan, 1998; Pasterick, 1998). These failures to take advantage of insurance suggest that even wealthy societies adapt poorly to foreseeable hazards.

The residual damages of hazard events also are inequitably distributed across populations. This was shown clearly by studies of Hurricane Andrew in Florida (Peacock *et al*., 1997), leading the director of the Pan American Health Organization to state that "those who lost the most had the least to lose" (PAHO, 1999). Hurricane Mitch devastated Central America in 1998, exhibiting the extreme vulnerability of that region (La Red, 1999; UNICEF, 1999). Among the responsible factors were lack of land-use planning, deforestation, and inappropriate consumption and production systems (Hewitt, 1997; Mileti, 1999; PAHO, 1999).

Thus, available evidence concerning the effectiveness of adaptation to meteorological and geologic hazards indicates poor levels of individual and social adaptation to hazards. This failing extends well beyond the water management sector as conventionally defined and can be argued to reflect weaknesses in development control, planning guidance, public education, and fiscal incentives. The foregoing examples indicate that having the ability to adapt to change is not the same as actually adapting to change: The tools often are not used, for a variety of reasons.

4.6.5. Adaptation to Climate Change in the Water Sector: an Overview

Water managers are accustomed to adapting to changing circumstances, many of which can be regarded as analogs of future climate change, and a wide range of adaptive options has been developed. Supply-side options are more familiar to most water managers, but demand-side options increasingly are being implemented. Water management is evolving continually, and this evolution will affect the impact of climate change in practice. For reasons noted above, climate change is likely to challenge existing water management practices, especially in countries with less experience in incorporating uncertainty into water planning. The generic issue is incorporation of climate change into the types of uncertainty traditionally treated in water planning.

Integrated water resources management (IWRM) (Bogardi and Nachtnebel, 1994; Kindler, 2000) increasingly is regarded as the most effective way to manage water resources in a changing environment with competing demands. IWRM essentially involves three major components: explicit consideration of *all* potential supply-side and demand-side actions, inclusion of all stakeholders in the decision process, and continual monitoring and review of the water resources situation. IWRM is an effective approach in the absence of climate change, and there already are many good reasons for it to be implemented. Adopting integrated water resources management will go a long way toward increasing the ability of water managers to adapt to climate change.

There are three final points to make:

1) "Upstream" adaptation may have implications for "downstream" uses. In other words, the impact of climate change on one user may be very much determined by the actions of other users in response to climate change. This emphasizes the need for basin-scale management.
2) The emphasis in this section has been on managed water systems. In many countries, particularly in rural parts of the developing world, water supply is "managed" at the household level, utilizing local water sources. There is a need to look at the implications of climate change in circumstances of this type in which investment in substantial infrastructure is unlikely.
3) Adaptation to climate change to reduce vulnerability in the water sector should involve far more than just water managers. Increasing social vulnerability to water stress (in terms of drought and flood) in many parts of the world reflects a wide range of pressures, many of which are outside the responsibility of water managers. Reducing vulnerability to climate change-induced flood and drought will require decisions about issues such as development and planning control, fiscal incentives (such as subsidized insurance or government disaster relief) to occupy (and continue to occupy after loss) hazard-prone land, and wealth enhancement.

4.7. Integration: Water and Other Sectors

4.7.1. The Nonclimate Context

The impact of climate change in the water sector is a function of biophysical changes in water quantity and composition, the use to which the water is put, and the way in which those uses are managed. The implications of climate change for water resources therefore must be considered in the context of the many other pressures on water resources and their management. These pressures—and management responses to them—are evolving rapidly, and the water management system (legal, infrastructural, and institutional) in the future may be very different in many countries from that at present. Considerable efforts are underway in many international agencies and organizations (e.g., Global Water Partnership, World Bank) to improve the way water is used and managed; these actions will have very significant consequences not only for economies, access to safe water, and the environment but also for the impacts of climate change. *Adaptation to climate change in the water sector must be considered in the context of these other changes*—and, of course, climate change must be considered as a factor in the development of improved management techniques.

4.7.2. Water and Other Related Sectors

Water is a fundamental component of many economic activities. The impact of climate change on the quality and quantity of water therefore will be felt by such economic activities in one way or another. Examples of such linkages are given in the following subsections.

4.7.2.1. Ecosystems (TAR Chapter 5)

Changes in hydrological characteristics will lead to changes in aquatic and wetland ecosystems (as reviewed in Chapter 5)—as, indeed, may some of the actions taken by water managers to adapt to climate change. In practice, much water management increasingly focuses on ensuring that human use of water does not adversely impact the water environment, and maintaining and enhancing environmental quality is regarded as a legitimate management goal. Environmental demands, of course, will alter as climate changes.

Agriculture also will be affected by water availability, and actions taken by farmers in response to climate change may impact the water environment. For example, climate change may increase demands for irrigation from the agricultural sector, and if these extra needs are withdrawn from rivers or aquifers, there will be an effect on hydrological and ecological regimes: The "direct" effect of climate change on hydrological regimes and ecosystems may be enhanced. On the other hand, a lack of water resulting from climate change might mean that increased irrigation demands cannot be met, and changes in the water sector therefore are impacting directly on agricultural response to climate change. In addition, changes in agricultural land use resulting directly or indirectly from climate change may affect catchment water balance and water quality. These effects may be more substantial than the direct effects of climate change on hydrology.

4.7.2.2. Coastal and Marine Zones (TAR Chapter 6)

The ecology and morphology of river deltas reflect a balance between coastal and upstream processes. Changes in freshwater flow regimes will impact deltas, although the effects probably will be smaller than those of sea-level rise. Estuary characteristics also are affected by inflows from upstream, and the relative effects of sea-level rise and changes in river flows may be similar. Saline intrusion along estuaries, associated with higher sea levels and perhaps exacerbated by lower river flows, could threaten low-lying freshwater intakes, although adaptive options (relocation) are easy to implement. Saline intrusion into coastal aquifers also is a possibility, creating severe adaptation challenges in some settings—particularly low-lying islands such as atolls. Finally, rivers bring large quantities of nutrients and other materials to the coastal zone, and these fluxes are likely to be affected by changes in streamflow volumes in particular.

4.7.2.3. Settlements (TAR Chapter 7)

Provision of water to cities—especially the mega-cities emerging in some parts of the developing world—may become increasingly problematic, with consequent effects on city growth and access to safe water. Altered river flows also may affect the ability of settlements to dispose of waste safely. Urban storm drainage is potentially very sensitive to changes in short-duration rainfall and is both expensive to install and difficult to upgrade. Finally, changes in flood flows imply changes in urban flood risk; indications are that the risk generally will increase.

The most vulnerable parts of the mega-cities are the informal settlements that do not have planned water distribution and sanitation systems. Rural populations also are exposed to climate change, and it is possible that their sensitivity to change may be greater: The urban population enjoys planned water supply systems that can adapt to changes of climate change better than unplanned systems in rural areas.

4.7.2.4. Financial Services (TAR Chapter 8)

The main linkage with the finance sector is through insurance and public disaster relief. Insurance against flood losses is available in some countries, and major flood events in these countries could challenge—at least temporarily—local and perhaps international insurers.

4.7.2.5. Health (TAR Chapter 9)

Changes in hydrological regimes have the potential to alter health risks. Most important are potential changes in access to safe drinking water, but that is likely to be more affected by factors other than climate change (such as provision of water distribution systems and improved sanitation). Water-borne diseases and water-related insect vector diseases are more sensitive to changes in hydrological patterns (e.g., Patz *et al*., 1998; Checkley *et al*., 2000). Floods have associated health problems, and climate change also has the potential to alter contamination of water supplies (through changes in flow pathways that lead to increased leaching of pollutants and through reduced flows that lead to increased concentrations) and contamination of shellfish and fish.

4.7.3. Water and Conflict

A change in water availability has the potential to induce conflict between different users (Biswas, 1994; Dellapena, 1999). These users may be in the same area—cities versus farmers, for example—or they may be in different parts of the river basin. Much has been written about the potential for international conflict (hot or cold) over water resources (e.g., Gleick, 1998); where there are disputes, the threat of climate change is likely to exacerbate, rather than ameliorate, matters because of uncertainty about the amount of future resources that it engenders. One major implication of climate change for agreements between competing users (within a region or upstream versus downstream) is that allocating rights in absolute terms may lead to further disputes in years to come when the total absolute amount of water available may be different.

4.8. Science and Information Needs

4.8.1. Introduction

In the water sector, it is important to distinguish between the needs of those who wish to estimate the potential magnitude of climate change impacts on hydrology and water resources—to meet IPCC concerns, for example—and the more pragmatic needs of water managers who need to consider how best to adapt to climate change. The two sets of requirements are linked, but there are some important differences in emphasis.

4.8.2. Estimating Future Impacts of Climate Change

Some climate change analysts are essentially concerned with estimating what would actually happen under different climate futures: What are the impacts, for example, of continued growth of emissions of GHGs at 1% yr^{-1}, and what would be the impact of stabilizing CO_2 concentrations at, say, 550 ppmv by 2150? How do changes in variability affect the water environment? These impacts—and their costs—then could be compared with the impacts, costs, and benefits of mitigation. Such studies, in principle, could allow identification of "dangerous" levels of climate change. There also are important science questions concerning the processes by which climate change might impact the water environment. For example, how might flow pathways through soils change?

Such research questions need developments in the following areas:

- *Creation of credible climate change scenarios*. This involves improvements to GCMs so that they simulate present climate and its multi-decadal variability even better, development of conceptually sound downscaling techniques (in the absence of high-resolution global climate models), and characterization of potential changes in variability at time scales from daily to decadal. These requirements are common to all impact sectors and (with the exception of downscaling) are central to improving the understanding of climate change in the most general sense.
- *Characterization of natural climatic and hydrological variability*. Potential future climate changes resulting from increasing concentrations of GHGs need to be placed in context by appreciation of "natural" climatic and hydrological variability. Much needs to be learned about linkages between different components of the climate system in different parts of the world, which requires joint use of observational data (including remotely sensed data), palaeoclimatic data, and model simulations. Palaeoclimatic and palaeohydrological reconstructions can provide very useful information

on the variability in "natural" hydrological systems, as well as insights into nonlinear relationships between climate forcing and hydrological response.

- *Improved hydrological models.* Particularly important is development and application of process-based models of hydrological processes that include realistic representations of processes that generate streamflow and recharge and determine water quality. Key issues include development of models that do not need catchment calibration (but may require remotely sensed inputs) to assess the effects of climate change in parts of the world with limited hydrological data and development of coupled climate-hydrology models (which also are important for the improvement of climate model performance and for seasonal forecasting). The international collaborative research efforts summarized in Section 4.2.2 are extremely important.
- *Characterization of uncertainty*. How important are the different sources of uncertainty—in emissions, global climate response, and regional climate change—for estimated effects of climate change? Is downscaling cost-effective, given the wide range of changes in climate that might result from different emissions scenarios, for example? What can ensemble climate model experiments contribute? There has been little systematic analysis to date of the relative importance of different sources of uncertainty.
- *Impacts on real-world water systems*. Section 4.5 notes that there have been relatively few published studies on the impacts of climate change on real-world water resources systems, and inferences about impacts generally have been made from estimates of changes in streamflow alone. This may give a very misleading impression of the actual impacts of change because the characteristics of the water management system are a very important buffer between hydrological effect and impact on users and the environment. Therefore, more studies into real-world systems are needed.
- *Effects of adaptation.* Most impact studies have ignored adaptation by water managers, and in opposition it often is asserted that water managers will be able to adapt. However, how will managers make adaptation decisions in practice on the basis of incomplete information, and what would be the effects of inefficient adaptation on the impacts of climate change?

4.8.3. *Adapting to Climate Change*

Water managers are beginning to consider adapting to climate change. Some—but not all—water management plans and infrastructure have long lead times and long design lives. Improved understanding of the "science" of climate change impacts in the water sector is important but is not in itself enough to enable efficient adaptation. This is because it will *never* be feasible to base decisions on just one future climate scenario, particularly for time horizons greater than a decade. This is partly a result of incomplete knowledge but largely because of inherent uncertainty in future emissions of GHGs. Therefore, water managers always will be dealing with a range of scenarios, and research aimed at enabling efficient adaptation consequently must focus largely on appropriate analytical and management tools to cope with uncertainty and change rather than on "improving" climate change science and scenarios *per se*. In some aspects of water management—particularly associated with water quality—scientific research into processes is fundamental to allowing efficient adaptation.

Efficient adaptation to climate change in the water sector requires effort in five main areas:

- *Data for monitoring*. Adaptive water management requires reliable data on which to make decisions, calibrate models, and develop projections for the future. These data should cover not just hydrological characteristics but also indicators of water use.
- *Understanding patterns of variability*. An understanding of patterns of variability—in particular, the stability of a "baseline" climate—is important for medium-term water management. It is increasingly recognized that even in the absence of climate change, the recent past may not be a reliable guide to the hydrological resource base of the near future.
- *Analytical tools*. Effective water management requires numerous tools to assess options and the future. These tools include scenario analysis and risk analysis, which are used in some parts of water management but currently are by no means widespread.
- *Decision tools*. Scenario and risk analysis provides information on possible futures and their consequences. They must be supplemented with tools such as Bayesian and other decisionmaking tools to make decisions on the basis of the information provided. Again, techniques for decisionmaking under uncertainty are not widely used in water management at present, and some of the approaches being used are not very sophisticated.
- *Management techniques*. These are the techniques that are actually implemented to meet management objectives. The broad spectrum of techniques (such as building a reservoir or managing demand) is well known, but there is a need for research into specific aspects of many demand-side approaches in particular, as well as into opportunities for seasonal flow forecasting and innovative water supply and treatment technologies (such as desalination). It also is necessary to undertake research to determine how to enhance the range of techniques considered by water managers.

Note that the above efforts are needed to improve water management even in the absence of climate change, and there is an overarching need to improve the exchange of information between hydrological science and water managers.

Water managers have long been accustomed to dealing with change, although until recently this has been primarily change resulting from changes in demand and altered legislative or statutory requirements. Climate change does not in itself stimulate development of new adaptive strategies, but it encourages a more adaptive, incremental, risk-based approach to water management. More precisely, it provides further encouragement for a trend that already is gathering pace.

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