4

Climate change and water resources in systems and sectors

4.1 Ecosystems and biodiversity

4.1.1 Context

Temperature and moisture regimes are among the key variables that determine the distribution, growth and productivity, and reproduction of plants and animals. Changes in hydrology can influence species in a variety of ways, but the most completely understood processes are those that link moisture availability with intrinsic thresholds that govern metabolic and reproductive processes (Burkett et al., 2005). The changes in climate that are anticipated in the coming decades will have diverse effects on moisture availability, ranging from alterations in the timing and volume of streamflow to the lowering of water levels in many wetlands, the expansion of thermokarst lakes in the Arctic, and a decline in mist water availability in tropical mountain forests.

Observed global trends in precipitation, humidity, drought and runoff over the last century are summarised in WGI AR4 Chapter 3. Although changes in precipitation during the last century indicate considerable regional variation [WGI Figure 3.14], they also reveal some important and highly significant trends. Precipitation increased generally in the Northern Hemisphere from 1900 to 2005, but the tendency towards more widespread drought increased concomitantly for many large regions of the tropics and the Southern Hemisphere, notably the African Sahel and southern Africa, Central America, south Asia and eastern Australia. [WGI 3.3.5]

4.1.2 Projected changes in hydrology and implications for global biodiversity

The IPCC Fourth Assessment Report estimates of global warming vary in range from 0.5°C in the Southern Hemisphere to 2°C in the northern polar region by 2030 for SRES scenarios B1, A1 and A2, with B1 showing the highest warming. While the models simulate global mean precipitation increases, there is substantial spatial and temporal variation. General circulation models (GCMs) project an increase in precipitation at high latitudes, although the amount of that increase varies between models, and decreases in precipitation over many sub-tropical and mid-latitude areas in both hemispheres. [WGI Figures 10.8 and 10.12] Precipitation during the coming decades is projected to be more concentrated into more intense events, with longer periods of little precipitation in between. [WGI 10.3.6.1] The increase in the number of consecutive dry days is projected to be most significant in North and Central America, the Caribbean, north-eastern and south-western South America, southern Europe and the Mediterranean, southern Africa and western Australia. [WGI Figure 10.18] Impacts of warming and changes in precipitation patterns in tropical and sub-tropical regions have important implications for global biodiversity, because species diversity generally decreases with distance away from the Equator.

The changes in hydrology that are projected by WGI AR4 for the 21st century (see Section 2) will be *very likely* to impact biodiversity on every continent. Impacts on species have already been detected in most regions of the world. [WGII 1.3, 4.2] A review of 143 published studies by Root et al. (2003) indicates that animals and plants are already showing discernible changes consistent with the climatic trends of the 20th century. Approximately 80% of the changes were consistent with observed temperature change, but it should be recognised that temperature can also exert its influence on species through changes in moisture availability. [WGII 1.4.1]

Ecosystem responses to changes in hydrology often involve complex interactions of biotic and abiotic processes. The assemblages of species in ecological communities reflect the fact that these interactions and responses are often non-linear, which increases the difficulty of projecting specific ecological outcomes. Since the timing of responses is not always synchronous in species from different taxonomic groups, there may be a decoupling of species from their food sources, a disruption of symbiotic or facilitative relationships between species, and changes in competition between species. Owing to a combination of differential responses between species and interactions that could theoretically occur at any point in a food web, some of the ecological communities existing today could easily be disaggregated in the future (Root and Schneider, 2002; Burkett et al., 2005). [WGII 1.3.5.5, 4.2.2, 4.4]

Due to the combined effects of temperature and water stress, the extinction of some amphibians and other aquatic species is projected in Costa Rica, Spain and Australia (Pounds et al., 2006). [WGII Table 4.1] Drying of wetlands in the Sahel will affect the migration success of birds that use the Sahelian wetlands as stopovers in their migration to Northern Hemisphere breeding sites. In southern Africa, unprecedented levels of extinctions in both plant and animal species are envisaged. [WGII Table 9.1] In montane forests, many species depend on mist as their source of water: global warming will raise the cloud base and affect those species dependent on this resource. [WGII 13.4.1] Of all ecosystems, however, freshwater aquatic ecosystems appear to have the highest proportion of species threatened with extinction by climate change (Millennium Ecosystem Assessment, 2005b). [WGII 3.5.1]

4.1.3 Impacts of changes in hydrology on major ecosystem types

4.1.3.1 Lakes and streams

Impacts of global warming on lakes include an extended growing period at high latitudes, intensified stratification and nutrient loss from surface waters, decreased hypolimnetic oxygen (below the thermocline) in deep, stratified lakes, and expansion in range for many invasive aquatic weeds. Water levels are expected to increase in lakes at high latitudes, where climate models indicate increased precipitation, while water levels at mid- and low latitudes are projected to decline. Endorheic (terminal or closed) lakes are most vulnerable to a change in climate because of their sensitivity to changes in the balance of inflows and evaporation. Changes in inflows to such lakes can have very substantial effects and, under some climatic conditions, they may disappear entirely. The Aral Sea, for example, has been significantly reduced by increased abstractions of irrigation water upstream; and Qinghai Lake in China has shrunk following a fall in catchment precipitation. [WGII TAR 4.3.7]

The duration of ice cover in lakes and rivers at mid- to high latitudes has decreased by approximately two weeks during the past century in the Northern Hemisphere. [WGI TAR SPM] Increases in summer water temperature can increase anoxia in stratified lakes, increase the rate of phosphorus releases from lake-bottom sediments, and cause algal blooms that restructure the aquatic food web. [WGII 4.4.8] A unit increase in temperature in tropical lakes causes a proportionately higher density differential as compared with colder temperate lakes. Thus, projected tropical temperatures [WGI Chapters 10 and 11] will lead to strong thermal stratification, causing anoxia in deep layers of lakes and nutrient depletion in shallow lake waters. Reduced oxygen concentrations will generally reduce aquatic species diversity, especially in cases where water quality is impaired by eutrophication. [CCB 4.4]

Reduced oxygen concentrations tend to alter biotic assemblages, biogeochemistry and the overall productivity of lakes and streams. The thermal optima for many mid- to high-latitude cold-water taxa are lower than 20°C. Species extinctions are expected when warm summer temperatures and anoxia eliminate deep cold-water refugia. In the southern Great Plains of the USA, water temperatures are already approaching lethal limits for many native stream fish. Organic matter decomposition rates increase with temperature, thereby shortening the period over which detritus is available to aquatic invertebrates. [CCB 6.2] Invasive alien species represent a major threat to native biodiversity in aquatic ecosystems. [WGII 4.2.2] The rise in global temperature will tend to extend polewards the ranges of many invasive aquatic plants, such as *Eichhornia* and *Salvinia*. [RICC 2.3.6]

Effects of warming on riverine systems may be strongest in humid regions, where flows are less variable and biological interactions control the abundance of organisms. Drying of stream-beds and lakes for extended periods could reduce ecosystem productivity because of the restriction on aquatic habitat, combined with lowered water quality via increased oxygen deficits and pollutant concentrations. In semi-arid parts of the world, reductions in seasonal streamflow and complete drying up of lakes (such as in the Sahel of Africa) can have profound effects on ecosystem services, including the maintenance of biodiversity. [CCB 6.7]

Currently, species richness is highest in freshwater systems in central Europe and decreases to the north and south due to periodic droughts and salinisation (Declerck et al. 2005). Ensemble GCM runs for the IPCC AR4 indicate a south–north contrast in precipitation, with increases in the north and decreases in the south. [WGI 11.3.3.2] An increase in projected runoff and lower risk of drought could benefit the fauna of aquatic systems in northern Europe, while decreased water availability in the south could have the opposite effect (Álvarez Cobelas et al., 2005). [WGII 12.4.6]

4.1.3.2 Freshwater wetlands

The high degree of variability in the structure of wetland systems is due mainly to their individual hydrology, varying from peatland bogs in high-latitude boreal forests, through tropical monsoonal wetlands (e.g., the Kakadu wetlands, Australia), to high-altitude wetlands in the Tibetan and Andean mountains. Climate change will have its most pronounced effects on inland freshwater wetlands through altered precipitation and more frequent or intense disturbance events (droughts, storms, floods). Relatively small increases in precipitation variability can significantly affect wetland plants and animals at different stages of their life cycle (Keddy, 2000). [WGII 4.4.8] Generally, climatic warming is expected to start a drying trend in wetland ecosystems. This largely indirect influence of climate change, leading to alterations in the water level, would be the main agent in wetland ecosystem change and would overshadow the impacts of rising temperature and longer growing seasons in boreal and sub-Arctic peatlands (Gorham, 1991). Monsoonal areas are more likely to be affected by more intense rain events over shorter rainy seasons, exacerbating flooding and erosion in catchments and the wetlands themselves. [WGII TAR 5.8.3]

Most wetland processes are dependent on catchment-level hydrology, which can be altered by changes in land use as well as surface water resource management practices. [WGII TAR 5.ES] Recharge of local and regional groundwater systems, the position of the wetland relative to the local topography, and the gradient of larger regional groundwater systems are also critical factors in determining the variability and stability of moisture storage in wetlands in climatic zones where precipitation does not greatly exceed evaporation (Winter and Woo, 1990). Changes in recharge external to the wetland may be as important to the fate of the wetland under changing climatic conditions, as are the changes in direct precipitation and evaporation on the wetland itself (Woo et al., 1993). [WGII TAR 5.8.2.1] Thus, it may be very difficult, if not impossible, to adapt to the consequences of projected changes in water availability. [WGII TAR 5.8.4] Due, in part, to their limited capacity for adaptation, wetlands are considered to be among the ecosystems most vulnerable to climate change. [WGII 4.4.8]

Wetlands are often biodiversity hotspots. Many have world conservation status (Ramsar sites, World Heritage sites). Their loss could lead to significant extinctions, especially among amphibians and aquatic reptiles. [WGII 4.4.8] The TAR identified Arctic and sub-Arctic ombrotrophic ('cloud-fed') bogs and depressional wetlands with small catchments as the most vulnerable aquatic systems to climate change. [WGII TAR 5.8.5] The more recent AR4, however, suggests a very high degree of vulnerability for many additional wetland types, such as monsoonal wetlands in India and Australia, boreal peatlands, North America's prairie pothole wetlands and African Great Lake wetlands. [WGII 4.4.8, 4.4.10] The seasonal migration patterns and routes of many wetland species will have to change;

otherwise some species will be threatened with extinction. [WGII 4.4.8] For key habitats, small-scale restoration may be possible, if sufficient water is available. [WGII TAR 5.8.4]

Due to changes in hydrology associated with atmospheric warming, the area of wetland habitat has increased in some regions. In the Arctic region, thawing of permafrost is giving rise to new wetlands. [WGII 1.3] Thermokarst features, which result from the melting of ground ice in a region underlain by permafrost, can displace Arctic biota through either over-saturation or drying (Hinzman et al., 2005; Walsh et al., 2005). Extensive thermokarst development has been discovered in North America near Council, Alaska (Yoshikawa and Hinzman, 2003) and in central Yakutia (Gavriliev and Efremov, 2003). [WGI 4.7.2.3] Initially, permafrost thaw forms depressions for new wetlands and ponds that are interconnected by new drainage features. As the permafrost thaws further, surface waters drain into groundwater systems, leading to losses in freshwater habitat. [WGII 15.4.1.3] Warming may have already caused the loss of wetland area as lakes on the Yukon Delta expanded during the past century (Coleman and Huh, 2004). [WGII 15.6.2]

Small increases in the variability in precipitation regimes can significantly affect wetland plants and animals (Keddy, 2000; Burkett and Kusler, 2000). Biodiversity in seasonal wetlands, such as vernal pools, can be strongly impacted by changes in precipitation and soil moisture (Bauder, 2005). In monsoonal regions, prolonged dry periods promote terrestrialisation of wetlands, as witnessed in Keoladeo National Park (Chauhan and Gopal, 2001). [WGII 4.4.8]

4.1.3.3 Coasts and estuaries

Changes in the timing and volume of freshwater runoff will affect salinity, sediment and nutrient availability, and moisture regimes in coastal ecosystems. Climate change can affect each of these variables by altering precipitation and locally driven runoff or, more importantly, runoff from watersheds that drain into the coastal zone. [WGII 6.4.1.3] Hydrology has a strong influence on the distribution of coastal wetland plant communities, which typically grade inland from salt, to brackish, to freshwater species. [WGII 6.4.1.4]

The effects of sea-level rise on coastal landforms vary among coastal regions because the rate of sea-level rise is not spatially uniform [WGI 5.5.2] and because some coastal regions experience uplift or subsidence due to processes that are independent of climate change. Such processes include groundwater withdrawals, oil and gas extraction, and isostacy (adjustment of the Earth's surface on geological timescales to changes in surface mass; e.g., due to changes in ice sheet mass following the last deglaciation). In addition to changes in elevation along the coast, factors arising inland can influence the net effect of sea-level rise on coastal ecosystems. The natural ecosystems within watersheds have been fragmented and the downstream flow of water, sediment and nutrients to the coast has been disrupted (Nilsson et al., 2005). Land-use change and hydrological modifications have had downstream impacts, in addition to localised influences, including human development on the coast. Erosion has increased the sediment load reaching the coast; for example, suspended loads in the Huanghe (Yellow) River have increased 2–10 times over the past 2,000 years (Jiongxin, 2003). In contrast, damming and channelisation have greatly reduced the supply of sediments to the coast on other rivers through the retention of sediment in dams (Syvistki et al., 2005), and this effect will probably dominate during the 21st century. [WGII 6.4]

Climate model ensemble runs by Milly et al. (2005) indicate that climate change during the next 50–100 years will increase discharges to coastal waters in the Arctic, in northern Argentina and southern Brazil, parts of the Indian sub-continent and China, while reduced discharges to coastal waters are suggested in southern Argentina and Chile, western Australia, western and southern Africa, and in the Mediterranean Basin. [WGII 6.3.2; see Figure 2.10 in this volume] If river discharge decreases, the salinity of coastal estuaries and wetlands is expected to increase and the amount of sediments and nutrients delivered to the coast to decrease. In coastal areas where streamflow decreases, salinity will tend to advance upstream, thereby altering the zonation of plant and animal species as well as the availability of freshwater for human use. The increased salinity of coastal waters since 1950 has contributed to the decline of cabbage palm forests in Florida (Williams et al., 1999) and bald cypress forests in Louisiana (Krauss et al., 2000). Increasing salinity has also played a role in the expansion of mangroves into adjacent marshes in the Florida Everglades (Ross et al., 2000) and throughout south-eastern Australia during the past 50 years (Saintilan and Williams, 1999). [WGII 6.4.1.4] Saltwater intrusion as a result of a combination of sea-level rise, decreases in river flows and increased drought frequency are expected to alter estuarine-dependent coastal fisheries during this century in parts of Africa, Australia and Asia. [WGII 6.4.1.3, 9.4.4, 10.4.1, 11.4.2]

Deltaic coasts are particularly vulnerable to changes in runoff and sediment transport, which affect the ability of a delta to cope with the physical impacts of climatic change. In Asia, where human activities have led to increased sediment loads of major rivers in the past, the construction of upstream dams is now depleting the supply of sediments to many deltas, with increased coastal erosion becoming a widespread consequence (Li et al., 2004; Syvitski et al., 2005; Ericson et al., 2006). [WGII 6.2.3, 6.4.1] In the subsiding Mississippi River deltaic plain of south-east Louisiana, sediment starvation due to human intervention in deltaic processes and concurrent increases in the salinity and water levels of coastal marshes occurred so rapidly that 1,565 km^2 of intertidal coastal marshes and adjacent coastal lowlands were converted to open water between 1978 and 2000 (Barras et al., 2003). [WGII 6.4.1]

Some of the greatest potential impacts of climate change on estuaries may result from changes in physical mixing characteristics caused by changes in freshwater runoff (Scavia et al., 2002). Freshwater inflows into estuaries influence water residence time, nutrient delivery, vertical stratification, salinity, and control of phytoplankton growth rates (Moore et al., 1997). Changes in river discharges into shallow near-shore marine environments will lead to changes in turbidity, salinity, stratification and nutrient availability (Justic et al., 2005). [WGII 6.4.1.3]

4.1.3.4 Mountain ecosystems

The zonation of ecosystems along mountain gradients is mediated by temperature and soil moisture. Recent studies (Williams et al., 2003; Pounds and Puschendorf, 2004; Andreone et al., 2005; Pounds et al., 2006) have shown the disproportionate risk of extinctions in mountain ecosystems and, in particular, among endemic species. [WGII 4.4.7] Many species of amphibians, small mammals, fish, birds and plants are highly vulnerable to the ongoing and projected changes in climate that alter their highly specialised mountain niche. [WGII 1.3.5.2, 4.4.7, 9.4.5]

In many snowmelt-dominated watersheds, temperature increase has shifted the magnitude and timing of hydrological events. A trend towards earlier peak spring streamflow and increased winter base flows has been observed in North America and Eurasia. [WGII 1.3.2] A greater fraction of annual precipitation is falling as rain rather than snow at 74% of the weather stations studied in the western mountains of the USA between 1949 and 2004 (Knowles et al., 2006). Since the 1970s, winter snow depth and spring snow cover have decreased in Canada, particularly in the west, where air temperatures have consistently increased (Brown and Braaten, 1998). Spring and summer snow cover is decreasing in the western USA (Groisman et al., 2004). The April 1st snow water equivalent (SWE) has decreased by 15–30% since 1950 in the western mountains of North America, particularly at lower elevations in spring, primarily due to warming rather than to changes in precipitation (Mote et al., 2005). Streamflow peaks in the snowmelt-dominated western mountains of the USA occurred 1–4 weeks earlier in 2002 than in 1948 (Stewart et al., 2005). [WGII 14.2.1]

The duration and depth of snow cover, often correlated with mean temperature and precipitation (Keller et al., 2005; Monson et al., 2006), is a key factor in many alpine ecosystems (Körner, 1999). Missing snow cover exposes plants and animals to frost, and influences water supply in spring (Keller et al., 2005). If animal movements are disrupted by changing snow patterns, as has been found in Colorado (Inouye et al., 2000), increased wildlife mortality may result through a mismatch between wildlife and environment. [WGII 4.4.7] For each 1°C of temperature increase, the duration of snow cover is expected to decline by several weeks at mid-elevations in the European Alps. It is *virtually certain* that European mountain flora will undergo major changes in response to climate change, with changes in snow-cover duration being a more important driver than the direct effects of temperature on animal metabolism. [WGII 12.4.3]

Changing runoff from glacier melt has significant effects on ecosystem services. Biota of small-watershed streams sustained by glacial melt are highly vulnerable to extirpation. [WGII 1.3.1, 3.2, 3.4.3]

4.1.3.5 Forests, savannas and grasslands

The availability of water is a key factor in the restructuring of forest and grassland systems as the climate warms. Climate change is known to alter the likelihood of increased wildfire size and frequency, while also inducing stress in trees, which indirectly exacerbates the effects of these disturbances. Many forest ecosystems in the tropics, high latitudes and high altitudes are becoming increasingly susceptible to drought and associated changes in fire, pests and diseases. [WGII Chapter 4, 5.1.2, 13.4] It has been estimated that up to 40% of the Amazonian forests could be affected by even slight decreases in precipitation (Rowell and Moore, 2000). Multi-model GCM simulations of precipitation changes over South America during the next 100 years show a substantial (20% or more) decrease in June, July and August precipitation in the Amazon Basin, but a slight increase (approximately 5%) in December, January and February. [WGI 11.6.3.2] These projected changes in precipitation, coupled with increased temperature, portend a replacement of some Amazonian forests by ecosystems that have more resistance to the multiple stresses caused by temperature increase, droughts and fires. [WGII 13.4.2]

Increases in drought conditions in several regions (Europe, parts of Latin America) during the growing season are projected to accompany increasing summer temperatures and precipitation declines, with widespread effects on forest net ecosystem productivity. Effects of drought on forests include mortality due to disease, drought stress and pests; a reduction in resilience; and biotic feedbacks that vary from site to site. [WGII 4.4.5] In some regions, forests are projected to replace other vegetation types, such as tundra and grasslands, and the availability of water can be just as important as temperature and CO_2-enrichment effects on photosynthesis. [WGII 4.4.3, 4.4.5]

Numerous studies have evaluated the direct CO_2 fertilisation impact and warming effects on dominant forest and grassland types. Studies involving a wide range of woody and herbaceous species suggest that enhancements in photosynthesis due to projected CO_2 enrichment will be dependent upon water availability. [WGII 4.4.3] Higher-order effects of CO_2 enrichment in forests and savannas can have important feedbacks on water resources. For example, atmospheric CO_2 enrichment can have adverse effects on the nutritional value of litter in streams (Tuchman et al., 2003), and soil water balance can be strongly influenced by elevated CO_2 in most grassland types. [WGII 4.4.10] Grassland and savanna productivity is highly sensitive to precipitation variability. In assessments of tall-grass prairie productivity, for example, increased rainfall variability was more significant than rainfall amount, with a 50% increase in dry-spell duration causing a 10% reduction in net primary productivity (Fay et al., 2003a). [WGII 4.4.3]

4.2 Agriculture and food security, land use and forestry

4.2.1 Context

The productivity of agricultural, forestry and fisheries systems depends critically on the temporal and spatial distribution of precipitation and evaporation, as well as, especially for crops, on the availability of freshwater resources for irrigation. [WGII 5.2.1] Production systems in marginal areas with respect to water face increased climatic vulnerability and risk under climate change, due to factors that include, for instance, degradation of land resources through soil erosion, over-extraction of groundwater and associated salinisation, and over-grazing of dryland (FAO, 2003). [WGII 5.2.2] Smallholder agriculture in such marginal areas is especially vulnerable to climate change and variability, and socio-economic stressors often compound already difficult environmental conditions. [WGII 5.2.2, Table 5.2, Box 5.3] In forests, fires and insect outbreaks linked to the frequency of extreme events have been shown to increase climate vulnerability. In fisheries, water pollution and changes in water resources also increase vulnerability and risk. [WGII 5.2.2]

4.2.1.1 Agriculture and food security

Water plays a crucial role in food production regionally and worldwide. On the one hand, more than 80% of global agricultural land is rain-fed; in these regions, crop productivity depends solely on sufficient precipitation to meet evaporative demand and associated soil moisture distribution (FAO, 2003). [WGII 5.4.1.2] Where these variables are limited by climate, such as in arid and semi-arid regions in the tropics and sub-tropics, as well as in Mediterranean-type regions in Europe, Australia and South America, agricultural production is very vulnerable to climate change (FAO, 2003). On the other hand, global food production depends on water not only in the form of precipitation but also, and critically so, in the form of available water resources for irrigation. Indeed, irrigated land, representing a mere 18% of global agricultural land, produces 1 billion tonnes of grain annually, or about half the world's total supply; this is because irrigated crops yield on average 2–3 times more than their rain-fed counterparts[19] (FAO, 2003).

While too little water leads to vulnerability of production, too much water can also have deleterious effects on crop productivity, either directly, e.g., by affecting soil properties and by damaging plant growth, or indirectly, e.g., by harming or delaying necessary farm operations. Heavy precipitation events, excessive soil moisture and flooding disrupt food production and rural livelihoods worldwide (Rosenzweig et al., 2002). [WGII 5.4.2.1]

By critically affecting crop productivity and food production, in addition to being a necessity in food preparation processes, water plays a critical role in food security. Currently, 850 million people in the world are still undernourished (FAO, 2003). [WGII 5.3.2.1, 5.6.5] Socio-economic pressures over the next several decades will lead to increased competition between irrigation needs and demand from non-agricultural sectors, potentially reducing the availability and quality of water resources for food. [WGII 3.3.2] Recent studies indicate that it is *unlikely* that the Millennium Development Goal (MDG) for hunger will be met by 2015. [WGII 5.6.5] At the same time, during this century, climate change may further reduce water availability for global food production, as a result of projected mean changes in temperature and precipitation regimes, as well as due to projected increases in the frequency of extreme events, such as droughts and flooding (Rosenzweig et al., 2002). [WGII 5.6.5]

Climate impacts assessments of food production are, in general, critically dependent upon the specifics of the GCM precipitation projections used. [WGII 5.4.1.2] A wide range of precipitation scenarios is currently available. In general, assessments using scenarios of reduced regional precipitation typically result in negative crop production signals, and *vice versa*. Projections of increased aridity in several Mediterranean-type environments (Europe, Australia and South America), as well as in marginal arid and semi-arid tropical regions, especially sub-Saharan Africa, appear to be robust across models (see Figure 2.10). These regions face increased vulnerability under climate change, as shown in Figure 4.1. [WGII 5.3.1]

4.2.1.2 Land use and forest ecosystems

Forest ecosystems occupy roughly 4 billion ha of land, an area comparable to that used by crops and pastures combined. Of this land, only about 200 million ha are used for commercial forestry production globally (FAO, 2003). [WGII 4.4.5, 5.1.1, 5.4.5]

Forests are key determinants of water supply, quality and quantity, in both developing and developed countries. The importance of forests as watersheds may increase substantially in the next few decades, as freshwater resources become increasingly scarce, particularly in developing countries (Mountain Agenda, 1997; Liniger and Weingartner, 1998). [LULUCF 2.5.1.1.4; WGII 4.1.1]

Forests contribute to the regional water cycle, with large potential effects of land-use changes on local and regional climates (Harding, 1992; Lean et al., 1996). On the other hand, forest protection can have drought and flood mitigation benefits, especially in the tropics (Kramer et al., 1997; Pattanayak and Kramer, 2000). [LULUCF 2.5.1.1.6]

Afforestation and reforestation may increase humidity, lower temperature and increase rainfall in the regions affected (Harding, 1992; Blythe et al., 1994); deforestation can instead lead to decreased local rainfall and increased temperature. In Amazonia and Asia, deforestation may lead to new climate conditions unsuitable for successful regeneration of rainforest species (Chan, 1986; Gash and Shuttleworth, 1991; Meher-Homji, 1992). [LULUCF 2.5.1.1.6]

[19] See Section 1.3 for a discussion of the interrelationships between irrigation, climate change and groundwater recharge. This is also mentioned in Sections 5.1.3 (on Africa) and 5.2.3 (on Asia).

Forest ecosystems are differentially sensitive to climatic change (e.g., Kirschbaum and Fischlin, 1996; Sala et al., 2000; Gitay et al., 2001), with temperature-limited biomes being sensitive to impacts of warming, and water-limited biomes being sensitive to increasing levels of drought. Some, such as fire-dependent ecosystems, may change rapidly in response to climate and other environmental changes (Scheffer et al., 2001; Sankaran et al., 2005). [WGII 4.1, 4.4.5]

Forest ecosystems, and the biodiversity associated with them, may be particularly at risk in Africa, due to a combination of socio-economic pressures, and land-use and climate-change factors. [WGII 4.2] By 2100, negative impacts across about 25% of Africa (especially southern and western Africa) may cause a decline in both water quality and ecosystem goods and services. [WGII 4.ES, 4.4.8] Indeed, changes in a variety of ecosystems are already being detected and documented, particularly in southern Africa. [WGII 9.2.1.4]

4.2.2 Observations

4.2.2.1 Climate impacts and water

Although agriculture and forestry are known to be highly dependent on climate, evidence of observed changes related to regional climate changes, and specifically to water, is difficult to find. Agriculture and forestry are also strongly influenced by non-climate factors, especially management practices and technological changes (Easterling, 2003) on local and regional scales, as well as market prices and policies related to subsidies. [WGII 1.3.6]

Although responses to recent climate change are difficult to identify in human systems, due to multiple non-climate driving forces and the existence of adaptation, effects have been detected in forestry and a few agricultural systems. Changes in several aspects of the human health system have been related to recent warming. Adaptation to recent warming is beginning to be systematically documented. In comparison with other factors, recent warming has been of limited consequence in agriculture and forestry. A significant advance in phenology, however, has been observed for agriculture and forestry in large parts of the Northern Hemisphere, with limited responses in crop management. The lengthening of the growing season has contributed to an observed increase in forest productivity in many regions, while warmer and drier conditions are partly responsible for reduced forest productivity and increased forest fires in North America and the Mediterranean Basin. Both agriculture and forestry have shown vulnerability to recent trends in heatwaves, droughts and floods. [WGII 1.3.6, 1.3.9, 5.2]

4.2.2.2 Atmospheric CO_2 and water dynamics

The effects of elevated atmospheric CO_2 on plant function may have important implications for water resources, since leaf-level water-use efficiency increases due to increased stomatal resistance as compared to current concentrations. For C_3 plant species (including most food crops), the CO_2 effect may be relatively greater for crops that are under moisture stress, compared to well-irrigated crops. [WGII TAR 5.3.3.1]

However, the large-scale implications of CO_2–water interactions (i.e., at canopy, field and regional level) are highly uncertain. In general, it is recognised that the positive effects of elevated CO_2 on plant water relations are expected to be offset by increased evaporative demand under warmer temperatures. [WGII TAR 5.3.3.1]

Many recent studies confirm and extend TAR findings that temperature and precipitation changes in future decades will modify, and often limit, direct CO_2 effects on plants. For instance, high temperatures during flowering may lower CO_2 effects by reducing grain number, size and quality (Thomas et al., 2003; Baker et al., 2004; Caldwell et al., 2005). Likewise, increased water demand under warming may reduce the expected positive CO_2 effects. Rain-fed wheat grown at 450 ppm CO_2 shows grain yield increases up to 0.8°C warming, but yields then decline beyond 1.5°C warming; additional irrigation is needed to counterbalance these negative effects. [WGII 5.4.1.2]

Finally, plant physiologists and crop modellers alike recognise that the effects of elevated CO_2, measured in experimental settings and implemented in models, may overestimate actual field and farm-level responses. This is due to many limiting factors that typically operate at the field level, such as pests, weeds, competition for resources, soil water and air quality. These critical factors are poorly investigated in large-scale experimental settings, and are thus not well integrated into the leading plant growth models. Understanding the key dynamics characterising the interactions of elevated CO_2 with climate, soil and water quality, pests, weeds and diseases, climate variability and ecosystem vulnerability remains a priority for understanding the future impacts of climate change on managed systems. [WGII 5.4.1, 5.8.2]

4.2.3 Projections

Changes in water demand and availability under climate change will significantly affect agricultural activities and food security, forestry and fisheries in the 21st century. On the one hand, changes in evaporation:precipitation ratios will modify plant water demand with respect to a baseline with no climate change. On the other hand, modified patterns of precipitation and storage cycles at the watershed scale will change the seasonal, annual and interannual availability of water for terrestrial and aquatic agro-ecosystems (FAO, 2003). Climate changes increase irrigation demand in the majority of world regions due to a combination of decreased rainfall and increased evaporation arising from increased temperatures. [WGII 5.8.1]

It is expected that projected changes in the frequency and severity of extreme climate events, such as increased frequency of heat stress, droughts and flooding, will have significant consequences on food, forestry (and the risk of forest fires) and other agro-ecosystem production, over and above the impacts of changes in mean variables alone. [WGII 5.ES] In particular, more than 90% of simulations predict increased droughts in the sub-tropics by the end of the 21st century [WGI SPM], while increased extremes in precipitation are projected in the major agricultural production areas of southern and eastern Asia, eastern Australia and northern Europe. [WGI 11.3, 11.4, 11.7] It should be noted that climate change impact models for food, forest products and fibre do not yet include these recent findings on the projected patterns of precipitation change; negative impacts are projected to be worse than currently computed, once the effects of extremes on productivity are included. [WGII 5.4.1, 5.4.2]

Percentage changes in annual mean runoff are indicative of the mean water availability for vegetation cover. Projected changes between now and 2100 [WGII Chapter 3] show some consistent patterns: increases in high latitudes and the wet tropics, and decreases in mid-latitudes and some parts of the dry tropics (Figure 4.1b). Declines in water availability are indicative of increased water stress, indicating, in particular, a worsening in regions where water for production is already a scarce commodity (e.g., in the Mediterranean Basin, Central America and sub-tropical regions of Africa and Australia, see Figure 4.1b). [WGII 5.3.1]

Finally, it may be important to recognise that production systems and water resources will be critically shaped in the coming decades by the concurrent interactions of socio-economic and climate drivers. For instance, increased demand for irrigation water in agriculture will depend both on changed climatic conditions and on increased demand for food by a growing population; in addition, water availability for forest productivity will depend on both climatic drivers and critical anthropogenic impacts, particularly deforestation in tropical zones. In the Amazon Basin, for instance, a combination of deforestation and increased fragmentation may trigger severe droughts over and above the climate signal, leading to increased fire danger. [WGII 5.3.2.2]

4.2.3.1 Crops

In general, while moderate warming in high-latitude regions would benefit crop and pasture yields, even slight warming in low-latitude areas, or areas that are seasonally dry, would have a detrimental effect on yields. Modelling results for a range of sites show that, in high-latitude regions, moderate to medium increases in local temperature (1–3°C), along with associated CO_2 increases and rainfall changes, can have small, beneficial impacts on crop yields. However, in low-latitude regions, even moderate temperature increases (1–2°C) are *likely* to have negative yield impacts for major cereals. Further warming has increasingly negative impacts in all regions. [WGII 5.ES]

Regions where agriculture is currently a marginal enterprise, largely due to a combination of poor soils, water scarcity and rural poverty, may suffer increasingly as a result of climate change impacts on water. As a result, even small changes in climate will increase the number of people at risk of hunger, with the impact being particularly great in sub-Saharan Africa. [WGII 5.ES]

Increases in the frequency of climate extremes may lower crop yields beyond the impacts of mean climate change. Simulation studies since the TAR have considered specific aspects of increased climate variability within climate change scenarios. Rosenzweig et al. (2002) computed that, under scenarios of increased heavy precipitation, production losses due to excessive soil moisture (already significant today) would double in the USA to US$3 billion/yr in 2030. In Bangladesh, the risk of crop losses is projected to increase due to higher flood frequency under climate change. Finally, climate change impact studies that incorporate higher rainfall intensity indicate an increased risk of soil erosion; in arid and semi-arid regions, high rainfall intensity may be associated with a higher possibility of

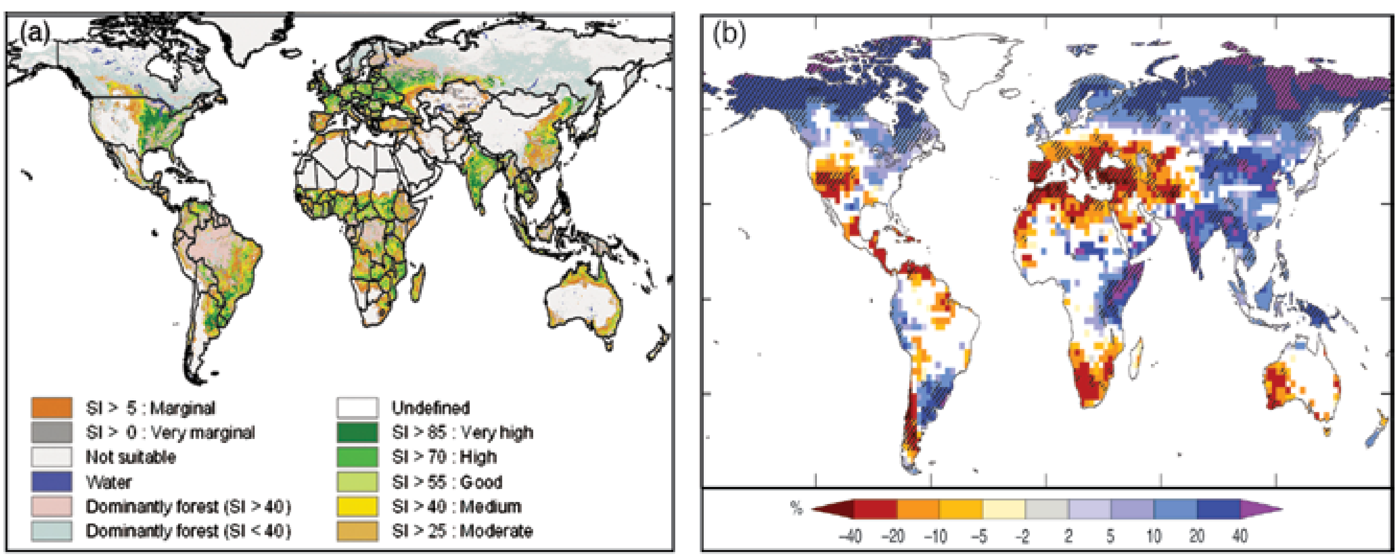

Figure 4.1: *(a) Current suitability for rain-fed crops (excluding forest ecosystems) (after Fischer et al., 2002b). SI = suitability index [WGII Figure 5.1a]; (b) ensemble mean percentage projected change in annual mean runoff between the present (1980–1999) and 2090–2099. [Based on SYR Figure 3.5]*

salinisation, due to increased loss of water past the crop root zone. [WGII 5.4.2.1]

Impacts of climate change on irrigation water requirements may be large. A few new studies have further quantified the impacts of climate change on regional and global irrigation requirements, irrespective of the positive effects of elevated CO_2 on crop water-use efficiency. Döll (2002), in considering the direct impacts of climate change on crop evaporative demand, but without any CO_2 effects, estimated an increase in *net* crop irrigation requirements (i.e., net of transpiration losses) of between 5% and 8% globally by 2070, with larger regional signals (e.g., +15%) in south-east Asia. [WGII 5.4.2.1]

Fischer et al. (2006), in a study that included positive CO_2 effects on crop water-use efficiency, computed increases in global net irrigation requirements of 20% by 2080, with larger impacts in developed *versus* developing regions, due to both increased evaporative demands and longer growing seasons under climate change. Fischer et al. (2006) and Arnell et al. (2004) also projected increases in water stress (measured as the ratio of irrigation withdrawals to renewable water resources) in the Middle East and south-east Asia. Recent regional studies have likewise underlined critical climate change/water dynamics in key irrigated areas, such as northern Africa (increased irrigation requirements; Abou-Hadid et al., 2003) and China (decreased requirements; Tao et al., 2003a). [WGII 5.4.2.1]

At the national scale, some integrative studies exist. In the USA, two modelling studies on adaptation of the agricultural sector to climate change (i.e., shifts between irrigated and rain-fed production) foresee a decrease in both irrigated areas and withdrawals beyond 2030 under various climate scenarios (Reilly et al., 2003; Thomson et al., 2005a). This is related to a declining yield gap between irrigated and rain-fed agriculture caused either by yield reductions of irrigated crops due to higher temperatures, or by yield increases of rain-fed crops due to higher precipitation. These studies did not take into account the increasing variability of daily precipitation and, as such, rain-fed yields are probably overestimated. [WGII 3.5.1]

For developing countries, a 14% increase in irrigation water withdrawal by 2030 was foreseen in an FAO study that did not consider the impacts of climate change (Bruinsma, 2003). However, the four Millennium Ecosystem Assessment scenarios project much smaller increases in irrigation withdrawal at the global scale, as they assume that the area under irrigation will only increase by between 0% and 6% by 2030; and between 0% and 10% by 2050. [WGII 3.5.1]

The overwhelming water use increases are *likely* to occur in the domestic and industrial sectors, with withdrawals increasing by between 14% and 83% by 2050 (Millennium Ecosystem Assessment, 2005a, b). This is based on the idea that the value of water will be much higher for domestic and industrial uses, which is particularly true under conditions of water stress. [WGII 3.5.1]

Locally, irrigated agriculture may face new problems linked to the spatial and temporal distribution of streamflow. For instance, at low latitudes, especially in south-east Asia, early snowmelt may cause spring flooding and lead to a summer irrigation water shortage. [WGII 5.8.2]

4.2.3.2 Pastures and livestock

Many of the world's rangelands are in semi-arid areas and susceptible to water deficits; any further decline in water resources will greatly impact carrying capacity. As a result, increased climate variability and droughts may lead to livestock loss. Specifically, the impact on animal productivity due to increased variability in weather patterns is *likely* to be far greater than effects associated with changes in average climatic conditions. The most frequent catastrophic losses arising from a lack of prior conditioning to weather events occur in confined cattle feedlots, with economic losses from reduced cattle performance exceeding those associated with cattle death losses by several-fold. [WGII 5.4.3.1]

Many of the world's rangelands are affected by El Niño–Southern Oscillation (ENSO) events. Under ENSO-related drought events, in dry regions there are risks of positive feedback between the degradation of both soils and vegetation and reductions in rainfall, with consequences in terms of loss of both pastoral and farming lands. [WGII 5.4.3.1] However, while WGI TAR indicated an increased likelihood of ENSO frequency under climate change, the WGI AR4 did not find correlations between ENSO and climate change. [WGI TAR SPM; WGI 10.3.5.4]

A survey of experimental data worldwide suggested that mild warming generally increases grassland productivity, with the strongest positive responses at high latitudes, and that the productivity and composition of plant species in rangelands are highly correlated with precipitation. In addition, recent findings (see Figure 4.1) projected declines in rainfall in some major grassland and rangeland areas (e.g., South America, southern and northern Africa, western Asia, Australia and southern Europe). [WGII 5.4.3.2]

Elevated atmospheric CO_2 can reduce soil water depletion in different native and semi-native temperate and Mediterranean grassland. However, in conjunction with climate change, increased variability in rainfall and warmer temperatures may create more severe soil moisture limitations, and hence reduced productivity, offsetting the beneficial effects of CO_2. Other impacts on livestock occur directly through the increase in thermal heat load. [WGII 5.4.3.2]

4.2.3.3 Fisheries

Negative impacts of climate change on aquaculture and freshwater fisheries include: stress due to increased temperature and oxygen demand and decreased pH; uncertain future water quality and volume; extreme weather events; increased frequency of disease and toxic events; sea-level rise and conflicts of interest with coastal defence needs; and uncertain

Box 4.1: Climate change and the fisheries of the lower Mekong – an example of multiple stresses due to human activity on a megadelta fisheries system. [WGII Box 5.3]

Fisheries are central to the lives of the people, particularly the rural poor, who live in the lower Mekong countries. Two-thirds of the basin's 60 million people are in some way active in fisheries, which represent about 10% of the GDP of Cambodia and the Lao People's Democratic Republic (PDR). There are approximately 1,000 species of fish commonly found in the river, with many more marine vagrants, making it one of the most prolific and diverse faunas in the world (MRC, 2003). Recent estimates of the annual catch from capture fisheries alone exceed 2.5 million tonnes (Hortle and Bush, 2003), with the delta contributing over 30% of this.

Direct effects of climate change will occur due to changing patterns of precipitation, snowmelt and rising sea level, which will affect hydrology and water quality. Indirect effects will result from changing vegetation patterns that may alter the food chain and increase soil erosion. It is *likely* that human impacts on the fisheries (caused by population growth, flood mitigation, increased water abstractions, changes in land use, and over-fishing) will be greater than the effects of climate, but the pressures are strongly interrelated.

An analysis of the impact of climate change scenarios on the flow of the Mekong (Hoanh et al., 2004) estimated increased maximum monthly flows of 35–41% in the basin and 16–19% in the delta (the lower value is for years 2010–2038 and the higher value for years 2070–2099, compared with 1961–1990 levels). Minimum monthly flows were estimated to decrease by 17–24% in the basin and 26–29% in the delta. Increased flooding would positively affect fisheries yields, but a reduction in dry season habitat may reduce the recruitment of some species. However, planned water-management interventions, primarily dams, are expected to have the opposite effects on hydrology, namely marginally decreasing wet-season flows and considerably increasing dry-season flows (World Bank, 2004b).

Models indicate that even a modest sea-level rise of 20 cm would cause contour lines of water levels in the Mekong delta to shift 25 km inland during the flood season and saltwater to move further upstream (although confined within canals) during the dry season (Wassmann et al., 2004). Inland movement of saltwater would significantly alter the species composition of fisheries, but may not be detrimental for overall fisheries yields.

future supplies of fishmeal and oils from capture fisheries. A case study of the multiple stresses that may affect fisheries in developing countries is included in Box 4.1. [WGII 5.4.6.1]

Positive impacts include increased growth rates and food conversion efficiencies; increased length of growing season; range expansion; and the use of new areas due to decreased ice cover. [WGII 5.4.6.1]

4.2.4 Adaptation, vulnerability and sustainable development

Water management is a critical component that needs to adapt in the face of both climate and socio-economic pressures in the coming decades. Changes in water use will be driven by the combined effects of: changes in water availability, changes in water demand from land, as well as from other competing sectors including urban, and changes in water management.

Practices that increase the productivity of irrigation water use – defined as crop output per unit water use – may provide significant adaptation potential for all land production systems under future climate change. At the same time, improvements in irrigation efficiency are critical to ensure the availability of water both for food production and for competing human and environmental needs. [WGII 3.5.1]

Several simulation studies suggest the possibility of relative benefits of adaptation in the land sector with low to moderate warming, although several response strategies may place extra stress on water and other environmental resources as warming increases. *Autonomous adaptation* actions are defined as responses that will be implemented by individual farmers, rural communities and/or farmers' organisations, depending on perceived or real climate change in the coming decades, and without intervention and/or co-ordination by regional and national governments and international agreements. To this end, maladaptation, e.g., pressure to cultivate marginal land, or to adopt unsustainable cultivation practices as yields drop, may increase land degradation and endanger the biodiversity of both wild and domestic species, possibly jeopardising future ability to respond to increasing climate risk later in the century. *Planned adaptation*, therefore, including changes in policies, institutions and dedicated infrastructure, will be needed to facilitate and maximise long-term benefits of adaptation responses to climate change. [WGII 5.5]

4.2.4.1 Autonomous adaptation

Options for autonomous adaptation are largely extensions or intensifications of existing risk management and production enhancement activities, and are therefore already available to farmers and communities. These include, with respect to water:

- adoption of varieties/species with increased resistance to heat shock and drought;
- modification of irrigation techniques, including amount, timing or technology;
- adoption of water-efficient technologies to 'harvest' water, conserve soil moisture (e.g. crop residue retention), and reduce siltation and saltwater intrusion;
- improved water management to prevent waterlogging, erosion and leaching;
- modification of crop calendars, i.e., timing or location of cropping activities;
- implementation of seasonal climate forecasting.

Additional adaptation strategies may involve land-use changes that take advantage of modified agro-climatic conditions. [WGII 5.5.1]

A few simulation studies show the importance of irrigation water as an adaptation technique to reduce climate change impacts. In general, however, projections suggest that the greatest relative benefit from adaptation is to be gained under conditions of low to moderate warming, and that adaptation practices that involve increased irrigation water use may in fact place additional stress on water and environmental resources as warming and evaporative demand increase. [WGII 5.8.1]

Many adaptation strategies in key production sectors other than crop agriculture have also been explored, although, without a direct focus on water issues. Adaptation strategies that may nonetheless affect water use include, for livestock systems, altered rotation of pastures, modification of times of grazing, alteration of forage and animal species/breeds, altered integration within mixed livestock/crop systems, including the use of adapted forage crops, care to ensure adequate water supplies, and the use of supplementary feeds and concentrates. Pastoralist coping strategies in semi-arid and arid Kenya and southern Ethiopia are discussed in Box 4.2. [WGII 5.4.7]

Adaptation strategies for forestry may include changes in management intensity, species mix, rotation periods, adjusting to altered wood size and quality, and adjusting fire management systems. [WGII 5.5.1]

With respect to marine ecosystems, with the exception of aquaculture and some freshwater fisheries, the exploitation of natural fish populations precludes the kind of management adaptations to climate change suggested for the crop, livestock and forest sectors. Adaptation options thus centre on altering catch size and effort. The scope for autonomous adaptation is increasingly restricted as new regulations governing the exploitation of fisheries and marine ecosystems come into force. [WGII 5.5.1]

If widely adopted, adaptation strategies in production systems have substantial potential to offset negative climate change impacts and take advantage of positive ones. However, there has been little evaluation of how effective and widely adopted these adaptations may be, given the complex nature of decision making; the diversity of responses across regions; time lags

Box 4.2: Pastoralist coping strategies in northern Kenya and southern Ethiopia. [WGII Box 5.5]

African pastoralism has evolved in adaptation to harsh environments with very high spatial and temporal variability of rainfall (Ellis, 1995). Several recent studies (Ndikumana et al., 2000; Hendy and Morton, 2001; Oba, 2001; McPeak and Barrett, 2001; Morton, 2006) have focused on the coping strategies used by pastoralists during recent droughts in northern Kenya and southern Ethiopia, and the longer-term adaptations that underlie them.

- *Mobility* remains the most important pastoralist adaptation to spatial and temporal variations in rainfall, and in drought years many communities make use of fall-back grazing areas unused in 'normal' dry seasons because of distance, land tenure constraints, animal disease problems or conflict. However, encroachment on and individuation of communal grazing lands, and the desire to settle in order to access human services and food aid, have severely limited pastoral mobility.
- Pastoralists engage in *herd accumulation*, and most evidence now suggests that this is a rational form of insurance against drought.
- A small proportion of pastoralists now hold some of their wealth in bank accounts, and others use informal savings and credit mechanisms through shop-keepers.
- Pastoralists also use *supplementary feed* for livestock, purchased or lopped from trees, as a coping strategy; they intensify *animal disease management* through indigenous and scientific techniques; they pay for *access to water* from powered boreholes.
- *Livelihood diversification* away from pastoralism in this region predominantly takes the form of shifts into low-income or environmentally unsustainable occupations such as charcoal production, rather than an adaptive strategy to reduce *ex ante* vulnerability.
- A number of *intra-community mechanisms* distribute both livestock products and the use of live animals to the destitute, but these appear to be breaking down because of the high levels of covariate risk within communities.

in implementation; and possible economic, institutional and cultural barriers to change. For example, the realisable adaptive capacity of poor subsistence farming/herding communities is generally considered to be very low. Likewise, large areas of forests receive minimal direct human management, limiting adaptation opportunities. Even in more intensively managed forests, where adaptation activities may be more feasible, long time lags between planting and harvesting may complicate the adoption of effective adaptation strategies. [WGII 5.1.1]

4.2.4.2 Planned adaptation

Planned adaptation solutions should focus on developing new infrastructure, policies, and institutions that support, facilitate, co-ordinate and maximise the benefits of new management and land-use arrangements. This can be achieved in general through improved governance, including addressing climate change in development programmes; increasing investment in irrigation infrastructure and efficient water-use technologies; ensuring appropriate transport and storage infrastructure; revising land tenure arrangements (including attention to well-defined property rights); and establishing accessible, efficiently functioning markets for products and inputs (including water pricing schemes) and for financial services (including insurance). [WGII 5.5]

Planned adaptation and policy co-ordination across multiple institutions may be necessary to facilitate adaptation to climate change, in particular where falling yields create pressure to cultivate marginal land or adopt unsustainable cultivation practices, increasing both land degradation and the use of resources, including water. [WGII 5.4.7]

A number of global-, national- and basin-scale adaptation assessments show that, in general, semi-arid and arid basins are most vulnerable with respect to water stress. If precipitation decreases, then demand for irrigation water would make it impossible to satisfy all other demands. Projected streamflow changes in the Sacramento-Joaquin and Colorado River Basins indicate that present-day water demand cannot be fulfilled by 2020, even with adaptive management practices. Increased irrigation usage would reduce both runoff and downstream flow (Eheart and Tornil, 1999). [WGII 3.5.1]

Policies aimed at rewarding improvements in irrigation efficiency, either through market mechanisms or increased regulations and improved governance, are an important tool for enhancing adaptation capacity at a regional scale. Unintended consequences may be increased consumptive water use upstream, resulting in downstream users being deprived of water that would otherwise have re-entered the stream as return flow (Huffaker, 2005). [WGII 3.5.1]

In addition to techniques already available to farmers and land managers today, new technical options need to be made available through dedicated research and development efforts, to be planned and implemented now, in order to augment overall capacity to respond to climate change in future decades. Technological options for enhanced R&D include traditional breeding and biotechnology for improved resistance to climate stresses such as drought and flooding in crop, forage, livestock, forest and fisheries species (Box 4.3).

Box 4.3: Will biotechnology assist agricultural and forest adaptation? [WGII Box 5.6]

Biotechnology and conventional breeding may help develop new cultivars with enhanced traits better suited to adapt to climate change conditions. These include drought and temperature stress resistance; resistance to pests and disease, salinity and waterlogging. Additional opportunities for new cultivars include changes in phenology or enhanced responses to elevated CO_2. With respect to water, a number of studies have documented genetic modifications to major crop species (e.g., maize and soybeans) that increased their water-deficit tolerance (as reviewed by Drennen et al., 1993; Kishor et al., 1995; Pilon-Smits et al., 1995; Cheikh et al., 2000), although this may not extend to the wider range of crop plants. In general, too little is currently known about how the desired traits achieved by genetic modification perform in real farming and forestry applications (Sinclair and Purcell, 2005).

4.2.4.3 Food security and vulnerability

All four dimensions of food security: namely, food availability (production and trade), access to food, stability of food supplies, and food utilisation (the actual processes involved in the preparation and consumption of food), are *likely* to be affected by climate change. Importantly, food security will depend not only on climate and socio-economic impacts on food production, but also (and critically so) on changes to trade flows, stocks, and food aid policy. In particular, climate change will result in mixed and geographically varying impacts on food production and, thus, access to food. Tropical developing countries, many of which have poor land and water resources and already face serious food insecurity, may be particularly vulnerable to climate change. [WGII 5.6.5]

Changes in the frequency and intensity of droughts and flooding will affect the stability of, and access to, critical food supplies. Rainfall deficits can dramatically reduce both crop yields and livestock numbers in the semi-arid tropics. Food insecurity and loss of livelihood would be further exacerbated by the loss of both cultivated land and coastal fish nurseries as a result of inundation and coastal erosion in low-lying areas. [WGII 5.6.5]

Climate change may also affect food utilisation through impacts on environmental resources, with important additional health consequences. [WGII Chapter 8] For example, decreased water availability in already water-scarce regions, particularly in the sub-tropics, has direct negative implications for both food processing and consumption. Conversely, the increased risk of flooding of human settlements in coastal areas from both rising sea levels and increased heavy precipitation may increase food contamination and disease, reducing consumption patterns. [WGII 5.6.5]

4.2.4.4 Water quality issues

In developing countries, the microbiological quality of water is poor because of the lack of sanitation, lack of proper treatment methods, and poor health conditions (Lipp et al., 2001; Jiménez, 2003; Maya et al., 2003; WHO, 2004). Climate change may impose additional stresses on water quality, especially in developing countries (Magadza, 2000; Kashyap, 2004; Pachauri, 2004). As yet there are no studies focusing on micro-organism life cycles relevant to developing countries under climate change, including a much-needed focus on the effects of poorly treated wastewater use for irrigation and its links to endemic outbreaks of *helminthiasis* (WHO/UNICEF, 2000). [WGII 3.4.4]

About 10% of the world's population consumes crops irrigated with untreated or poorly treated wastewater, mostly in developing countries in Africa, Asia and Latin America. This number is projected to grow with population and food demand. [WGII 8.2.5] Increased use of properly treated wastewater for irrigation is therefore a strategy to combat both water scarcity and some related health problems. [WGII 3.4.4]

4.2.4.5 Rural communities, sustainable development and water conflicts

Transboundary water co-operation is recognised as an effective policy and management tool to improve water management across large regions sharing common resources. Climate change and increased water demand in future decades will represent an added challenge to such framework agreements, increasing the potential for conflict at the local level. For instance, unilateral measures for adapting to climate-change-related water shortages can lead to increased competition for water resources. Furthermore, shifts in land productivity may lead to a range of new or modified agricultural systems, necessary to maintain production, including intensification practices. The latter, in turn, can lead to additional environmental pressures, resulting in loss of habitat and reduced biodiversity, siltation, soil erosion and soil degradation. [WGII 5.7]

Impacts on trade, economic, and environmental development and land use may also be expected from measures implemented to substitute fossil fuels through biofuels, such as by the European Biomass Action Plan. Large-scale biofuel production raises questions on several issues including fertiliser and pesticide requirements, nutrient cycling, energy balance, biodiversity impacts, hydrology and erosion, conflicts with food production, and the level of financial subsidies required. In fact, the emerging challenges of future decades include finding balance in the competition for land and raw materials for the food, forestry and energy sectors, e.g., devising solutions that ensure food and local rural development rights while maximising energy and climate mitigation needs. [LULUCF 4.5.1]

In North America, drought may increase in continental interiors and production areas may shift northwards (Mills, 1994), especially for maize and soybean production (Brklacich et al., 1997). [WGII TAR 15.2.3.1] In Mexico, production losses may be dominated by droughts, as agro-ecological zones suitable for maize cultivation decrease (Conde et al., 1997). [WGII TAR 14.2.2.1] Drought is an important issue throughout Australia for social, political, geographical and environmental reasons. A change in climate towards drier conditions as a result of lower rainfall and higher evaporative demand would trigger more frequent or longer drought declarations under current Australian drought policy schemes. [WGII TAR 12.5.6]

Water resources are a key vulnerability in Africa for household, agricultural and industrial uses. In shared river basins, regional co-operation protocols are needed to minimise both adverse impacts and the potential for conflicts. For instance, the surface area of Lake Chad varies from 20,000 km^2 during the dry season to 50,000 km^2 during the wet season. While precise boundaries have been established between Chad, Nigeria, Cameroon and Niger, sectors of these boundaries that are located in the rivers that drain into Lake Chad have never been determined, and additional complications arise as a result of both flooding and water recession. Similar problems on the Kovango River between Botswana and Namibia led to military confrontation. [WGII TAR 10.2.1.2]

Growing water scarcity, increasing population, degradation of shared freshwater ecosystems and competing demands for shrinking natural resources distributed over such a huge area involving so many countries have the potential for creating bilateral and multilateral conflicts. In semi-arid Africa, pastoralism is the main economic activity, with pastoral communities including transnational migrants in search of new seasonal grazing. In drought situations, such pastoralists may come into conflict with settled agrarian systems. [WGII TAR 10.2.1.2]

Asia dominates world aquaculture, with China alone producing about 70% of all farmed fish, shrimp and shellfish (FAO, 2006). Fish, an important source of food protein, is critical to food security in many countries of Asia, particularly among poor communities in coastal areas. Fish farming requires land and water, two resources that are already in short supply in many countries in Asia. Water diversion for shrimp ponds has lowered groundwater levels noticeably in coastal areas of Thailand. [WGII TAR 11.2.4.4]

At least 14 major international river watersheds exist in Asia. Watershed management is challenging in countries with high population density, which are often responsible for the use of even the most fragile and unsuitable areas in the watersheds for cultivation, residential, and other intensive activities. As a result, in many countries, in particular Bangladesh, Nepal, the Philippines, Indonesia and Vietnam, many watersheds suffer badly from deforestation, indiscriminate land conversion, excessive soil erosion and declining land productivity. In the absence of appropriate adaptation strategies, these watersheds are highly vulnerable to climate change. [WGII TAR 11.2.3.2]

4.2.4.6 Mitigation

Adaptation responses and mitigation actions may occur simultaneously in the agricultural and forestry sector; their efficacy will depend on the patterns of realised climate change in the coming decades. The associated interactions between these factors (climate change, adaptation and mitigation) will frequently involve water resources. [WGIII 8.5, Table 8.9]

Adaptation and mitigation strategies may either exhibit synergies, where both actions reinforce each other, or be mutually counter-productive. With respect to water, examples of adaptation strategies that reduce mitigation options largely involve irrigation, in relation to the energy costs of delivering water and the additional greenhouse gas emissions that may be associated with modified cultivation practices. Using renewables for water extraction and delivery could, however, eliminate such conflict. Likewise, some mitigation strategies may have negative adaptation consequences, such as increasing dependence on energy crops, which may compete for water resources, reduce biodiversity, and thus increase vulnerability to climatic extremes. [WGIII 12.1.4, 12.1.4]

On the other hand, many carbon-sequestration practices involving reduced tillage, increased crop cover and use of improved rotation systems, in essence constitute – and were in fact originally developed as – 'good-practice' agro-forestry, leading to production systems that are more resilient to climate variability, thus providing good adaptation in the face of increased pressure on water and soil resources (Rosenzweig and Tubiello, 2007). [WGII 5.4.2; WGIII 8.5]

4.3 Human health

4.3.1 Context

Human health, incorporating physical, social and psychological well-being, depends on an adequate supply of potable water and a safe environment. Human beings are exposed to climate change directly through weather patterns (more intense and frequent extreme events), and indirectly through changes in water, air, food quality and quantity, ecosystems, agriculture, livelihoods and infrastructure. [WGII 8.1.1] Due to the very large number of people that may be affected, malnutrition and water scarcity may be the most important health consequences of climate change (see Sections 4.2 and 4.4). [WGII 8.4.2.3]

Population health has improved remarkably over the last 50 years, but substantial inequalities in health persist within and between countries. The Millennium Development Goal (MDG) of reducing the mortality rate in children aged under 5 years old by two-thirds by 2015 is *unlikely* to be reached in some developing countries. Poor health increases vulnerability and reduces the capacity of individuals and groups to adapt to climate change. Populations with high rates of disease and disability cope less successfully with stresses of all kinds, including those related to climate change. [WGII 8.1.1]

The World Health Organization (WHO) and UNICEF Joint Monitoring Programme currently estimates that 1.1 billion people (17% of the global population) lack access to water resources, where access is defined as the availability of at least 20 litres of water per person per day from an improved water source within a distance of 1 km. An improved water source is one that provides 'safe' water, such as a household connection or a bore hole. Nearly two-thirds of the people without access are in Asia. In sub-Saharan Africa, 42% of the population is without access to improved water. The WHO estimates that the total burden of disease due to inadequate water supply, and poor sanitation and hygiene, is 1.7 million deaths per year. Health outcomes related to water supply and sanitation are a focal point of concern for climate change in many countries. In vulnerable regions, the concentration of risks from both food and water insecurity can make the impact of any weather extreme (for example, flood and drought) particularly severe for the households affected. [WGII 9.2.2]

Changes in climate extremes have the potential to cause severe impacts on human health. Flooding is expected to become more severe with climate change, and this will have implications for human health. Vulnerability to flooding is reduced when the infrastructure is in place to remove solid waste, manage waste water, and supply potable water. [WGII 8.2.2]

Lack of water for hygiene is currently responsible for a significant burden of disease worldwide. A small and unquantified proportion of this burden can be attributed to climate variability or climate extremes. 'Water scarcity' is associated with multiple adverse health outcomes, including diseases associated with water contaminated with faecal and other hazardous substances (e.g., parasites).

Childhood mortality and morbidity due to diarrhoea in low-income countries, especially in sub-Saharan Africa, remains high despite improvements in care and the use of oral rehydration therapy. Climate change is expected to increase water scarcity, but it is difficult to assess what this means at the household level for the availability of water, and therefore for health and hygiene. There is a lack of information linking large-scale modelling of climate change to small-scale impacts at the population or household level. Furthermore, any assessments of future health impacts via changes in water availability need to take into account future improvements in access to 'safe' water. [WGII 8.2.5, 8.4.2.2]

4.3.1.1 Implications for drinking-water quality

The relationship between rainfall, river flow and contamination of the water supply is highly complex, as discussed below both for piped water supplies and for direct contact with surface waters. If river flows are reduced as a consequence of less rainfall, then their ability to dilute effluent is also reduced – leading to increased pathogen or chemical loading. This could represent an increase in human exposures or, in places with piped water supplies, an increased challenge to water treatment plants. During the dry summer of 2003, low flows in the Netherlands resulted in apparent changes in water quality (Senhorst and Zwolsman, 2005). The marked seasonality of cholera outbreaks in the Amazon was associated with low river flow in the dry season (Gerolomo and Penna, 1999), probably due to high pathogen concentrations in pools. [WGII 8.2.5]

Drainage and storm water management is important in low-income urban communities, as blocked drains can cause flooding and increased transmission of vector-borne diseases (Parkinson and Butler, 2005). Cities with combined sewer overflows can experience increased sewage contamination during flood events. [WGII 8.2.5]

In high-income countries, rainfall and runoff events may increase the total microbial load in watercourses and drinking-water reservoirs, although the linkage to cases of human disease is less certain because the concentration of contaminants is diluted. The seasonal contamination of surface water in early spring in North America and Europe may explain some of the seasonality in sporadic cases of water-borne diseases such as *cryptosporidiosis* and *campylobacteriosis*. A significant proportion of notified water-borne disease outbreaks are related to heavy precipitation events, often in conjunction with treatment failures. [WGII 14.2.5, 8.2.5]

Freshwater harmful algal blooms (HABs) produce toxins that can cause human diseases. The occurrence of such blooms in surface waters (rives and lakes) may increase due to higher temperatures. However, the threat to human health is very low, as direct contact with blooms is generally restricted. There is a low risk of contamination of water supplies with algal toxins but the implications for human health are uncertain. [WGII 8.2.4, 3.4.4]

In areas with poor water supply infrastructure, the transmission of enteric pathogens peaks during the rainy season. In addition, higher temperatures were found to be associated with increased episodes of diarrhoeal disease (Checkley et al., 2000; Singh et al., 2001; Vasilev, 2003; Lama et al., 2004). The underlying incidence of these diseases is associated with poor hygiene and lack of access to safe water. [WGII 8.2.5]

4.3.1.2 Disasters, including wind storms and floods

The previous sections have described how climate change will affect the risk of water-related disasters, including glacial lake outburst floods (GLOFs), increased storm surge intensity, and changes in flood risk (see Section 3.2) including flash flooding and urban flooding, with some reductions in risk of spring snowmelt floods. [WGII 3.4.3] Floods have a considerable impact on health both in terms of number of deaths and disease burden, and also in terms of damage to the health infrastructure. [WGII 8.2.2] While the risk of infectious disease following flooding is generally low in high-income countries, populations with poor infrastructure and high burdens of infectious disease often experience increased rates of diarrhoeal diseases after flood events. There is increasing evidence of the impact that climate-related disasters have on mental health, with people who have suffered the effects of floods experiencing long-term anxiety and depression. [WGII 8.2.2, 16.4.5]

Flooding and heavy rainfall may lead to contamination of water with chemicals, heavy metals or other hazardous substances, either from storage or from chemicals already in the environment (e.g., pesticides). Increases in both population density and industrial development in areas subject to natural disasters increase both the probability of future disasters and the potential for mass human exposure to hazardous materials during these events. [WGII 8.2.2]

4.3.1.3 Drought and infectious disease

For a few infectious diseases, there is an established rainfall association that is not related to the consumption of drinking-water (quality or quantity) or arthropod vectors. The spatial distribution, intensity and seasonality of meningococcal (epidemic) *meningitis* in the Sahelian region of Africa is related to climatic and environmental factors, particularly drought, although the causal mechanism is not well understood. The geographical distribution of *meningitis* has expanded in West Africa in recent years, which may be attributable to environmental change driven both by land-use changes and by regional climate change. [WGII 8.2.3.1]

4.3.1.4 Dust storms

Windblown dust originating in desert regions of Africa, the Arabian Peninsula, Mongolia, central Asia and China can affect air quality and population health in distant areas. When compared with non-dust weather conditions, dust can carry large concentrations of respirable particles; trace elements that can affect human health; fungal spores; and bacteria. [WGII 8.2.6.4]

4.3.1.5 Vector-borne diseases

Climate influences the spatial distribution, intensity of transmission, and seasonality of diseases transmitted by vectors (e.g., malaria) and diseases that have water snails as an intermediate host (e.g., *schistosomiasis*). [WGII 8.2.8] During droughts, mosquito activity is reduced but, if transmission drops significantly, the population of non-immune individuals may increase. In the long term, the incidence of mosquito-borne diseases such as malaria decreases because mosquito abundance is reduced, although epidemics may still occur when suitable climate conditions occur. [WGII 8.2.3.1]

The distribution of *schistosomiasis*, a water-related parasitic disease with aquatic snails as intermediate hosts, is influenced by climate factors in some locations, For example, the observed change in the distribution of *schistosomiasis* in China over the past decade may in part reflect the recent warming trend. Irrigation schemes have also been shown to increase the incidence of *schistosomiasis*, when appropriate control measures are not implemented. [WGII 8.2.8.3]

4.3.2 Observations

There is a wide range of driving forces that can affect and modify the impact of climate change on human health outcomes. Because of the complexity of the association between climate factors and disease, it is often not possible to attribute changes in specific disease patterns to observed climate changes. Furthermore, health data series of sufficient quality and length are rarely available for such studies. There are no published studies of water-related impacts on health that describe patterns of disease that are robustly attributed to observed climate change. However, there are several reports of adaptive responses in the water sector designed to reduce the impacts of climate change. [WGII Chapter 7]

Observed trends in water-related disasters (floods, wind storms) and the role of climate change are discussed elsewhere. [WGII 1.3]

4.3.3 Projections

Climate change is expected to have a range of adverse effects on populations where the water and sanitation infrastructure is inadequate to meet local needs. Access to safe water remains an extremely important global health issue. More than two billion people live in the dry regions of the world, and these people suffer more than others from malnutrition, infant mortality and diseases related to contaminated or insufficient water. Water scarcity constitutes a serious constraint to sustainable development (Rockstrom, 2003). [WGII 8.2.5, 8.4.2.2]

4.3.4 Adaptation, vulnerability and sustainable development

Weak public health systems and limited access to primary health care contribute both to high levels of vulnerability and to low adaptive capacity for hundreds of millions of people. [WGII 8.6] Fundamental constraints exist in low-income countries, where population health will depend upon improvements in the health, water, agriculture, transport, energy and housing sectors. Poverty and weak governance are the most serious obstacles to effective adaptation. Despite economic growth, low-income countries are *likely* to remain vulnerable over the medium term, with fewer options than high-income countries for adapting to climate change. Therefore, if adaptation strategies are to be effective, they should be designed in the context of the development, environment and health policies in place in the target area. Many options that can be used to reduce future vulnerability are of value in adapting to current climate, and can also be used to achieve other environmental and social objectives. [WGII 8.6.3]

The potential adverse health effects of any adaptation strategy should be evaluated before that strategy is implemented. For example, a micro-dam and irrigation programmes have been shown to increase local malaria mortality. [WGII 8.6.4] Measures to combat water scarcity, such as the reuse of untreated or partially treated wastewater for irrigation, also have implications for human health. Irrigation is currently an important determinant of the spread of infectious diseases such as malaria and *schistosomiasis* (Sutherst, 2004). Strict water-quality guidelines for wastewater irrigation are designed to prevent health risks from pathogenic organisms, and to guarantee crop quality (Steenvoorden and Endreny, 2004). Some diseases, such as *helminthiasis*, are transmitted by consuming crops irrigated with polluted water or wastewater and, in the rural and peri-urban areas of most low-income countries, the use of sewage and wastewater for irrigation, a common practice, is a source of faecal–oral disease transmission. At present, at least one-tenth of the world's population consumes crops irrigated with wastewater. However, increasing water scarcity and food demand, coupled with poor sanitation, will facilitate the use of low-quality water. If such problems are to be controlled, then programmes of wastewater treatment and planned wastewater reuse need to be developed. [WGII 8.6.4, 3.4.4]

4.4 Water supply and sanitation

The observed effects of climate change on water resource quantity and quality have been discussed in detail in Sections 4.2 and 4.3. This section summarises the main points and describes their implications for water supply and sanitation services.

4.4.1 Context

Statistics on present-day access to safe water have already been provided in Section 4.3.1. Access to safe water is now regarded as a universal human right. However, the world is facing increasing problems in providing water services, particularly in developing countries. There are several reasons for this, which are not necessarily linked to climate change. A lack of available water, a higher and more uneven water demand resulting from population growth in concentrated areas, an increase in urbanisation, more intense use of water to improve general well-being, and the challenge to improve water governance, are variables that already pose a tremendous challenge to providing satisfactory water services. In this context, climate change simply represents an additional burden for water utilities, or any other organisation providing water services, in meeting customers' needs. It is difficult to identify climate change effects at a local level, but the observed effects combined with projections provide a useful basis to prepare for the future.

4.4.2 Observations

Table 4.1 summarises possible linkages between climate change and water services.

Table 4.1: Observed effects of climate change and its observed/possible impacts on water services. [WGII Chapter 3]

Observed effect	Observed/possible impacts
Increase in atmospheric temperature	• Reduction in water availability in basins fed by glaciers that are shrinking, as observed in some cities along the Andes in South America (Ames, 1998; Kaser and Osmaston, 2002)
Increase in surface water temperature	• Reductions in dissolved oxygen content, mixing patterns, and self purification capacity • Increase in algal blooms
Sea-level rise	• Salinisation of coastal aquifers
Shifts in precipitation patterns	• Changes in water availability due to changes in precipitation and other related phenomena (e.g., groundwater recharge, evapotranspiration)
Increase in interannual precipitation variability	• Increases the difficulty of flood control and reservoir utilisation during the flooding season
Increased evapotranspiration	• Water availability reduction • Salinisation of water resources • Lower groundwater levels
More frequent and intense extreme events	• Floods affect water quality and water infrastructure integrity, and increase fluvial erosion, which introduces different kinds of pollutants to water resources • Droughts affect water availability and water quality

4.4.3 Projections

Reduced water availability may result from:
a. decreased flows in basins fed by shrinking glaciers and longer and more frequent dry seasons,
b. decreased summer precipitation leading to a reduction of stored water in reservoirs fed with seasonal rivers (du Plessis et al., 2003),
c. interannual precipitation variability and seasonal shifts in streamflow,
d. reductions in inland groundwater levels,
e. the increase in evapotranspiration as a result of higher air temperatures, lengthening of the growing season and increased irrigation water usage,
f. salinisation (Chen et al., 2004).

According to projections, the number of people at risk from increasing water stress will be between 0.4 billion and 1.7 billion by the 2020s, between 1.0 billion and 2.0 billion by the 2050s and between 1.1 billion and 3.2 billion by the 2080s (Arnell, 2004), the range being due to the different SRES scenarios considered. [WGII 3.2, 3.5.1]

In some areas, low water availability will lead to groundwater over-exploitation and, with it, increasing costs of supplying water for any use as a result of the need to pump water from deeper and further away. Additionally, groundwater over-exploitation may lead in some cases to water quality deterioration. For some regions of India, Bangladesh, China, north Africa, Mexico and Argentina, there are more than 100 million people suffering from arsenic poisoning and fluorosis (a disease of the teeth or bones caused by excessive consumption of fluoride in drinking water) (UN, 2003); this can result in an even worse situation if people are forced to use more water from groundwater as a result of the lack of reliable surface water sources. [WGII 3.4.4]

Increasing water scarcity combined with increased food demand and/or water use for irrigation as a result of higher temperatures are *likely* to lead to enhanced water reuse. Areas with low sanitation coverage might be found to be practising (as a new activity or to a greater degree) uncontrolled water reuse (reuse that is performed using polluted water or even wastewater). [WGII 3.3.2, 8.6.4]

Water quality deterioration as result of flow variation. Where a reduction in water resources is expected, a higher water pollutant concentration will result from a lower dilution capacity. [WGII 3.4.4, 14.4.1] At the same time, increased water flows will displace and transport diverse compounds from the soil to water resources through fluvial erosion. [WGII 3.4]

Similarly, an increase in morbidity and mortality rates from water-borne diseases for both more humid and drier scenarios is expected, owing to an insufficient supply of potable water (Kovats et al., 2005; Ebi et al., 2006), and the greater presence of pathogens conveyed by high water flows during extreme precipitation. Increased precipitation may also result in higher turbidity and nutrient loadings in water. The water utility of New York City has identified heavy precipitation events as one of its major climate-change-related concerns because they can raise turbidity levels in some of the city's main reservoirs by up to 100 times the legal limit for source quality at the utility's intakes, requiring substantial additional treatment and monitoring costs (Miller and Yates, 2006). [WGII 3.5.1]

Increased runoff. In some regions, more water will be available which, considering the present global water situation, will be generally beneficial. Nevertheless, provisions need to be made to use this to the world's advantage. For example, while increased runoff in eastern and southern Asia is expected as a result of climate change, water shortages in these areas may not be addressed, given a lack of resources for investing in the new storage capacity required to capture the additional water and to enable its use during the dry season. [WGII 3.5.1]

Higher precipitation in cities may affect the performance of sewer systems; uncontrolled surcharges may introduce microbial and chemical pollutants to water resources that are difficult to handle through the use of conventional drinking-water treatment processes. Several studies have shown that the transmission of enteric pathogens resistant to chlorination, such as *Cryptosporidium*, is high during the rainy season (Nchito et al., 1998; Kang et al., 2001). This is a situation that could be magnified in developing countries, where health levels are lower and the pathogen content in wastewater is higher (Jiménez, 2003). In addition, extreme precipitation leading to floods puts water infrastructure at risk. During floods, water and wastewater treatment facilities are often out of service, leaving the population with no sanitary protection. [WGII 3.2, 3.4.4, 8.2.5]

Water quality impairment as result of higher temperatures. Warmer temperatures, combined with higher phosphorus concentrations in lakes and reservoirs, promote algal blooms that impair water quality through undesirable colour, odour and taste, and possible toxicity to humans, livestock and wildlife. Dealing with such polluted water has a high cost with the available technology, even for water utilities from developed countries (Environment Canada, 2001). Higher water temperatures will also enhance the transfer of volatile and semi-volatile pollutants (ammonia, mercury, PCBs (polychlorinated biphenyls), dioxins, pesticides) from water and wastewater to the atmosphere. [WGII 3.4.4]

Increased salinisation. The salinisation of water supplies from coastal aquifers due to sea-level rise is an important issue, as around one-quarter of the world's population live in coastal regions that are generally water-scarce and undergoing rapid population growth (Small and Nicholls, 2003; Millennium Ecosystem Assessment, 2005b). Salinisation can also affect inland aquifers due to a reduction in groundwater recharge (Chen et al., 2004). [WGII 3.2, 3.4.2]

The populations that will be most affected by climate change with respect to water services are those located in the already water-stressed basins of Africa, the Mediterranean region, the Near East, southern Asia, northern China, Australia, the USA, central and northern Mexico, north-eastern Brazil and the west coast of South America. Those particularly at risk will be populations living in megacities, rural areas strongly dependent on groundwater, small islands, and in glacier- or snowmelt-fed basins (more than one-sixth of the world's population live in snowmelt basins). Problems will be more critical in economically depressed areas, where water stress will be enhanced by socio-economic factors (Alcamo and Henrichs, 2002; Ragab and Prudhomme, 2002). [WGII 3.3.2, 3.5.1]

4.4.4 Adaptation, vulnerability and sustainable development

Given the problems envisaged above, it is important for water utilities located in regions at risk to plan accordingly. Most water supply systems are well able to cope with the relatively small changes in mean temperature and precipitation that are projected to occur in the decades ahead, except at the margin where a change in the mean requires a change in the system design or the technology used; e.g., where reduced precipitation makes additional reservoirs necessary (Harman et al., 2005), or leads to saline intrusion into the lower reaches of a river, or requires new water treatment systems to remove salts. A recent example of adaptation is in southern Africa (Ruosteenoja et al. 2003), where the city of Beira in Mozambique is already extending its 50 km pumping main a further 5 km inland to be certain of fresh water. [WGII 7.4.2.3.1]

Water services are usually provided using engineered systems. These systems are designed using safety factors and have a life expectancy of 20–50 years (for storage reservoirs it can be even longer). Reviews of the resilience of water supplies and the performance of water infrastructure have typically been done by using observed conditions alone. The use of climate projections should also be considered, especially in cases involving systems that deal with floods and droughts.

Decrease in water availability. Except for a few industrialised countries, water use is increasing around the world due to population and economic growth, lifestyle changes and expanded water supply systems. [WGII 3.3] It is important to implement efficient water-use programmes in regions where water availability is *likely* to decrease, as large investments might be required to ensure adequate supplies, either by building new storage reservoirs or by using alternative water sources. Reductions in water use can delay, or even eliminate, the need for additional infrastructure. One of the quickest ways to increase water availability is through minimising water losses in urban networks and in irrigation systems. Other alternatives for reducing the need for new water supplies include rainwater harvesting as well as controlled reuse. [WGII 3.5, 3.6]

Lower water quality caused by flow variations. The protection of water resources is an important, cost-effective strategy for facing future problems concerning water quality. While this is a common practice for some countries, new and innovative approaches to water quality management are required around the world. One such approach is the implementation of water safety plans (WSP) to perform a comprehensive assessment and management of risks from the catchment to consumer, as proposed by the WHO (2005). Also, the design and operation of water and wastewater treatment plants should be reviewed periodically, particularly in vulnerable areas, to ensure or increase their reliability and their ability to cope with uncertain flow variations.

Desalinisation. Water treatment methods are an option for dealing with increasing salt content in places at risk, such as highly urbanised coastal areas relying on aquifers sensitive to saline intrusion. At present, available technologies are based mostly on membranes and are more costly than conventional methods for the treatment of freshwater supplies. The desalination cost for seawater is estimated at around US\$1/m^3, for brackish water it is US\$0.60/m^3 (Zhou and Tol, 2005), and freshwater chlorination costs US\$0.02/m^3. Fortunately the cost of desalinisation has been falling, although it still has a high energy demand. Desalinisation costs need to be compared with the costs of extending pipelines and eventually relocating water treatment works in order to have access to freshwater. As a rough working rule, the cost of construction of the abstraction and treatment works and the pumping main for an urban settlement's water supply is about half the cost of the entire system. [WGII 7.5] However, in the densely populated coastal areas of Egypt, China, Bangladesh, India and south-east Asia, desalination costs may still be prohibitive. [WGII 3.5.1] If the use of desalination increases in the future, environmental side-effects such as impingement on and entrainment of marine organisms by seawater desalination plants, and the safe disposal of highly concentrated brines that can also contain other chemicals, will need to be addressed. [WGII 3.3.2]

More and different approaches for coping with wastewater. For sewers and wastewater treatment plants, strategies for coping with higher and more variable flows will be needed. These should include new approaches such as the use of decentralised systems, the construction of separate sewers, the treatment of combined sewer overflows (i.e., the mixture of wastewater and runoff in cities), and injecting rainwater into the subsoil. Given the high cost involved in increasing the capacity of urban wastewater treatment plants, appropriately financed schemes should be put in place to consider local conditions. For rural areas, sanitation coverage is generally too low, and local action plans need to be formulated using low-cost technologies, depending on the locality and involving the community. [WGII 7.4.2.3]

Better administration of water resources. As well as considering the adaptation measures already discussed, integrated water management, including climate change as an additional variable, should be considered as an efficient tool. Reduced, increased or a greater variability in water availability will lead to conflicts between water users (agriculture, industries, ecosystems and settlements). The institutions governing water allocation will play a major role in determining the overall social impact of a change in water availability, as well as the distribution of gains and losses across different sectors of society. Institutional settings need to find better ways to allocate water, using principles – such as equity and efficiency – that may be politically difficult to implement in practice. These settings also need to consider the management of international basins and surface and groundwater basins. [WGII 3.5.1]

To confront the additional stress induced by climate change, public participation in water planning will be necessary, particularly in regard to changing views on the value of water, the importance and role that water reuse will play in the future, and the contribution that society is willing to make to the mitigation of water-related impacts.

To implement policy based on the principles of integrated water management, better co-ordination between different governmental entities should be sought, and institutional and legal frameworks should be reviewed to facilitate the implementation of adaptation measures. Climate change will be felt by all stakeholders involved in the water management process, including users. Therefore, all should be aware of its possible impacts on the system in order to take appropriate decisions and be prepared to pay the costs involved. In the case of wastewater disposal norms, for example, the overall strategy used will possibly need to be reviewed, as long as it is based on the self-purification capacity of surface water, which will be reduced by higher temperatures. [WGII 3.4.4]

Developed countries. In developed countries, drinking-water receives extensive treatment before it is supplied to the consumer and the wastewater treatment level is high. Such benefits, as well as proper water source protection, need to be maintained under future climatic change, even if additional cost is to be incurred, for instance by including additional water treatment requirements. For small communities or rural areas, measures to be considered may include water source protection as a better cost–benefit option.

Developing countries. Unfortunately, some countries may not have sufficient economic resources to face the challenges posed by climate change. Poor countries already need additional resources to overcome problems with inadequate infrastructure, and thus they will be more vulnerable to projected impacts on water quantity and quality, unless low-cost options and affordable finance options are available.

Because several of the already identified adaptation and mitigation options are simply not viable, it is expected that developing countries may have to adapt by using unsustainable practices such as increasing groundwater over-exploitation or reusing a greater amount of untreated wastewater. These 'solutions' are attractive because they can easily be implemented at an individual, personal, level. Therefore, low-cost and safe options which do not necessarily imply conventional solutions need to be developed, particularly to provide water services for poor communities that do not even have formal water utilities in many instances. Unfortunately, there are few studies available on this issue. [WGII 3.4.3, 8.6.4]

In summary, climate change can have positive and negative impacts on water services. It is important, therefore, to be aware of its consequences at a local level and to plan accordingly. At the present time, only some water utilities in a few countries, including the Netherlands, the UK, Canada and the USA, have begun to consider the implications of climate change in the context of flood control and water supply management. [WGII 3.6]

4.5 Settlements and infrastructure

Changes in water availability, water quality, precipitation characteristics, and the likelihood and magnitude of flooding events are expected to play a major role in driving the impacts of climate change on human settlements and infrastructure (Shepherd et al., 2002; Klein et al., 2003; London Climate Change Partnership, 2004; Sherbinin et al., 2006). These impacts will vary regionally. In addition, impacts will depend greatly on the geophysical setting, level of socio-economic development, water allocation institutions, nature of the local economic base, infrastructure characteristics and other stressors. These include pollution, ecosystem degradation, land subsidence (due either to loss of permafrost, natural isostatic processes, or human activities such as groundwater use) and population growth (UNWWAP, 2003, 2006; Faruqui et al., 2001; UNDP, 2006). Globally, locations most at risk of freshwater supply problems due to climate change are small islands, arid and semi-arid developing countries, regions whose freshwater is supplied by rivers fed by glacial melt or seasonal snowmelt, and countries with a high proportion of coastal lowlands and coastal megacities, particularly in the Asia–Pacific region (Alcamo and Henrichs, 2002; Ragab and Prudhomme, 2002). [WGII 6.4.2, 20.3]

Growing population density in high-risk locations, such as coastal and riverine areas, is *very likely* to increase vulnerability to the water-related impacts of climate change, including flood and storm damages and water quality degradation as a result of saline intrusion. [WGII 6.4.2, 7.4.2.4] Settlements whose economies are closely linked to a climate-sensitive water-dependent activity, such as irrigated agriculture, water-related tourism and snow skiing, are *likely* to be especially vulnerable to the water resource impacts of climate change (Elsasser and Burki, 2002; Hayhoe et al., 2004). [WGII 7.4.3, 12.4.9]

Infrastructure associated with settlements includes buildings, transportation networks, coastal facilities, water supply and wastewater infrastructure, and energy facilities. Infrastructure impacts include both direct damages, for example as a result of flood events or structural instabilities caused by rainfall erosion or changes in the water table, as well as impacts on the performance, cost and adequacy of facilities that were not designed for the climate conditions projected to prevail in the future. [WGII 3.4.3, 3.5, 7.4.2.3]

4.5.1 Settlements

Many human settlements currently lack access to adequate, safe water supplies. The World Health Organization estimates that 1.1 billion people worldwide do not have access to safe drinking water, and 2.4 billion are without access to adequate sanitation (WHO/UNICEF, 2000). Poor urban households frequently do not have networked water supply access, and thus are especially vulnerable to rising costs for drinking water (UN-HABITAT, 2003; UNCHS, 2003, 2006; UNDP, 2006). For example, in Jakarta, some households without regular water service reportedly spend up to 25% of their income on water and, during the hot summer of 1998 in Amman, Jordan, refugee-camp residents who were not connected to the municipal water system paid much higher rates for water than other households (Faruqui et al., 2001). The impacts of climate change on water availability and source water quality are *very likely* to make it increasingly difficult to address these problems, especially in areas where water stress is projected to increase due to declining runoff coupled with increasing population. [WGII 3.5.1] Rapidly growing settlements in semi-arid areas of developing countries, particularly poor communities that have limited adaptive capacity, are especially vulnerable to declines in water availability and associated increases in the costs of securing reliable supplies (Millennium Ecosystem Assessment, 2005b). [WGII 7.4]

In both developed and developing countries, the expected continuation of rapid population growth in coastal cities will increase human exposure to flooding and related storm damages from hurricanes and other coastal storms. [WGII 7.4.2.4] That very development is contributing to the loss of deltaic wetlands that could buffer the storm impacts. [WGII 6.4.1.2] In addition, much of the growth is occurring in relatively water-scarce coastal areas, thus exacerbating imbalances between water demand and availability (Small and Nicholls, 2003; Millennium Ecosystem Assessment, 2005b).

4.5.2 Infrastructure

4.5.2.1 Transportation networks

Flooding due to sea-level rise and increases in the intensity of extreme weather events (such as storms and hurricanes) pose threats to transportation networks in some areas. These include localised street-flooding, flooding of subway systems, and flood and landslide-related damages to bridges, roads and railways. For example, in London, which has the world’s oldest subway system, more intense rainfall events are predicted to increase the risk of flooding in the Underground and highways. This would necessitate improvements in the drainage systems of these networks (Arkell and Darch, 2006). Similarly, recent research on the surface transportation system of the Boston Metropolitan Area has predicted that increased flooding will cause increased trip delays and cancellations, which will result in lost workdays, sales and production (Suarez et al., 2005). However, those costs would be small in comparison to flood-related damages to Boston's transportation infrastructure (Kirshen et al., 2006). [WGII 7.4.2.3.3] An example of present-day vulnerability that could be exacerbated by increased precipitation intensity is the fact that India's Konkan Railway annually suffers roughly US$1 million in damages due to landslides during the rainy season (Shukla et al., 2005). [WGII 7.4.2.3.3]

4.5.2.2 Built environment

Flooding, landslides and severe storms (such as hurricanes) pose the greatest risks for damages to buildings in both developed and developing countries, because housing and other assets are increasingly located in coastal areas, on slopes, in ravines and other risk-prone sites (Bigio, 2003; UN-HABITAT, 2003). Informal settlements within urban areas of developing-country cities are especially vulnerable, as they tend to be built on relatively hazardous sites that are susceptible to floods, landslides and other climate-related disasters (Cross, 2001; UN-HABITAT, 2003). [WGII 7.4.2.4]

Other impacts on buildings include the potential for accelerated weathering due to increased precipitation intensity and storm frequency (e.g., Graves and Phillipson, 2000), and increased structural damage due to water table decline and subsidence (e.g., Sanders and Phillipson, 2003), or due to the impacts of a rising water table (Kharkina, 2004). [WGII 3.5]

Another area of concern is the future performance of storm-water drainage systems. In regions affected by increasingly intense storms, the capacity of these systems will need to be increased to prevent local flooding and the resulting damages to buildings and other infrastructure (UK Water Industry Research, 2004). [WGII 7.6.4]

4.5.2.3 Coastal infrastructure

Infrastructure in low-lying coastal areas is vulnerable to damage from sea-level rise, flooding, hurricanes and other storms. The stock of coastal infrastructure at risk is increasing rapidly as a result of the continuing growth of coastal cities and expanding tourism in areas such as the Caribbean (e.g., Hareau et al., 1999; Lewsey et al., 2004; Kumar, 2006). In some areas, damage costs due to an increase in sea level have been estimated, and are often substantial. For example, in Poland, estimated damage costs due to a possible rise in sea level of 1 metre by 2100 are US$30 billion, due to impacts on urban areas, sewers, ports and other infrastructure (Zeidler, 1997). The same study estimated that a projected 1 metre rise in sea level in Vietnam would subject 17 million people to flooding and cause damages of up to US$17 billion, with substantial impacts penetrating inland beyond the coastal zone. [WGII 6.3, 6.4, 6.5]

4.5.2.4 Energy infrastructure

Hydrological changes will directly affect the potential output of hydro-electric facilities – both those currently existing and possible future projects. There are large regional differences in the extent of hydropower development. In Africa, where little of the continent's hydropower potential has been developed, climate change simulations for the Batoka Gorge hydro-electric scheme on the Zambezi River projected a significant reduction in river flows (e.g., a decline in mean monthly flow from 3.21×10^9 m^3 to 2.07×10^9 m^3) and declining power production (e.g., a decrease in mean monthly production from 780 GWh to 613 GWh) (Harrison and Whittington, 2002). A reduction in hydro-electric power is also anticipated elsewhere, where and when river flows are expected to decline (e.g., Whittington and Gundry, 1998; Magadza, 2000). In some other areas, hydro-electric generation is projected to increase. For example, estimates for the 2070s, under the IS92a emissions scenario, indicate that the electricity production potential of hydropower plants existing at the end of the 20th century would increase by 15–30% in Scandinavia and northern Russia, where between 19% (Finland) and almost 100% (Norway) of the electricity is produced by hydropower (Lehner et al., 2005). [WGII 3.5] Other energy infrastructure, such as power transmission lines, offshore drilling rigs and pipelines, may be vulnerable to damage from flooding and more intense storm events. [WGII 7.5] In addition, problems with cooling water availability (because of reduced quantity or higher water temperature) could disrupt energy supplies by adversely affecting energy production in thermal and nuclear power plants (EEA, 2005).

4.5.3 Adaptation

The impacts of changes in the frequency of floods and droughts or in the quantity, quality or seasonal timing of water availability could be tempered by appropriate infrastructure investments, and by changes in water and land-use management. Co-ordinated planning may be valuable because there are many points at which impacts on the different infrastructures interact. For instance, the failure of flood defences can interrupt power supplies, which in turn puts water and wastewater pumping stations out of action.

Improved incorporation of current climate variability into water-related management would make adaptation to future climate change easier (*very high confidence*). [WGII 3.6] For example, managing current flood risks by maintaining green areas and natural buffers around streams in urban settings would also help to reduce the adverse impacts of future heavier storm runoff. However, any of these responses will entail costs, not only in monetary terms but also in terms of societal impacts, including the need to manage potential conflicts between different interest groups. [WGII 3.5]

4.6 Economy: insurance, tourism, industry, transportation

4.6.1 Context

Climate and water resources impact on several secondary and tertiary sectors of the economy such as insurance, industry, tourism and transportation. Water-related effects of climate change in these sectors can be positive as well as negative, but extreme climate events and other abrupt changes tend to affect human systems more severely than gradual change, partly because they offer less time for adaptation. [WGII 7.1.3]

Global losses reveal rapidly rising costs due to extreme weather-related events since the 1970s. One study has found that, while the dominant signal remains that of the significant increases in the values of exposure at risk, once losses are normalised for exposure, there still remains an underlying rising trend. For specific regions and perils, including the most extreme floods on some of the largest rivers, there is evidence for an increase in occurrence. [WGII 1.3.8.5]

To demonstrate the large impact of climate variability on insurance losses, flooding is responsible for 10% of weather-related insurance losses globally. Drought also has an impact: data from the UK show a lagged relationship between the cost of insurance claims related to subsidence and (low) summer rainfall. However, in developing countries, losses due to extreme events are measured more in terms of human life than they are in terms of insurance. For example, the Sahelian drought, despite its high severity, had only a small impact on the formal financial sector, due to the low penetration of insurance. [WGII TAR 8.2.3]

4.6.2 Socio-economic costs, mitigation, adaptation, vulnerability, sustainable development

Of all the possible water-related impacts on transportation, the greatest cost is that of flooding. The cost of delays and lost trips is relatively small compared with damage to the infrastructure and to other property (Kirshen et al., 2006). In the last 10 years, there have been four cases when flooding of urban underground rail systems has caused damages of more than €10 million (US$13 million) and numerous cases of lesser damage (Compton et al., 2002). [WGII 7.4.2.3.3]

Industrial sectors are generally thought to be less vulnerable to the impacts of climate change than such sectors as agriculture. Among the major exceptions are industrial facilities located in climate-sensitive areas (such as floodplains) (Ruth et al., 2004) and those dependent on climate-sensitive commodities such as food-processing plants. [WGII 7.4.2.1]

The specific insurance risk coverage currently available within a country will have been shaped by the impact of past catastrophes. Because of the high concentration of losses due to catastrophic floods, private-sector flood insurance is generally restricted (or even unavailable) so that, in several countries, governments have developed alternative state-backed flood insurance schemes (Swiss Re, 1998). [WGII 7.4.2.2.4]

For the finance sector, climate-change-related risks are increasingly considered for specific ‘susceptible’ sectors such as hydro-electric projects, irrigation and agriculture, and tourism (UNEP/GRID-Arendal, 2002). [WGII 7.4.2.2]

Effects of climate change on tourism include changes in the availability of water, which could be positive or negative (Braun et al., 1999; Uyarra et al., 2005). Warmer climates open up the possibility of extending exotic environments (such as palm trees in western Europe), which could be considered by some tourists as positive but could lead to a spatial extension and amplification of water- and vector-borne diseases. Droughts and the extension of arid environments (and the effects of extreme weather events) might discourage tourists, although it is not entirely clear what they consider to be unacceptable. [WGII 7.4.2.2.3] Areas dependent on the availability of snow (e.g., for winter tourism) are among those most vulnerable to global warming. [WGII 11.4.9, 12.4.9, 14.4.7]

Transportation of bulk freight by inland waterways, such as the Rhine, can be disrupted during floods and droughts (Parry, 2000). [WGII 7.4.2.2.2]

Insurance spreads risk and assists with adaptation, while managing insurance funds has implications for mitigation. [WGII 18.5] Adaptation costs and benefits have been assessed in a more limited manner for transportation infrastructure (e.g., Dore and Burton, 2001). [WGII 17.2.3]