Chapter 12

Evolving hazards – and emerging opportunities

Author: Bruce Stewart

Contributors: Yoganath Adikari, Vladimir Aizen, Ali Chavoshia, Hu Chunhong, Pablo García, M. Gopalakrishnan, Hege Hisdal, A.W. Jayawardena, Zbigniew Kundzewicz, Peter Letitre, Robert Naiman, Julian Olden, Roberto Pizzaro, Erich Plate, Carmen Revenga, James Robertson, Léna Salamé, Kyoji Sassa, Pratap Singh, Vladimir Smakhtin, Lena M. Tallaksen, Jos G. Timmerman, Carel De Villeneuve, Des Walling and Maciej Zalewski

Coordinator: Andras Szöllösi-Nagy (UNESCO)

Facilitator: Denis Hughes

Key messages

- In many places climate-related events have become more frequent and more extreme. In developing countries extreme floods can result in many deaths, while in developed countries they can result in billions of dollars in damages. More intense droughts in the past decade, affecting an increasing number of people, have been linked to higher temperatures and decreased precipitation but are also frequently a consequence of the mismanagement of resources and the neglect of risk management.
- Changes in flow and inputs of chemical and biological waste from human activity have altered the water quality and ecological functioning of many of the world's rivers. Global warming is expected to have substantial effects on energy flows and matter recycling through its impact on water temperature, resulting in algal blooms, increases in toxic cyanobacteria bloom and reductions in biodiversity.
- In areas of increasing water stress groundwater is an important buffer resource, capable of responding to increased water demands or of compensating for the declining availability of surface water.

A review of recent changes in the global water cycle that analysed more than 100 studies (based on observations) found rising global and regional trends in runoff, floods and droughts, and other climate-related events and variables in the second half of the 20th century that together support the perception of an intensification of the hydrologic cycle.[1] Meanwhile, substantial uncertainty remains about trends of hydroclimate variables due to differences in responses by variables and across regions, major spatial and temporal limitations in data (see chapter 13) and the effects of modifications in water resources development (withdrawals, reservoirs, land use changes and so on) on flow regimes.

Hazards vary with climate regions

Just as regions are experiencing different degrees of change related to climate variations and population and development pressures, so are they responding differently to changes in hydrologic extremes. This chapter identifies the areas that are most sensitive to changes in extremes and hazards and those that are likely to experience the most negative impacts on water resources.

- *Deserts* face conflicting influences under climate change: potentially seeing more vegetation with higher carbon dioxide levels, but overall facing increases in drought and

Regions in the transition zone between major climate zones are susceptible to drought and thus to potential changes in climate

temperatures. With an already fragile environment, desert ecosystems could experience severe impacts.

- *Grasslands* are influenced by precipitation, both its total amount and its variability. Changing seasonal variability is important even when total precipitation is rising, and declining summer rainfall could damage grassland fauna.
- *Mediterranean ecosystems* are diverse and vulnerable, susceptible to changes in water conditions. Even with a temperature rise of 2°C, the Southern Mediterranean may lose 60%-80% of species.
- *Tundra and Arctic regions* face the loss of permafrost and the potential for methane release with greater warming at the poles.
- *Mountains* are seeing shortened and earlier snow and ice melt and related changes in flooding. At higher altitudes increased winter snow can lead to delayed snow melt.
- *Wetlands* will be negatively affected where there is decreasing water volume, higher temperatures and higher-intensity rainfall.

Some studies have used climate models and greenhouse gas emission scenarios from the recent assessment by the Intergovernmental Panel on Climate Change (IPCC) to forecast differences between climate zones today and in 2100.[2] They have found that under both high- and low-emission scenarios many regions would experience biome-level changes, suggesting that rainforest, tundra or desert areas may no longer have the same type of vegetation by 2100 because of climate shifts (box 12.1).[3] By the end of the 21st century large portions of the Earth's surface may experience climates not found today, and some 20th century climate characteristics may disappear.

Regions in the transition zone between major climate zones (particularly between temperate and dry climates) are susceptible to drought and thus to potential changes in climate. A shift in climate may create a new transition zone, with unknown feedback mechanisms. A northward shift is observed in Southern Europe, causing a decline in summer precipitation in Central and Eastern Europe. Climate models consistently predict an increase in summer temperature variability in these areas and attribute it mainly to strong land-atmosphere interactions. This could cause more droughts and heat waves in this and other mid-latitude regions. Regional climate models suggest that towards the end of the 21st century about every second summer could be as warm as or warmer (and as dry as or dryer) than the summer of 2003 in Europe.

Snow cover has decreased in most regions, especially in spring and summer. Snow cover in the Northern Hemisphere observed by satellite from 1966 to 2005 decreased in every month except November and December, with a step-wise drop of 5% in annual mean in the late 1980s. In the Southern Hemisphere the few long records or proxies show mostly decreases or no changes in the past 40 years or more.[4]

The Himalayan region is highly vulnerable to climate change because its major river drainage systems depend on substantial contributions from snow and glacier melt. In India the river systems originating from the Himalayas (Ganges-Brahmaputra and Indus) contribute more than 60% to the total annual runoff for all the rivers of India. These river systems hold immense potential as a future water source and drain the major plains of the country. Some Himalayan rivers receive more than half their flow from snow and glacier melt runoff near the foothills of the Himalayas. Melting of glaciers and a reduction in solid precipitation in mountain regions would directly affect water resources for domestic supplies, irrigated agriculture, hydropower generation and other water-dependent activities.

Changes in average streamflow

While hazards are normally associated with hydrologic extremes, changes in average streamflow, especially in already water-stressed areas, could cause substantial risks to human activities. The IPCC report suggests that by 2050 annual average runoff will have increased by 10%-40% at high latitudes and decreased by 10%-30% over some dry regions at mid-latitudes and semi-arid low latitudes.[5] However, in many water-scarce regions land use change and increasing water resources development and use could mask the effects of climate change. At high latitudes, where an increase in annual flow is predicted, the impact on low flow and drought depends on the seasonal distribution of precipitation, the storage capacity of the catchment (ability to take advantage of higher winter precipitation), changes in evapotranspiration and the length of the growing season.

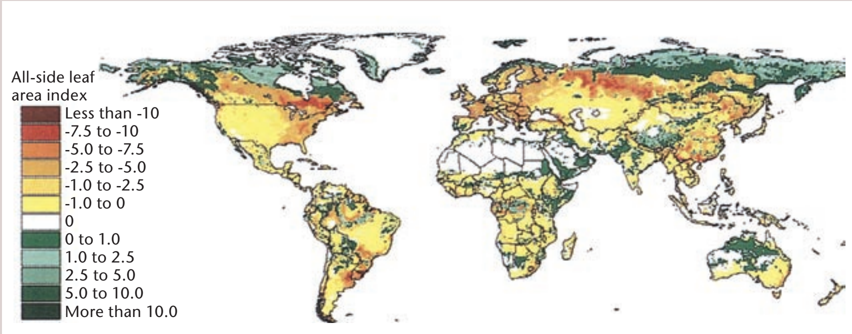
Box 12.1 A global perspective on regional vegetation and hydrologic sensitivities to climate change

The Mapped Atmosphere-Plant-Soil System (MAPSS), a biogeographic model, predicts changes in vegetation leaf area index, site water balance, runoff and biome boundaries. Global equilibrium impacts on these ecosystem properties were simulated under five general circulation model (GCM) potential climate scenarios with doubled carbon dioxide concentration.

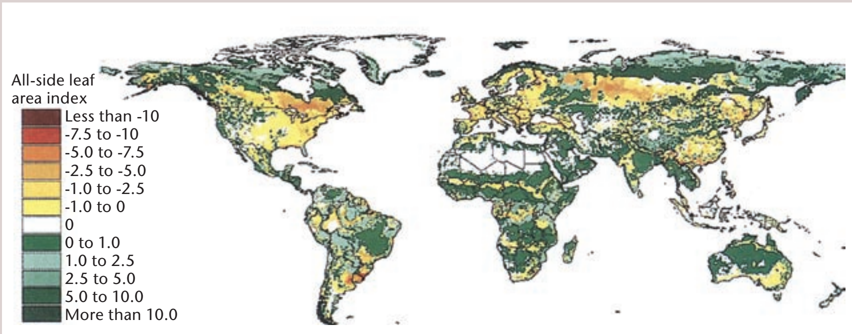
Leaf area index is the ratio of the vegetation's leaf surface area per unit of ground area. The greater the leaf surface area, the more rapidly the vegetation will extract soil water. Most ecosystems will grow as much leaf area as can be supported by the water available during an average growing season. Thus, under normal conditions many ecosystems are very near a drought threshold. Warming lengthens the growing season, and evaporative demand increases exponentially with rising temperature. Consequently, entire landscapes can extract all soil moisture before the end of the growing season and become susceptible to sudden decline under rapid warming, especially if coincident with a short-term drying trend. Regional increases in precipitation and benefits to plant water use efficiency from elevated carbon dioxide concentrations can offset the increased drought stress in some ecosystems. However, at global scales most ecosystem models show that the rapid increases in evaporative demand can overwhelm these benefits over large areas, possibly within the next few decades.

Average simulated change in vegetation leaf area index from five general circulation model scenarios

With no change in water use efficiency



With increase in water use efficiency



Note: All-side leaf area index is the leaf area (all-sides) per unit ground area; it is a non-dimensional (unitless) measure.
Source: Neilson and Marks 1994.

Regional patterns of vegetation change and annual runoff are surprisingly consistent across the five GCM scenarios, considering the relative lack of consistency in predicted changes in regional precipitation patterns (see bottom map). Eastern North America and Eastern Europe to western Russia show particular sensitivity to drought-induced forest decline. Uncertainties about potential evapotranspiration and vegetation water use efficiency can alter the sign of the simulated regional responses, but the relative responses of adjacent regions appear to be a function largely of the background climate rather than of the vagaries of the GCMs and are intrinsic to the landscape. Thus, spatial uncertainty maps can be drawn even under the current generation GCMs.

Source: Ronald P. Neilson, Department of Forest Ecosystems and Society, Oregon State University; Neilson et al. 1998; Scholze et al. 2006.

The IPCC report notes increased annual runoff and earlier spring peak discharge in many glacier- and snow-fed rivers, indicating a regime shift for some rivers. This trend is projected to continue in response to increasing temperatures, resulting in increased summer streamflow in downstream regions receiving melt water from major mountain ranges, followed eventually by reduced streamflow.

Changes in extreme events

Extreme water-related events can have positive as well as negative impacts. They recharge natural ecosystems, providing more abundant water for food production, health and sanitation (box 12.2). In the lower Mekong River delta, for example, Cambodians trap water and nutrients carried down by the sediment during flood periods and use them to replenish rice paddies. Floods can be important to the aquatic and riparian ecology, as demonstrated during the artificial flooding of the Colorado River at the Grand Canyon in the United States. But extreme water-related events also destroy lives and property. The most common extreme events are floods and droughts.

Floods and flooding

With global climate change and projected increases in global temperature, scientists generally agree that the hydrologic cycle will intensify and that extremes will become more common.

Box 12.2 Managing urban stormwater in association with land use and land-cover planning can convert a nuisance into a resource

Urban areas cause substantial changes in stormwater hydrology, increasing runoff volumes and peak discharges and altering water quality. In the traditional view urban runoff is a nuisance to be removed as quickly and effectively as possible. However, new studies and initiatives in several countries around the world have shown that stormwater can become a resource, not merely a nuisance. Optimal management of runoff is determined by local conditions and can include recharge of aquifers, retention and detention to improve water quality and reduce downstream flood impacts and the cost of drainage systems, and on-site use of the water (rainwater-harvesting) to irrigate and enhance the urban environment. Stormwater management can be exercised from the household level to the entire built area of a city.

Traditionally planners decide on land uses and land cover and then give engineers the task of designing drainage systems to remove the runoff. In a framework known as water-sensitive planning, water considerations are incorporated in land use and land-cover planning from the outset, following best management practices on the distribution of pervious and impervious land cover and on constructed facilities for capturing, detaining, storing and infiltrating runoff. Efficient water use and conservation, recycling of grey water and possible use of treated wastewater should also be incorporated in planning.

With some effort, water-sensitive designs can also be applied to existing urban areas. By connecting roof drains to pervious spaces, constructing low walls around properties to make them into mini-detention basins that store and infiltrate runoff and directing excess water to playgrounds, planners can make better use of stormwater runoff and reduce flooding damages in open public spaces and parks. In the Coastal Plain of Israel, for example, where annual rainfall is just 500 millimetres, it has been estimated that the aquifer recharge could be increased by about 25,000-77,000 cubic metres per square kilometre of urban area by connecting roof drains to a 15% pervious area on the property and surrounding the property with a low (approximately 20 centimetres) wall.

Source: Carmon and Shamir 1997.

The moisture-holding capacity of the atmosphere has been increasing at a rate of about 7% per 1°C of warming, creating the potential for heavier precipitation. There have likely been increases in the number of heavy precipitation events in many land regions – consistent with a warming climate and the observed increase in atmospheric water vapour, even where total precipitation has declined.

In developing countries extreme floods can result in many deaths, while in developed countries extreme floods cause material damage in the billions and tens of billions of dollars (see table 12.1 for examples). Destructive floods in the last decade across the globe have led to record high material damage. Other extreme high-impact water-related events not listed in table 12.1 are floods in Europe in 1997 and 2002 and floods in China in 1996 ($26 billion in material damage) and 1998 ($30 billion in material damage). Yearly economic losses from extreme events rose tenfold between the 1950s and 1990s in inflation-adjusted dollars.[6]

The question is whether the frequency and magnitude of flooding are also increasing and, if so, whether that is in response to climate variability and change. Disaster losses, mostly weather and water related, have grown much more rapidly than population or economic growth, suggesting a climate change factor. Globally, the number of great inland flood catastrophes was twice as large per decade between 1996 and 2005 as between 1950 and 1980, and economic losses were five times as great. The dominant drivers of these upward trends are socioeconomic factors, such as population growth, land use change and greater use of vulnerable areas.

Documented trends in floods show no evidence for a globally widespread change. One study identified an apparent increase in the frequency of 'large' floods (exceeding 100-year return period levels) in 16 large basins across much of the globe during the 20th century.[7] Analyses of long time series of monthly river flow data showed that seven of eight 100-year floods occurred in the more recent half of the records.

However, subsequent studies have provided less widespread evidence. A global change detection study does not support the hypothesis of a global increase of annual maximum river flows.[8] The study found increases in 27 cases, decreases in 31 cases and no trend in the remaining 137 cases of the 195 catchments examined worldwide. Of the 70 time series for Europe only 20 show statistically significant changes (11 increases and 9 decreases). However, the overall maxima for the period (1961-2000) occurred more frequently (46 times) in the later subperiod, 1981-2000, than in the earlier subperiod (24 times), 1961-80. Evidence is stronger for changes in the timing of floods, with increasing late autumn and winter floods. Fewer ice-jam related floods have been observed in Europe.

Low flows and droughts

Climate change is expected to influence precipitation, temperature and potential evapotranspiration and, through their combined effects, to influence the

Table 12.1 Examples of major floods and flooding worldwide, 1860-2008

Date	Location	Meteorological conditions	Peak discharge (cubic metres per second)	Impact material damage (US$ millions)	Human losses
January 2008	Zambezi River, Mozambique	Heavy torrential precipitation in Mozambique and neighbouring countries	3,800	2	20 dead, 113,000 displaced
May 2006	Lower Yukon, United States	Snowmelt, ice-jam break-up	na	na	na
April-May 2003	Santa Fe, Argentina	Saturated soil due to heavy precipitation in summer 2002 and April 2003	4,100	na	22 dead, 161,500 displaced
February 2000	Limpopo River, Mozambique	Extreme precipitation in tropical depression, enforced with torrential rain of three cyclones	10,000	na	700 dead, 1,500,000 displaced
July 1997	Czech Republic	Saturated ground after extreme long-lasting precipitation and extreme precipitation	3,000	1.8	114 dead, 40,000 displaced
June 1997	Brahmaputra River, Bangladesh	Torrential monsoon rains during monsoon season	10,200	400	40 dead, 100,000 displaced
March-April 1997	Red River, United States	Heavy rains and snowmelt	3,905	16,000	100,000 homes flooded, 50,000 displaced
November 1996	Subglacial Lake Grímsvötn, Iceland	Jökulhlaup flood	50,000	12	na
February 1996	West Oregon, United States	Extreme spring snowmelt and heavy spring precipitation	na	na	9 dead, 25,000 displaced
July 1995	Athens, Greece	Storm of a short duration and extreme intensity	650	na	50,000 displaced
November 1994	Po River, Italy	Cold front associated with cyclonic circulation and heavy rainfall	11,300	na	60 dead, 16,000 displaced
February 1994	Meuse River, Europe	Heavy rain due to low pressure system	3,100	na	na
September 1993	Mississippi River, United States	Heavy precipitation in June and July; saturated soil due to extremely high precipitation	na	15,000	50 dead, 75,000 displaced
November 1988	Hat Yai City, Thailand	Brief torrential monsoon rain	na	172	664 dead, 301,000 displaced
January 1983	Northern Peru	El Niño situation with heavy rains	3,500	na	380 dead, 700,000 displaced
August 1979	Machu River, India	Exceptionally heavy rainfall, swollen river, resulting in collapse of the Matchu Dam	16,307	100	1,500 dead, 400,000 displaced
June-September 1954	Yangtze River, China	Intensive rainfall over several months	66,800	na	30,000 dead, 18,000 displaced
January 1953	North Sea, Netherlands	High spring tide and a severe European windstorm	na	504	1,835 dead, 100,000 displaced
January 1910	Seine River, France	Very wet period for six months followed by heavy rains in January	460	na	200,000 displaced
May 1889	Johnstown, Pennsylvania, United States	Extremely heavy rainfall due to storm followed by breach of dike	na	17	2,200 dead
July 1860	Eastern Norway	Frost and heavy snowfall followed by snowmelt and heavy precipitation	3,200	na	12 dead

na is not available or not applicable.

Source: Compiled by Siegfried Demuth, International Hydrological Programme, UNESCO.

In the past three decades droughts have become more widespread, more intense and more persistent

occurrence and severity of droughts. But it is difficult to disentangle the impacts of climate change from those of other human influences (engineered effects and land use changes) and multidecadal climate variability. More intense droughts, affecting more people and linked to higher temperatures and decreased precipitation, have been observed in the 21st century, in Europe and globally.[9] A similar pattern is found for heat waves. The high pressure system that developed over Western Europe in 2003 blocked moist air masses from the west and allowed warm, dry air masses from Northern Africa to move northwards. The result was large precipitation deficits and record-breaking temperatures across most of Central and Southern Europe, with drought conditions lasting from March to September.

Several summaries of observed and predicted impacts of climate change on hydrologic droughts have been published.[10] A study of spatial and temporal changes in streamflow droughts using a dataset of more than 600 daily European streamflow records from the European Water Archive of the UNESCO Flow Regime from International Experimental Data (FRIEND) detected no significant changes for most stations.[11] However, distinct regional differences were found. For 1962-90, examples of increasing drought were found in Spain, the eastern part of Eastern Europe and large parts of the United Kingdom, whereas examples of decreasing drought were found in large parts of Central Europe and the western part of Eastern Europe.

These trends in streamflow drought could be explained largely by changes in precipitation or artificial hydrologic influences in the catchment. However, the period analysed and the selection of stations can also influence regional patterns. Recent trend studies of long time series in the Czech Republic show that, following a catastrophic flood in 2002, extreme hydrologic drought occurred in 2003 and 2004 as a result of an increasing trend in air temperature and a long-term decline in precipitation, especially during the summer months.[12] Extreme droughts occurred in Europe in 2003 and 2006. All these recent droughts could well change the spatial pattern of droughts found for Europe in the earlier study.

The heat wave and drought between June and mid-August 2003 in Europe were accompanied by annual precipitation deficits of up to 300 millimetres. Vegetation and ecosystems suffered heat and drought stress, and record wildfires were experienced (more than 5% of the forest area of Portugal burned). Gross primary production of terrestrial ecosystems across Europe fell to an estimated 30% of normal. Damages resulting from agricultural crop losses and higher production costs were estimated at more than €13 billion. Major rivers, including the Danube, Loire, Po and Rhine, were at record low levels, disrupting inland navigation, irrigation and power-plant cooling. Extreme glacier melt mitigated the effects of low rainfall and high evaporation on streamflows in rivers partly fed by glaciers, such as the Danube and the Rhine.

In the past three decades droughts have become more widespread, more intense and more persistent due to decreased precipitation over land and rising temperatures, resulting in enhanced evapotranspiration and drying. The occurrence of droughts seems to be determined largely by changes in sea surface temperatures, especially in the tropics, through associated changes in atmospheric circulation and precipitation. In the western United States diminishing snow pack and resultant reductions in soil moisture also appear to be factors. In Australia (box 12.3) and Europe the extremely high temperatures and heat waves accompanying recent droughts have implied direct links to global warming. Sahelian droughts have led to severe losses of livestock, with losses as high as 62% observed in part of Ethiopia in 1998-99.[13] Globally, very dry areas (land areas with a Palmer Drought Severity Index of 3.0 or less) have more than doubled since the 1970s (from about 12% to 30%), with a large jump in the early 1980s due to an El Niño Southern

Box 12.3 **Drought in Australia, 1996-2007**

For large parts of southern and eastern Australia dry conditions have persisted since October 1996. For some areas the rainfall deficit over this period exceeded a full year's normal rainfall. In the agriculturally important Murray-Darling River basin October 2007 marked the sixth year of lower than average rainfall, with November 2001-October 2007 being the driest such six-year period on record.

The recent drought in Australia has contributed to changes in Australia's management of water resources. Acknowledging that too much water has been taken from rivers and aquifers, particularly in the Murray-Darling basin, Australia has decided that it must make better use of its water resources. This means improved efficiency and productivity of water use and better use of water markets to optimize the economic benefits that water brings (see box 4.2 in chapter 4). Australia understands that it must secure water supplies for current and future needs, including from a range of new sources that rely less on rainfall given the clear threat climate change poses to traditional water sources.

Water restrictions have been put in place in all major cities in response to the severe drought. These include restrictions on watering lawns, using sprinkler systems, washing vehicles, hosing in paved areas, refilling swimming pools and others. Restrictions can be adjusted to current conditions. In some cities water inspectors monitor water use and can impose fines or shut off water supplies for water use infractions.

Source: www.mdbc.gov.au/ and www.bom.gov.au/.

Oscillation-related precipitation decrease over land and subsequent increases due primarily to surface warming.[14]

Climate change and other global trends such as increasing population and increasing deforestation demand better risk assessment in the management of vulnerable water resources, balancing social, environmental and economic requirements, to achieve a sustainable water supply system.

Changes in groundwater

The groundwater portion of the water cycle has been subjected to massive changes, particularly during the past hundred years as humans learned to dig or drill wells and abstract groundwater using pumps. Use of groundwater for irrigated agricultural has increased enormously in the past 50 years, and some 70% of global groundwater abstraction is now estimated to be used in irrigation. Particularly in areas associated with the green revolution, heavy groundwater pumping has led to unsustainable conditions, with falling water levels, degraded groundwater aquifers and increased salinization. Pollution of shallow aquifers became widespread four or five decades ago and has triggered water quality protection measures in many countries (see chapter 8).

Groundwater abstractions have also contributed to the development of rural economies,[15] indicating that a balance has to be found in groundwater development. Groundwater serves a water shortage buffer function during short-term climate variations and is important to adaptation strategies. In many places groundwater mining from fossil aquifers is the only reliable means of obtaining water (see chapter 11). These groundwater resources are increasingly being used for agricultural, industrial and domestic water supplies, although they are almost never recharged.

Changing land use and water infrastructure have also greatly modified groundwater regimes, with groundwater pumping from deep aquifers now a worldwide phenomenon. In many places groundwater is pumped with no understanding of its source or its annual recharge and therefore of how much may be used sustainably. Results include falling water levels, desiccated wetlands, dewatered rock sequences and land subsidence (box 12.4). More data are urgently needed to quantify groundwater resources worldwide as a basis for improved groundwater management.

Changes in erosion, landslides, river morphology and sedimentation patterns

A more vigorous hydrologic cycle would imply greater water extremes, which could affect the relationships between hydrology

Heavy groundwater pumping has led to unsustainable conditions, with falling water levels, degraded groundwater aquifers and increased salinization

Box 12.4 Controlled exploitation and artificial recharge as effective measures against detrimental subsidence

Industrial and agricultural development in the last century, accompanied by an exponential growth of cities, led to concentrated pumping of groundwater resources worldwide. During the 1960s and 1970s subsidence occurred in many parts of the world, with widespread damage to property and infrastructure. Large cities built on highly compressible sediments in coastal areas increasingly experienced flooding and salt intrusion. Controlled pumping schemes and artificial recharge measures have managed to slow and even reverse subsidence. But with sea levels projected to rise as a result of global climate change, maintaining these schemes and minimizing the contribution of subsidence has become even more urgent.

Even as Venice experienced a relative sea level rise of 23 centimetres over the last century, the subsidence associated with aquifer depletion increased exponentially until 1961. With curtailing of overexploitation since 1970, subsidence has stabilized at the rate of natural subsidence, at less than 0.5 millimetre a year, and the artesian aquifers have begun to rebound.

The effects of rapid urbanization and industrialization are especially apparent in China, where increasing subsidence has led to extensive environmental and economic damage in more than 45 cities, more than 11 of which have experienced cumulative subsidence of more than 1 metre. Tianjin experienced related economic losses from 1959 to 1993 estimated at $27 billion. Shanghai took drastic measures in 1965, as total subsidence since 1920 had reached as much as 2.63 metres. Pumping has been reduced by 60%, and users are requested to inject the same quantity of water into aquifers in winter as is used in summer. While pumping-related subsidence has been controlled, drainage for construction and compaction of foundation layers have been causing subsidence rates of up to 10 millimetres a year since 1990.

Many groundwater basins in the arid and semi-arid United States experienced subsidence in response to heavy pumping, effectively reducing aquifer storage. As a result of rapid growth of Las Vegas, Nevada, pumping rates have exceeded natural recharge since about 1960, despite imports of Colorado River water. In the late 1980s the Las Vegas Water Valley District initiated an artificial recharge programme, injecting Colorado River water into the principal aquifers. Net annual pumpage has now been reduced to the level of natural recharge. The water level drawdown has recovered from a maximum of 90 metres to as few as 30 metres. Subsidence has also decreased considerably, although the depressurized aquifer continues to compact, evidence that the detrimental effects of overpumping can continue long after control measures have been taken.

Source: Ger de Lange, the Netherlands Organisation for Applied Scientific Research, Built Environment and Geosciences; Poland 1984; Carbognin, Teatini, and Tosi 2005; Hu et al. 2004; Chai et al. 2004; Wang 2007; Bell et al. 2008.

Increased erosion rates have important implications for the sustainability of the global soil resource, food security and environment

and geomorphology. More intense rainfall could lead to more water-induced erosion, while drier climates could result in wind-induced erosion. And changes in the seasonal distributions of rainfall can have significant implications for patterns of vegetation growth and thus for soil erosion. Climate and erosion are interdependent components of the Earth's hydrologic cycle and of the environment. In addition to being affected by shifts in climate, soil erosion can affect climate. Desertification processes are intertwined with soil degradation and vegetation changes. These changes, possibly exacerbated by erosion, result in the loss of soil carbon and the release of carbon dioxide into the atmosphere, contributing to global warming. Changes in vegetative growth and land use that are driven by accelerated erosion can also influence the hydrologic cycle and thus the climate.

Changes in the key hydrologic drivers, such as rainfall amount and intensity, surface runoff and river discharge, caused by climate change and changes in land cover and land use, can be expected to cause significant increases in global soil erosion and in the sediment loads transported by rivers. Changes in sediment load could reflect both changing rates of sediment mobilization and supply to the river system and changes in transport capacity caused by changes in discharge and the impact of reservoirs and other human-made sinks and stores in reducing downstream fluxes. In turn, changes in the sediment regimes of rivers affect the storage capacity of reservoirs and the yield of water resources systems. Although data are limited, it is possible to assess the general magnitude and direction of changes in erosion and sediment transport over the past decades.

Erosion rates

The conversion of native vegetation to agriculture has been shown to increase soil erosion rates 10- to 100-fold.[16] With agricultural land now occupying about 37% of the ice-free area of the continents, it is clear that agriculture has had an enormous impact on global erosion rates. Increased erosion rates have important implications for the sustainability of the global soil resource, food security and the environment.

Much of the world's farmland has been cultivated for centuries and in some regions for millennia. Major increases in soil erosion rates are unlikely to have occurred within these areas in the recent past. But in other areas, particularly in developing countries, a rapidly expanding population has led to recent land clearance and rapid expansion of cultivated land. Since 1960 world population has approximately doubled, and cropland has increased by more than 10%.[17]

From a global perspective, however, such recent increases in soil loss are likely to have been at least partially offset by reduced erosion in other regions following implementation of soil conservation programmes and improved land management during the 20th century. In the United States soil conservation and related measures promoted by the Food Security Act of 1985 have reduced total annual erosion from cropland by an estimated 40%, from 3.4 gigatonnes (Gt) a year to 2.0 Gt.[18] In China erosion control measures in the loess region of the Middle Yellow River basin after 1978 helped reduce the annual sediment load of the Middle Yellow River from about 1.6 Gt in the mid-20th century to 0.7 Gt at the end of the 20th century.[19] Elsewhere, the progressive introduction of no-till and minimum till practices – now implemented on an estimated 5% of world cropland[20] – has also reduced erosion rates on cultivated land. Such measures typically reduce erosion rates by more than one order of magnitude.[21]

While an accurate assessment of the relative importance of these opposing trends for the contemporary global soil erosion budget is still not possible, it is clear that significant changes are occurring. Furthermore, there is increasing recognition that, with the greater variability of rainfall and the higher frequency of extreme storm events accompanying future climate change, erosion rates in many areas of the world are likely to rise. A recent study in the Midwestern United States, combining the output from general circulation models with erosion models that also took into account the likely impact of climate change on crop management and crops grown, suggested that erosion rates would increase in 10 of the 11 study area regions. Increases relative to 1990-99 were predicted to range from 33% to 274% by 2040-59.

Sediment loads

A river's sediment load is sensitive to a range of environmental controls related to both the supply of sediment to the river and its ability to transport that sediment. Long-term sediment measurements are unavailable for most of the world's rivers, precluding detailed analysis of global trends, but available data show that important changes are occurring.[22] For many rivers there is evidence of reduced sediment loads in recent years,[23] primarily because of the construction of dams, which trap a large proportion of the sediment load previously transported by the river. One estimate suggests that more than 40% of global river discharge is intercepted by large dams (dams with a storage capacity of more than 0.5 cubic kilometre).[24] Dams on the Colorado and the Nile Rivers have reduced the sediment load of those rivers to near zero.

Changes in sediment load have important implications for global geochemical cycling and sediment-associated carbon fluxes. From a more local perspective increased sediment loads frequently cause degradation of water quality and aquatic habitats and increased siltation of reservoirs, river channels, canal systems and harbours. In many contexts reduced sediment loads bring benefits, but in deltas and coastal areas reduced sediment inputs can remove important nutrient sources and lead to shoreline recession. Landslides, the most dramatic erosion process, present the gravest hazard to human communities. Until the International Geotechnical Society UNESCO Working Party on World Landslide Inventory was established during the International Decade for Natural Disaster Reduction of 1990-2000, there was no common definition of landslides. The international unified definition was agreed as 'the movement of a mass of rock, debris or earth down a slope'.[25] Landslides are classified by a combination of the type of material (rock, debris and earth) and type of movement (fall, slide, flow, topple and spread).

While the definition has been approved internationally, no unified map of the distribution of landslides has ever been prepared. However, a global-scale landslide susceptibility map was produced by the International Programme on Landslides with World Bank funding.[26] Landslide susceptibility is calculated from topography, earthquake and rainfall data. The model does not include the shear strength of soils, which is difficult to quantify at the global scale. Recently, the US National Aeronautics and Space Administration (an International Consortium on Landslides member) also compiled a landslide susceptibility map using Shuttle Radar Topography Mission data, the Food and Agriculture Organization's digital soil map and other information.

Changes in precipitation or precipitation-causing phenomena (such as cyclones and typhoons) can lead to increased severity or frequency of landslides. If these changes are accompanied by seismic activities, there is a strong potential for an increase in landslide-triggering events. For example, in 2004 Japan experienced the greatest number of typhoons in its history. After one of these typhoons the 2004 Niigata-ken Chuetsu earthquake occurred. The earthquake triggered more large-scale landslides than had events of a similar magnitude, such as the 1995 Hyogo ken-Nanbu (Kobe) earthquake and the 2005 Fukuoka-ken Saiho-oki offshore earthquake. In February 2006 a small earthquake, which occurred five days after three days of continuous rainfall, triggered a huge landslide in Leyte Island, Philippines, killing more than 1,000 people.

Climate change will affect water quality and ecosystem health through higher water temperatures, lower water levels, more flooding and changes in lake stratification patterns. Aquatic ecosystem dynamics are driven by temperature and water availability, which determine energy flow; the primary production, composition, structure and biological diversity of ecosystems; the range of global biomass; pattern of ecosystem succession and the type of climax biome.

Climate change will affect water quality and ecosystem health through higher water temperatures, lower water levels, more flooding and changes in lake stratification patterns

Increased water temperatures promote algal blooms and increase toxic cyanobacteria bloom. A toxin produced by microcistis (*Microcistina*-LR) is 10 times more toxic than strychnine. Toxic cyanobacteral blooms, already present on all continents, may intensify, requiring restrictions on people's use of water resources.

Relatively small increases in temperature also accelerate energy flow and matter cycling: a 1°C warming enhances ecosystem productivity by 10%-20% at all trophic levels. An increase in zooplankton consumption may reduce the density of this food source, resulting in a decline in the food base for fish, inhibiting growth and favouring small species over large (an insufficient food base for larger species). An overlapping of changing abiotic conditions, such as rising temperature and declining dissolved oxygen content, may be an additional stressor, contributing to a lowering of biodiversity and ecosystems function. This could mean shifts in dominant species, a destabilization of the ecosystem equilibrium and a shift to another steady-state. Rising water temperatures and related changes in ice cover, salinity, oxygen levels and water circulation have already contributed to global shifts in the range and abundance of algae, If hazards become more severe (in intensity or magnitude), countries will face new challenges, requiring additional cooperation with other concerned countries in mitigating hazards

zooplankton and fish in high-latitude oceans and high-altitude lakes, as well as to earlier migrations of fish in rivers.

The effects of increased temperatures and the acceleration of biological processes will differ depending on hydrologic type and the characteristics and complexity of aquatic ecosystems. In colder regions, for example, rising water temperatures can improve water quality during winter and spring, with earlier ice breakup increasing oxygen levels and reducing winter fish-kills.[27]

The response of river ecosystems to climate change will depend on their location within the river basin. Longitudinal linkages are important to the functioning of river ecosystems. Upper sections of rivers are usually driven by abiotic factors (flow and water quality), and the biotic structures are better adapted to high abiotic (hydrologic) variability, resistant to rapid and unexpected changes and better able to recover from stress. Down the river course, with more stable abiotic characteristics, biotic processes determine ecosystem dynamics, and ecosystems are more vulnerable to global warming.

Modification of precipitation patterns due to climate change will directly influence runoff and the timing and intensity of nutrient and pollutant supplies to rivers and lakes. Greater changes are expected in catchments with degraded vegetation cover, landscape drainage and wetland loss. Open nutrient cycles in the terrestrial ecosystems due to reduced nutrient retention in biomass and mineralization of organic matter in soils will intensify nutrient loss to freshwater. More intense rainfall events will also lead to greater fluvial erosion and increases in suspended solids loads (turbidity) in lakes and reservoirs.[28] Extension of the growing season due to global warming may increase the duration of agricultural activities, which may cause more nutrient leaching from agricultural areas.[29] All these processes will contribute to intensification of eutrophication, a common problem in lakes and rivers all over the world and a serious hazard for human activities (drinking water, aquaculture, recreation) and ecosystem functioning.

The expected overall lowering of water levels in rivers and lakes will worsen water quality. Water reserves will become more turbid through the resuspension of bottom sediments,[30] and the reduction in water supply will increase the concentration of pollutants in water resources. Oxygenation of river water – a key indictor of biological water quality – is enhanced under high flow conditions that encourage surface aeration. Simulations of stream conditions under several climate change scenarios found that decreased streamflows resulted in decreased oxygen levels and water quality.[31] Salinity levels will increase with decreasing streamflow in semi-arid and arid areas. Salt concentrations are predicted to increase 13%-19% by 2050 in the upper Murray-Darling River basin in Australia.[32] Salinization of water resources is also predicted to be a major hazard for island nations, where coastal seawater intrusion is expected with rising sea levels.

The higher temperature, change in precipitation patterns and shift in regional wind regimes associated with climate change are likely to alter the thermal stratification of lakes and reservoirs. Higher temperatures are likely to increase thermal stability and alter mixing patterns in lakes, resulting in reduced oxygen concentrations and increased release of phosphorous from sediments.[33] Simulations suggest that lakes in subtropical zones (latitude 30° to 45°) and subpolar zones (latitude 65° to 80°) are subject to greater relative changes in thermal stratification patterns than are mid-latitude or equatorial lakes and that in subtropical zones deep lakes are more sensitive than are shallow lakes.[34]

Simulations also show that winter stratification in cold regions would be weakened and the anoxic zone would disappear.[35] The greatest increases in water temperatures are foreseen in lakes where the duration of ice cover will be substantially reduced. In addition, simulations show a 10° or more northward shift in the boundary of ice-free conditions in the Northern Hemisphere.[36] Observations during droughts in the boreal region of northwestern Ontario, Canada, show that lower inflows and higher temperatures produce a deepening of the thermocline.[37] Changes in wind speed and direction contributing to patterns of lake and reservoir mixing and thermal stratification may alter the biomass cycling in lakes. Countries that share water resources may face additional challenges under conditions of changing hazards. In areas with experience of hazards countries are used to managing such crises. But if hazards become more severe (in intensity or magnitude), countries will face new challenges, requiring additional cooperation with other concerned countries in mitigating hazards.[38]

In new hazard-exposed areas there will be great variations in how countries mitigate hazards affecting international waters. In broad terms OECD countries in Europe, North America and South East Asia would be able to direct their institutional and financial resources towards new cooperative efforts. Developing countries, with limited resources and hazard mitigating experience, would be more exposed. Examples include the Mekong River basin and some of the major basins in West and Central Africa.[39]

Changes in transboundary water resources (through engineered developments or climate change) will present opportunities for international cooperation. The cooperation must be based on a common understanding of the nature of the resource as well as its value to the countries who share it. And it must involve collecting and sharing reliable data and applying compatible data analysis methods.

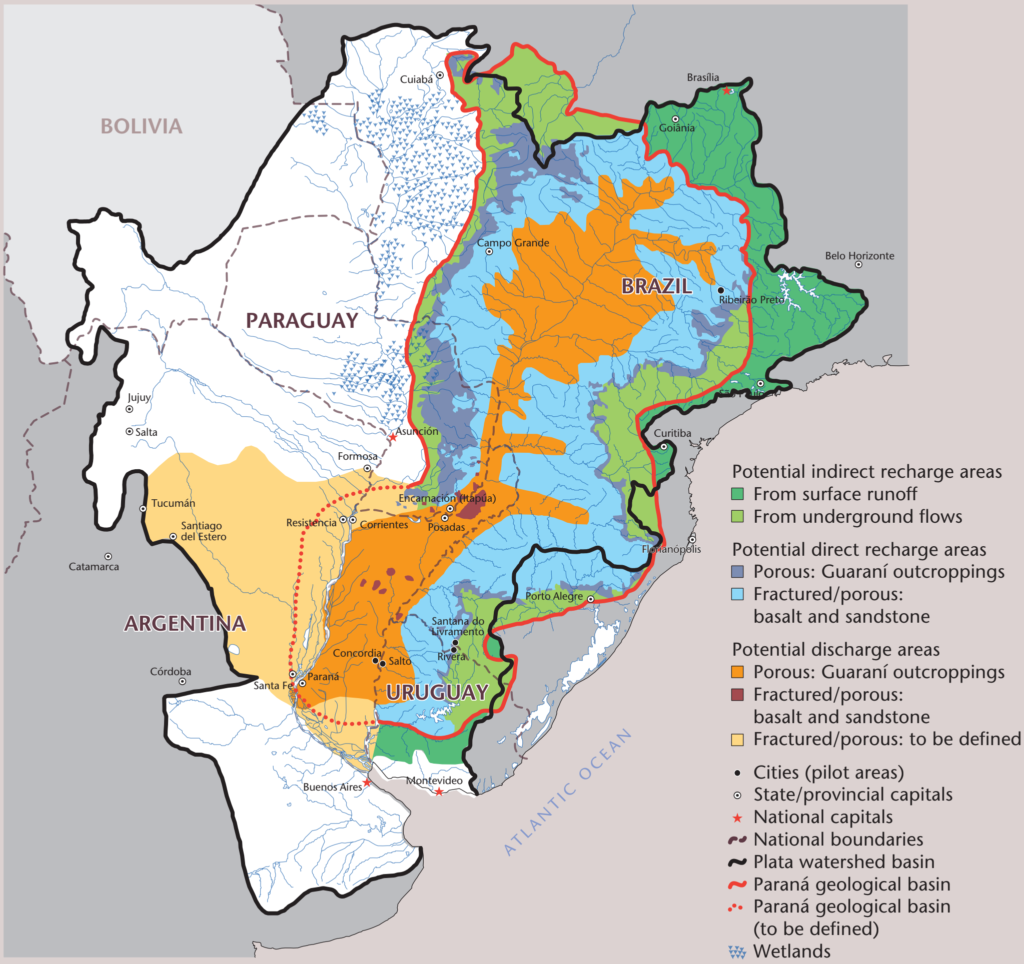
Attention is coming to transboundary groundwater issues much later than to surface water concerns. Governments, institutions and other stakeholders that have developed strategies for effective groundwater resources management at the local and national levels are learning that coordination is also necessary across administrative boundaries (see box 12.5 on the Guaraní aquifer). As a result, over

Box 12.5 Towards transboundary management of the Guaraní aquifer

The Guaraní aquifer in Argentina, Brazil, Paraguay and Uruguay averages some 250 metres in thickness and covers an estimated area of 1.2 million square kilometres. The aquifer's groundwater resources are contained in sand and sandstone beds deposited since the Mesozoic Era and mostly confined below volcanic rocks. Estimated annual recharge is about 166 cubic kilometres, produced mainly in the zones where there are outcroppings of unconfined parts of the aquifer. The climate in the area is humid to subhumid, with annual precipitation of 1,200-1,500 millimetres.

The quality of the Guaraní's groundwater is generally good, with a few exceptions. About 20 million people live over the aquifer, and some parts are intensely exploited, while others are virtually untouched. There are still many gaps in knowledge about the state and performance of this aquifer system.

Location of the Guaraní transboundary aquifer



Source: Guaraní Aquifer System Project 2003.

The four countries have cooperated since early 2003 in a project for sustainable management and protection of the aquifer, with support from the Global Environment Facility, the World Bank and the Organization of American States and with participation of the International Atomic Energy Agency and the German Federal Institute for Geosciences and Natural Resources. The project aims to explore and assess the aquifer system in more detail and to develop a framework for coordinated management. In addition, four pilot areas with emerging problems have been selected to gain experience in local management.

Source: www.sg-guarani.org/index; UNESCO/OAS ISARM 2007.

> **Over many generations the human race has shown an amazing ability to adapt and adjust to climate variability and increasing pressure on resources**

the last decade international and regional organizations have developed initiatives related to internationally shared aquifer resources management, in cooperation with countries in the regions concerned.[40]

Mapping and descriptions of transboundary aquifers are the first steps. The United Nations Economic Commission for Europe conducted an inventory of transboundary aquifers in Europe in 1999,[41] and inventories in other regions followed. Recent outcomes are an atlas of the 68 identified transboundary aquifers of the Americas[42] and an assessment report on transboundary rivers, lakes and aquifers that includes 51 transboundary aquifers in South-eastern Europe and 18 in the Caucasus and Central Asia region.[43] International projects are facilitating the exchange of information and experiences and developing improved methodologies and the scientific basis of transboundary aquifer management. A 2007 agreement created the UNESCO Regional Centre for Shared Aquifer Resources Management for Africa in Tripoli. The United Nations International Law Commission, in cooperation with the UNESCO-International Hydrological Programme, drafted articles on the Law on Transboundary Aquifers, which was subsequently approved by the UN General Assembly on 11 December 2008.

Challenges: hazards and opportunities

Based on identified trends, the future will see increased pressure on water resources and changes in the patterns and magnitudes of resource availability related to changing climate patterns. While climate change represents a huge challenge, it also represents an opportunity – for new growth, innovation in the management of water resources and development of a modern economy. Because humans have modified and adapted their lifestyles to the existing climate and its inherent variability, climate change is expected to affect most aspects of human life, notably through the hazardous aspects of water-related events. Some areas may gain greater access to water through increased precipitation, while others may have less or more variable water resources.

Over many generations the human race has shown an amazing ability to adapt and adjust to climate variability and increasing pressure on resources. There are many examples of countries that have managed their scarce resources efficiently and effectively, despite low rainfall and streamflows. Spain, a traditionally dry-climate country, has historically succeeded in managing its water resources through adaptation. An example of potential water gain is South Africa. Analysis of the actual evapotranspiration and yield of five commonly grown crops (beans, groundnuts, maize, millet and sorghum) in two selected districts found that yield increases with evapotranspiration, although the gap remains wide between actual and potential yield and actual and maximum evapotranspiration, especially for rainfed crops.[44] The analysis also showed that a 2°C rise in temperature and a doubling of carbon dioxide concentration in the atmosphere will shorten the growing period of maize, lowering crop water requirements.

The increased exposure to potential climate change hazards has raised awareness of critical issues related to water resources management that require solutions regardless of the impacts of climate change. The revision of management strategies in response to potential climate change threats therefore represents an opportunity to implement policies and practice that will lead to more sustainable use of resources. These could include improved observation networks (see chapter 13), increased integration of groundwater and surface water supplies (including artificial recharge), improved early warning and forecasting systems for hazardous events, improved risk-based approaches to management and the raising of community awareness of sustainable water resources use and individual responses to water-related hazards.

The threat of climate change has led to many developments in the simulation of atmospheric processes, improving the accuracy of climate and weather forecasts. Combined with improved technology for monitoring, collecting and analysing information, these developments should lead to improvements in warning systems for floods and droughts and other major water-related events. If these can be combined with hazard mitigation strategies involving all levels of affected communities, there are enormous opportunities to avoid loss of human life and economic losses.

There are also many specific examples of turning potential hazards into opportunities. These include using increased runoff from glacial melting to develop more reliable water supplies for larger areas and using flood water storage to increase the reliability of water supplies and improve floodplain management and planning (box 12.6).

Small and shallow alluvial aquifers scattered over the Earth's arid and semi-arid regions – preferential zones for human settlement – are probably the most vulnerable groundwater systems to climate change.[45] Yet in areas of increasing water stress groundwater is an important buffer resource, capable of responding to overall increased water demands or of compensating for loss in surface water availability.

This buffer capacity of groundwater systems depends on the ratio between the volume of stored groundwater and the mean annual recharge. Some major aquifers with non-renewable groundwater resources are found in arid environments of North and Southern Africa, the Arabian Peninsula and Australia and under permafrost in Northern Asia.[46] The direct impact of climate change on such resources is negligible, as their stored volumes are usually at least a thousand times the volume of mean annual recharge. Their stocks may be reduced more quickly than before, however, because of larger demands created by climate change and the decline of alternative water sources. Renewable groundwater systems with considerable storage will provide similar buffers in other parts of the world, and an increasingly larger share of total water abstraction is expected to come from groundwater.

The storage capacity of aquifers also offers opportunities for enhancing groundwater storage by artificial recharge or managed aquifer recharge. Managed aquifer recharge, applied at an ever-growing rate,[47] should be part of integrated water and catchment management strategies along with surface water and soil management, erosion and pollution control, demand and environmental management and wastewater reuse. Its role will become increasingly important as the impacts of climate change and variability become more apparent.[48]

Box 12.6 **Lake Sarez, Tajikistan – turning a hazard into an opportunity**

Lake Sarez, deep in the centre of the Pamir Mountains of Tajikistan, was created in February 1911, when an enormous rock collapsed from the bank of the Murgab River Valley, blocking the river and forming a dam behind which a lake formed. Lake Sarez is 55.8 kilometres long and averages 1.44 kilometres wide, with a maximum depth of 499.6 metres and maximum water volume of 16.074 cubic kilometres. The lake's water level is currently about 50 metres below the top of the dam and rising at a rate of 20 centimetres a year as a result of increased glacial melt, due largely to global warming. At the same time, the permeability of the dam material is changing, and the mineralization of water at the bottom levels is increasing. There is also a real threat of new landslides around the lake.

Multiple hypotheses were developed recently on how the natural barrier would behave in a future earthquake or other catastrophe. Evaluations varied from the categorical 'it will burst' to the no less firm 'it will not'.

While some sources stress that a catastrophic flood is unlikely, no one is dismissive of the risk considering the potential for devastation. A World Bank statement indicated that 'should such a flood occur, the impact on the downstream valleys would be devastating, affecting up to 5 million people'. The impact of a dam break would be felt not only across Tajikistan but also in Afghanistan, Turkmenistan and Uzbekistan.

Tajikistan recently proposed construction of a water pipeline that would serve all of Central Asia with safe drinking water through the regulated drainage of Lake Sarez. This would reduce the risk of a dam break or overflow, while supplying drinking water to the region. Lake Sarez is the largest freshwater reservoir in the upper watershed zone of the Aral Sea basin.

Source: Vefa Mustafaev, UNESCO; Sirodjidin Aslov, Ambassador of Tajikistan to the United Nations; and N. F. Gorelkin Uzbekistan Department of Hydrometerology; World Bank 2005.

Notes

1. Huntington 2006.
2. IPCC 2007.
3. For example, Williams, Jackson, and Kutzbach 2007.
4. IPCC 2007.
5. IPCC 2007.
6. IPCC 2001.
7. Milly et al. 2002.
8. Kundzewicz et al. 2005.
9. Zhang et al. 2007.
10. van Lanen, Tallaksen, and Rees 2007; Huntington 2006.
11. Hisdal et al. 2001.
12. Tallaksen, Demuth, and van Lanen 2007.
13. Easterling et al. 2007.
14. Dai, Trenberth, and Qian 2004.
15. Giordano and Villholth 2007.
16. Montgomery 2007.
17. Wilkinson and McElroy 2007.
18. Uri and Lewis 1999.
19. Hu et al. 2008.
20. Lal et al. 2004.
21. Montgomery 2007.
22. Walling 2006.
23. Walling and Fang 2003.
24. Vörösmarty et al. 2003.
25. Cruden 1991, p. 27.
26. IPL n.d.
27. IPCC 2007.
28. IPCC 2007.
29. Hillbricht-Ilkowska 1993.
30. Atkinson, DePinto, and Lam 1999.
31. Mimikou et al. 2000.
32. IPCC 2007.
33. Bates et al. 2008.
34. Meyer et al. 1999.
35. Fang and Stefan 1997.
36. Hostetler and Small 1999.
37. Schindler and Stainton 1996.
38. Romm 2007.
39. International Crisis Group 2007.
40. For details see www.isarm.net.
41. Almássy and Buzás 1999.
42. UNESCO/OAS ISARM 2007.
43. UNECE 2007.
44. World Bank 2007.

45. van der Gun forthcoming.
46. Foster and Loucks 2006.
47. UNESCO 2005; Fox 2007.
48. Gale 2005.

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