I would feel more optimistic about a bright future for man if he spent less time proving he can outwit Nature and more time tasting her sweetness and respecting her seniority.

E. B. White

CHAPTER 4

The State of the Resource

By

UNESCO
(United Nations Educational, Scientific and Cultural Organization)

WMO
(World Meteorological Organization)

IAEA
(International Atomic Energy Agency)

Top to bottom:
Perito Moreno Glacier, Argentina

Man collecting stagnant water for drinking, Uganda

Bus driving across flooded plateau in the Andes, Bolivia

Key messages:

Our water resources, irregularly distributed in space and time, are under pressure due to major population change and increased demand. Access to reliable data on the availability, quality and quantity of water, and its variability, form the necessary foundation for sound management of water resources. The different options for augmentation expand the boundaries of the water resource in a conventional sense, helping to match demand and supply. All components of the hydrological cycle, and the influence of human activities on it, need to be understood and quantified to efficiently and sustainably develop and protect our water resources.

- Climate change is having a significant impact on weather patterns, precipitation and the hydrological cycle, affecting surface water availability, as well as soil moisture and groundwater recharge.

- The growing uncertainty of surface water availability and increasing levels of water pollution and water diversions threaten to disrupt social and economic development in many areas as well as the health of ecosystems.

- Groundwater resources can, in many instances, supplement surface water, particularly as a source of drinking water. However, in many cases, these aquifers are being tapped at an unsustainable rate or affected by pollution. More attention should be paid to sustainable management of non-renewable groundwater.

- Many traditional practices are being refined (e.g. rainwater harvesting), while more recent advances (e.g. artificial recharge, desalination and water reuse) are being developed further. More support needs to be given to policy options, such as demand management, which stress more efficient use of water resources, as well as to technical solutions on the supply side.

- The projected increased variability in the availability and distribution of freshwater resources demands political commitment to supporting and advancing technology for the collection and analysis of hydrological data. More up-to-date information will enable policy-makers to make better informed decisions regarding water resources management.

Part 1. Global Hydrology and Water Resources

The need to develop more sustainable practices for the management and efficient use of water resources, as well as the need to protect the environmental ecosystems where these resources are located, has led to fundamental shifts in awareness and public concern over the past decade. However, despite increased awareness of the issues at stake, economic criteria and politically charged reasoning are still driving water resource development decisions at most local, regional, national and international levels. Though the long-term benefits of an integrated approach to achieving sustainable water resources development have been cited in many of the global water conferences over the past decade, considerable time and change in policy will be required to implement such an approach. At present, best available practice and scientific knowledge are rarely adequately factored into decision-making or well represented when establishing water resource policy or implementing management practices. In the meantime, the pressures on our water resources are increasing.

At present, best available practice and scientific knowledge are rarely adequately factored into decision-making

1a. The driving forces and pressures on our water resources

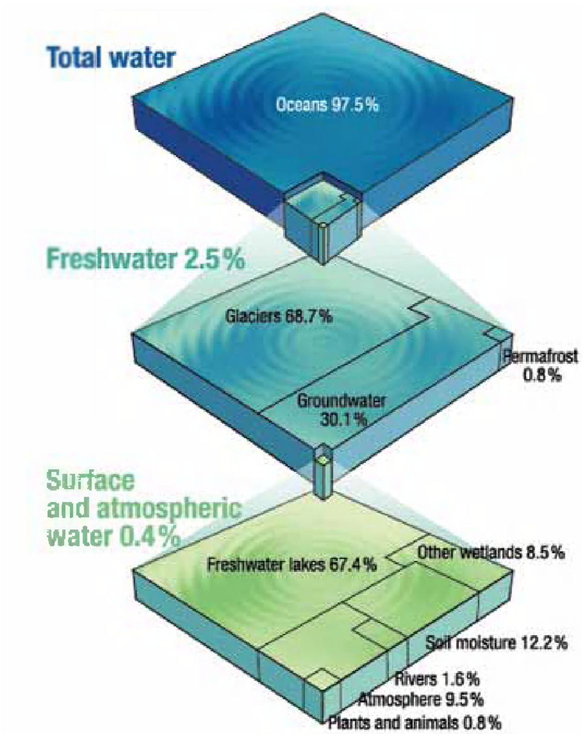
The combination of both naturally occurring conditions and humanity's actions creates pressure on our water resources. Climate change and natural variability in the distribution and occurrence of water are the natural driving forces that complicate the sustainable development of our water resources. Some of the main driving forces affecting water resources include:

- population growth, particularly in water-short regions
- major demographic changes as people move from rural to urban environments
- higher demands for food security and socio-economic well-being
- increased competition between users and usages
- pollution from industrial, municipal and agricultural sources.

While many issues remain on how to deal with and alleviate the pressures on our water resources, the progress being made in some sectors is worth noting. Natural units, such as river basins and aquifer systems, are becoming institutionally recognized: one example is the EU Water Framework Directive. Basin-oriented water resources assessment is increasingly being adopted by national and regional programmes and due consideration is given to the need to identify the critical volume and quality of water needed to maintain ecosystem resilience (environmental flows; see **Chapter 5**).

We are also seeing the emergence of highly detailed analyses of the processes involved as well as results-based diagnoses from catchment agencies, basin commissions and watershed and aquifer management authorities. These activities are being carried out globally in a variety of different economic and cultural settings and at different sizes and scales. Most of these organizations were created relatively recently for

Figure 4.1: Global distribution of the world's water



Source: Data from Shiklomanov and Rodda, 2003. Freshwater has a global volume of 35.2 million cubic kilometres (km^3).

jurisdictions that correspond to physical hydrological limits rather than historically defined administrative boundaries (Blomquist et al., 2005; WWF, 2003). Moving away from historically administrative boundaries to a consideration of water resources management practice based on physical hydrological limits allows us to better respond to nature's variability.

To better combat flooding, the Associated Programme of Flood Management (APFM), a WMO and GWP joint effort as well as UNESCO's International Flood Initiative (IFI) outline new approaches that are being developed for a better understanding of the links between natural settings and the legal, environmental and social conditions inherent to flooding and the mitigation of its impacts. In this way, communities commonly faced with flooding can now develop more sustainable methods to reduce the socio-economic effects of such high-impact events (see **Chapter 10**).

Further illustrations of emerging progress on countering the pressures on water resources are highlighted in **Chapters 6** through **13** and in some of the case study examples cited in **Chapter 14**.

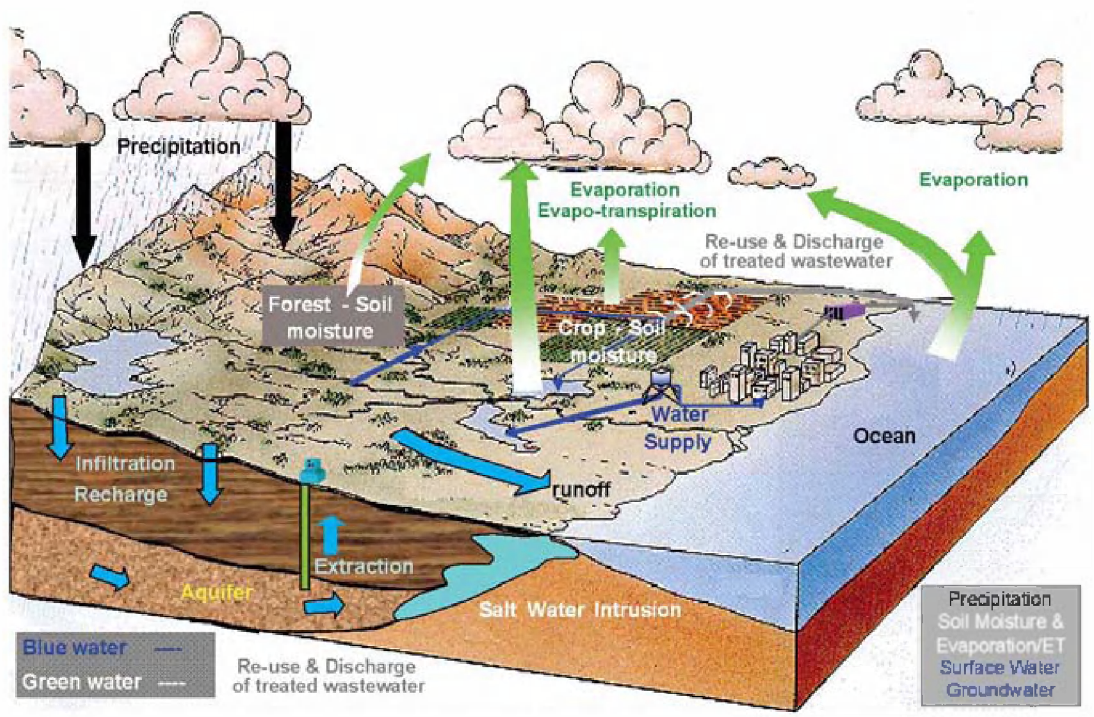
Ecohydrology stresses the important relationships and pathways shared among hydrological and ecological systems

1b. Water's global occurrence and distribution

The world's water exists naturally in different forms and locations: in the air, on the surface, below the ground and in the oceans (**Figure 4.1**).

Although a large volume of freshwater exists 'in storage', it is more important to evaluate the renewable annual water flows, taking into account where and how they move through/ the hydrological cycle (**Figure 4.2**). This schematic of the hydrological cycle illustrates how elements can be grouped as part of a conceptual model that has emerged from the new discipline of ecohydrology, which stresses the important relationships and pathways shared among hydrological and ecological systems (Zalewski et al., 1997). This conceptual model takes into consideration the detail of the fluxes of all waters and their pathways while differentiating between two components: 'blue water' and 'green water'. Blue waters are directly associated with aquatic ecosystems and flow in surface water bodies and aquifers. Green water is what supplies terrestrial ecosystems and rain-fed crops from the soil moisture zone, and it is green water that evaporates from plants and water surfaces into the

Figure 4.2: Schematic of the hydrologic cycle components in present-day setting



atmosphere as water vapour. This concept was developed by Falkenmark and Rockström (2004) who contend that the introduction of the concepts of 'green water'and 'blue water', to the extent that they simplify the discussion for non-technical policy-makers and planners, may help to focus attention and resources on the often neglected areas of rain-fed agriculture, grazing, grassland, forest and wetland areas of terrestrial ecosystems and landscape management.

Part 2. Nature, Variability and Availability

A young child plays in the monsoon rain in Thailand

The Earth's hydrological cycle is the global mechanism that transfers water from the oceans to the surface and from the surface, or subsurface environments, and plants to the atmosphere that surrounds our planet. The principal natural component processes of the hydrological cycle are: precipitation, infiltration, runoff, evaporation and transpiration. Human activities (settlements, industry, and agricultural developments) can disturb the components of the natural cycle through land use diversions and the use, reuse and discharge of wastes into the natural surface water and groundwater pathways.

2a. Precipitation

The Earth's atmosphere contains approximately 13,000 km^3 of water. This represents 10 percent of the world's freshwater resources not found in groundwater, icecaps or permafrost (**Figure 4.1**). This is similar to the volumes found in soil moisture and wetlands. However, of more importance is the fact that this vapour cycles in the atmosphere in a 'global dynamic envelope', which has a substantive annually recurring volume, estimated to be from 113,500 to 120,000 km^3 (Shiklomanov and Rodda, 2003; FAO-AQUASTAT, 2003). Precipitation occurs as rain, snow, sleet, hail, frost or dew. These large volumes illustrate precipitation's key role in renewing our natural water resources, particularly those used to supply natural ecosystems and rainfed crops. About 40 percent of the precipitation that falls on land comes from ocean-derived vapour. The remaining 60 percent comes from land-based sources. It is particularly pertinent to recognize that snowfall can contribute a large percentage of a region's total precipitation in temperate and cold climate regions. For example, in the western US, Canada and Europe, 40 to 75 percent of regional precipitation can occur as snow.

The International Panel on Climate Change (IPCC) has published the international reference for each country's average annual precipitation, based on the period of record from 1961 to 1990 (New et al., 1999; Mitchell et al., 2002). Countries' precipitation ranges from 100 mm/yr in arid, desert-like climates to over 3,400 mm/yr in tropical and highly mountainous terrains. Together with temperature, they define the significant variables in global climatic and ecosystem biodiversity settings. This long-term record base determines averages and defines predictable variability both in time (monthly, annually, seasonally) and place (nations, monitoring locations). This record is significant as its 30-year standard is commonly compared with actual annual amounts to define the relative current variability, frequently tied to regional and global evaluations of drought and climate change.

It is essential to understand the pathways of water as it arrives in the form of precipitation and migrates through the cycle components

It is essential to water resources development to understand the pathways of water as it arrives in the form of precipitation and migrates through the cycle components. **Table 4.1** illustrates how precipitation, in three relatively diverse climatic zones, generally either returns by evaporation or evapotranspiration back into the atmosphere, becomes surface water through runoff, or recharges groundwater.

Mapping precipitation's isotopic composition ($_3H$, $_{18}O$ and $_2H$) can help trace water movement through the water cycle components. This is routinely done as part of the Global Network of Isotopes in Precipitation (GNIP),[1] operated jointly by IAEA and WMO at 153 stations in 53 nations. IAEA has initiated several projects to study and distinguish among moisture sources and to better understand the cycle transport patterns using applied isotope techniques. Particular case studies have been carried out in India (Bhattacharya et al., 2003), Southeast Asia (Aggarwal et al., 2004) and with twenty-one research groups participating globally to monitor many other major rivers (**Figure 4.3**). This approach is of further significance as it assists in the evaluation of the hydrological cycle's response to climatic fluctuations and

1. See isohis.iaea.org for more information.

Table 4.1: Precipitation distribution into surface water and groundwater components (by climate region)

	Temperate climate		Semi-arid climate		Arid climate	
	%	mm	%	mm	%	mm
Total precipitation	100	500–1,500	100	200–500	100	0–200
Evaporation/ Evapotranspiration	~ 33	160–500	~ 50	100–250	~ 70	0–140
Groundwater recharge	~ 33	160–500	~ 20	40–100	~ 1	0–2
Surface runoff	~ 33	160–500	~ 30	60–150	~ 29	0–60

Source: Hydrogeology Center, University Neuchâtel, 2003.

can be used to calibrate and validate atmospheric circulation models used in climate change studies.

2b. Evapotranspiration and soil moisture

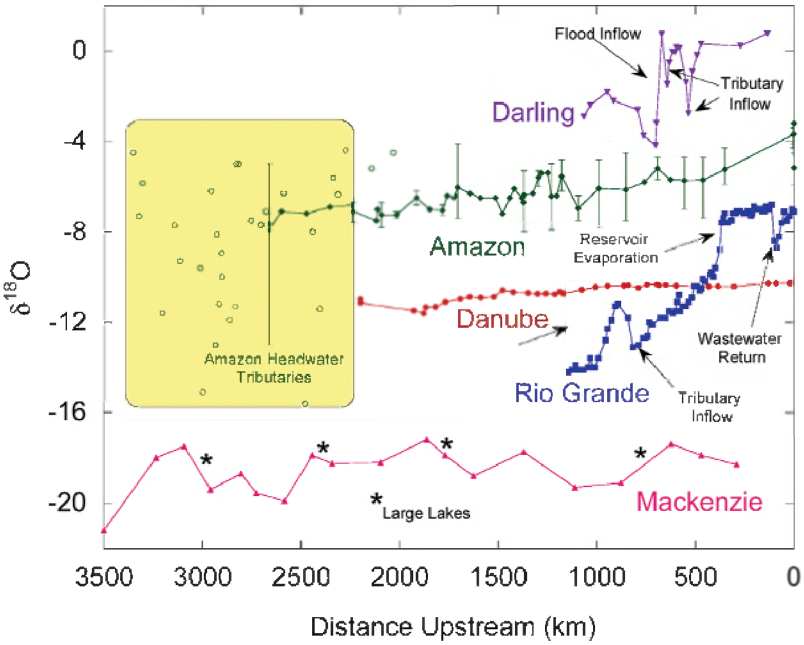
The processes of evaporation and transpiration (evapotranspiration) are closely linked to the water found in soil moisture; these processes act as driving forces on water transferred in the hydrological cycle. Movement through soil and vegetation is large and accounts for 62 percent of annual globally renewable freshwater. Evapotranspiration rates depend on many locally specific parameters and variables that are difficult to measure and require demanding analyses in order to calculate an acceptable level of accuracy. Other hydrological, cycle-related and meteorological data are also considered in the estimation of the rates. Today, however, local water management in basins or sub-basins can better calculate transpiration rates.

Evaporation from surface water bodies such as lakes, rivers, wetlands and reservoirs is also an important component of the hydrological cycle and integral to basin development and regional water management. In the case of artificially-created reservoirs, it has been estimated by Rekacewicz (2002) that the global volumes evaporating since the end of the 1960s have exceeded the volume consumed to meet both domestic and industrial needs.

From the standpoint of food production and ecosystem maintenance, soil moisture is the most important parameter to net primary productivity (NPP) and to the structure, composition and density of vegetation patterns (WMO, 2004). Near-surface soil moisture content strongly influences whether precipitation and irrigation waters either run off to surface water bodies or infiltrate into the soil column. Regionally, mapping soil moisture deficit is becoming a widely used technique to link climatological and hydrological information in agriculture (e.g. Illinois, US) and to reflect drought conditions (US Drought Mitigation Center, 2004). Soil moisture distribution is now identified as a prerequisite for effective river-flow forecasting, irrigation system maintenance, and soil conservation (Haider et al., 2004). Its distribution in time and place are now viewed as essential to hydrological, ecological and climatic models – both at the regional and global level (US NRC, 2000).

The Global Soil Moisture Data Bank (Robock and Vinnikov, 2005; Robock et al, 2000) archives contain data sets of national soil moisture records but the data sets are incomplete in terms of global coverage.

Figure 4.3: Oxygen-18 content of stream water along the main stem of large rivers



Note: Surveys of oxygen-18 along the main stem of large rivers, such as Darling, Amazon, Danube, Rio Grande and Mackenzie show the contribution and mixing of runoff sources to rivers, such as tributaries, irrigation water and wastewater. Isotopes also reflect impacts of climate and land use pattern changes on the water balance such as an evaporative enrichment of river water in arid regions.

Source: IAEA, 2002.

Satellite data can provide broader coverage with current results that can be more closely representative when combined with ground validation. From 2002, NASA's climate-monitoring 'Aqua' satellite has daily records of 50 to 60 km resolution data, readily obtained from NOAA (Njoku, 2004; Njoku et al., 2004). From 2010, the 'Hydros' satellite will exclusively monitor daily soil moisture changes around the globe with an improved spatial resolution of 3 to 10 km (Entekhabi et al., 2004; Jackson, 2004). This will be an important upgrade for remotely-sensed soil moisture data, which are becoming increasingly relied upon by agricultural marketing and administrative boards, commodity brokers, large-scale farms, flood- and drought-monitoring and forecasting agencies, water resources planning and soil conservation authorities and hydroelectric utility companies.

2c. Snow and ice

About three-quarters of the world's entire natural freshwater is contained within ice sheets and glaciers. However, most (97 percent) is not considered as a water resource as it is inaccessible, located in the Antarctic, Arctic and Greenland ice sheets. However, land-based glaciers and permanent snow and ice – found on all continents except Australia – cover approximately 680,000 km^2 and are critical to many nations' water resources. Even in situations where ice covers only a small percent of a basin's upland mountainous terrain (e.g. in the Himalayas, Rockies, Urals, Alps, Andes), glaciers can supply water resources to distant lowland regions. Thus, glacial ice and snow represents a highly valuable natural water reservoir. Typically it affects stream-flow quantity in terms of time and volume since glaciers temporarily store water as snow and ice and release runoff on many different time scales (Jansson et al., 2003; Hock et al., 2005). Glacial runoff characteristically varies with daily flow cycles that are melt-induced and seasonal since concentrated annual runoff occurs in summer when the water stored as snow in winter is released as stream flow. The seasonal runoff benefits occur principally in nations in the mid- and high latitudes where there are otherwise only periods of low flow, but benefits also occur in many semi-arid regions. Glaciers can also affect long-term annual water availability since runoff either increases or decreases as their mass balance decreases or increases, respectively. Finally, glaciers tend to act as stream-flow regulators that can minimize year-to-year variability when catchment areas are moderately (10 to 40 percent) glaciated. Runoff variability rises as glaciated percentage both increases and decreases. Glacier conditions are now monitored globally since climate change is affecting their size and mass balance.

2d. Surface waters

Surface waters include the lakes (as well as ponds), reservoirs, rivers and streams and wetlands our societies have depended upon and benefited from throughout history. The flow into and through these surface water bodies comes from rainfall, runoff from melting snow and ice and as base-flow from groundwater systems. While surface waters volumetrically hold only a small volume (0.3 percent) of the Earth's total freshwater resources, they represent about 80 percent of the annually renewable surface and groundwater. Ecosystem services from surface waters are widespread and diverse as well as being of critical importance. Reservoirs and large lakes effectively counteract high seasonal variability in runoff by providing longer-term storage. Other services supported by surface waters include shipping and transport, irrigation, recreation, fishing, drinking water and hydropower.

Lakes

Meybeck (1995), Shiklomanov and Rodda (2003) and most recently Lehner and Döll (2004) have provided extensive data characterizing the world's lakes on a global scale. Lakes store the largest volume of fresh surface waters (90,000 km^3) – over forty times more than is found in rivers or streams and about seven times more than is found in wetland areas. Together with reservoirs, they are estimated to cover a total area of about 2.7 million km^2, which represents 2 percent of the land's surface (excluding polar regions) (Lehner and Döll, 2004). Most lakes are small. The world's 145 largest lakes are estimated to contain over 95 percent of all lake freshwater. Lake Baikal (Russia) is the world's largest, deepest and oldest lake and it alone contains 27 percent of the freshwater contained in all the world's lakes. Lake waters serve commerce, fishing, recreation, and transport and supply water for much of the world's population. However, detailed hydrological studies have been conducted on only 60 percent of the world's largest lakes (Shiklomanov and Rodda, 2003). LakeNet[2] is one example of an organization working with local and regional governments, NGOs and IGOs in over 100 countries in order to address this knowledge deficit, to tackle degrading conditions, and to develop lake basin management programmes that include important protection strategies. Recently, a global database of

Glacier conditions are now monitored globally since climate change is affecting their size and mass balance

Torre del Paine, Chile. Glacial ice and snow represent a highly valuable natural water reservoir

2. See www.worldlakes.org for more information.

...the world's total runoff is unevenly distributed throughout the year for most regions of the globe...

lakes, reservoirs and wetlands (GLWD) has been created and validated at the Center for Environmental Systems Research, University of Kassel (CESR, Germany) in cooperation with the World Wildlife Fund (WWF) (Lehner and Döll, 2004). The primarily digital map-based approach, complete with fully downloadable data, facilitates the linking of existing local and regional registers and remotely sensed data with the new inventory. As such, it is an important achievement related to global hydrological and climatological models.

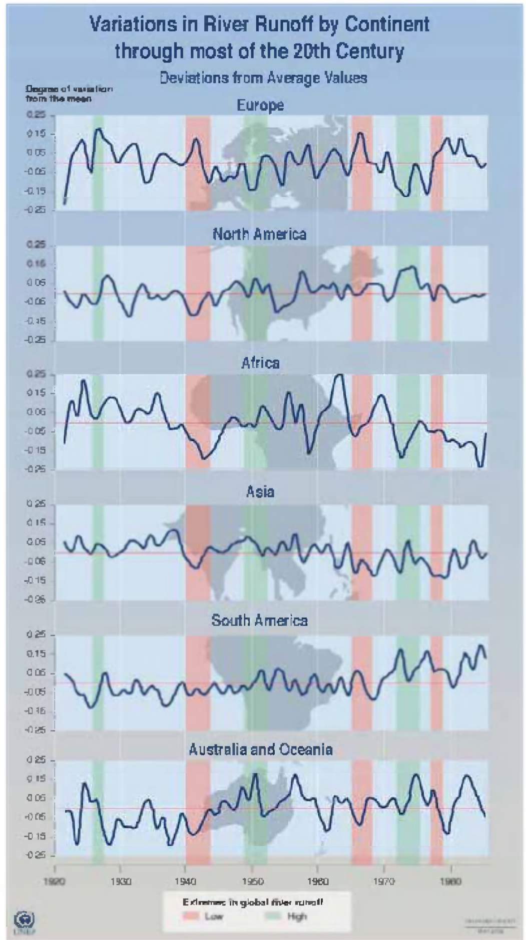
Rivers and streams

An estimated 263 international river basins have drainage areas that cover about 45 percent (231 million km^2) of the Earth's land surface (excluding polar regions) (Wolf et al., 1999, 2002). The world's twenty largest river basins have catchment areas ranging from 1 to 6 million km^2 and are found on all continents. The total volume of water stored in rivers and streams is estimated at about 2,120 km^3. The Amazon carries 15 percent of all the water returning to the world's oceans, while the Congo-Zaire basin carries 33 percent of the river flow in Africa (Shiklomanov and Rodda, 2003).[3]

Variability in runoff is depicted by river/stream flow vis-à-vis time graphs (hydrographs). In terms of variability, **Figure 4.4** (Digout, 2002) illustrates the three low and three high runoff periods that were experienced in the twentieth century by documenting the natural fluctuations in river runoff in terms of both time and place. These types of periodic variations are not particularly predictable as they occur with irregular frequency and duration. In contrast, we are commonly able to predict runoff variability on an annual and seasonal basis from long-term measurement records in many river locations. River-flow graphs representative of the principal climatic regions are illustrated in **Figure 4.5** (Stahl and Hisdal, 2004). Shown together with monthly precipitation and evaporation, they portray the annual variability that is relatively predictable and similar according to principal climatic regions of the world. From this climatic zone perspective, tropical regions typically exhibit greater river runoff volumes while arid and semi-arid regions, which make up an estimated 40 percent of the world's land area, have only 2 percent of the total runoff volume (Gleick, 1993).

Monitoring networks for river flow and water levels in rivers, reservoirs and lakes, supplemented by estimates for regions where there is no extensive monitoring, help understand runoff and evaluate how to predict its

Figure 4.4: Variations in continental river runoff through most of the twentieth century (deviations from average values)

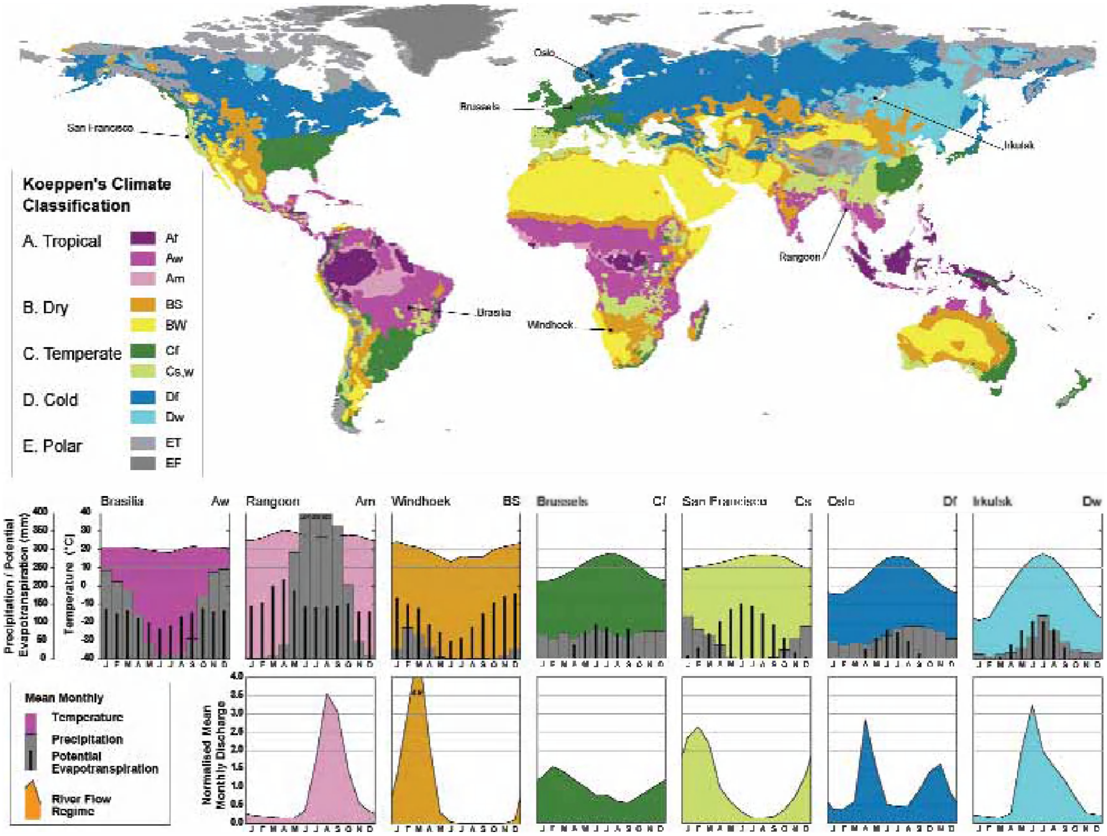


Source: Digout, 2002; UNEP/GRID Arendal; Shiklomanov, 1999.

variability. Measurement networks are relatively common in many developed populated areas. Most of the world's major contributing drainage areas have relatively adequate monitoring networks in place. The Global Runoff Data Center (GRDC, Koblenz, Germany), under WMO's auspices, routinely acquires, stores, freely distributes and reports on river discharge data from a network of 7,222 stations, about 4,750 of which have daily and 5,580 of which have monthly data (GRDC, 2005; **Map 4.1**). Other international programmes such as the European Water Archive (Rees and Demuth, 2000) and national data centres supplement this (data from private institutions are not included). The longer the flow record, the better we can predict variability in runoff – input that is especially important in the context of flood forecasting, hydropower generation and climate change studies. The quality and adequacy of data records for runoff vary tremendously. While some

3. Statistics related to the world's river systems (length, basin area, discharge, principal tributaries and cities served) are currently updated online at www.rev.net/~aloe/river/, as part of an open source physical sciences information gateway (PSIGate).

Figure 4.5: Typical hydrographs in accordance with climatic settings



Note: For tropical climates close to the equator (Af), perennial rivers flow all year. Towards the north and south the tropical climates have a distinct rainy season and a dry season (Am and Aw). In dry climates (B) rivers are often ephemeral and only flow periodically after a storm. In the temperate Cf climate, there is no distinct dry or wet season, whereas the 'Mediterranean climate' (Cs) has a pronounced seasonal water deficit in the summer and a rainy winter reflected in the hydrograph. The cold climates (D) have a distinct snowmelt runoff peak and the Df climate has an additional peak in the autumn caused by rain.

Source: Stahl and Hisdal 2004.

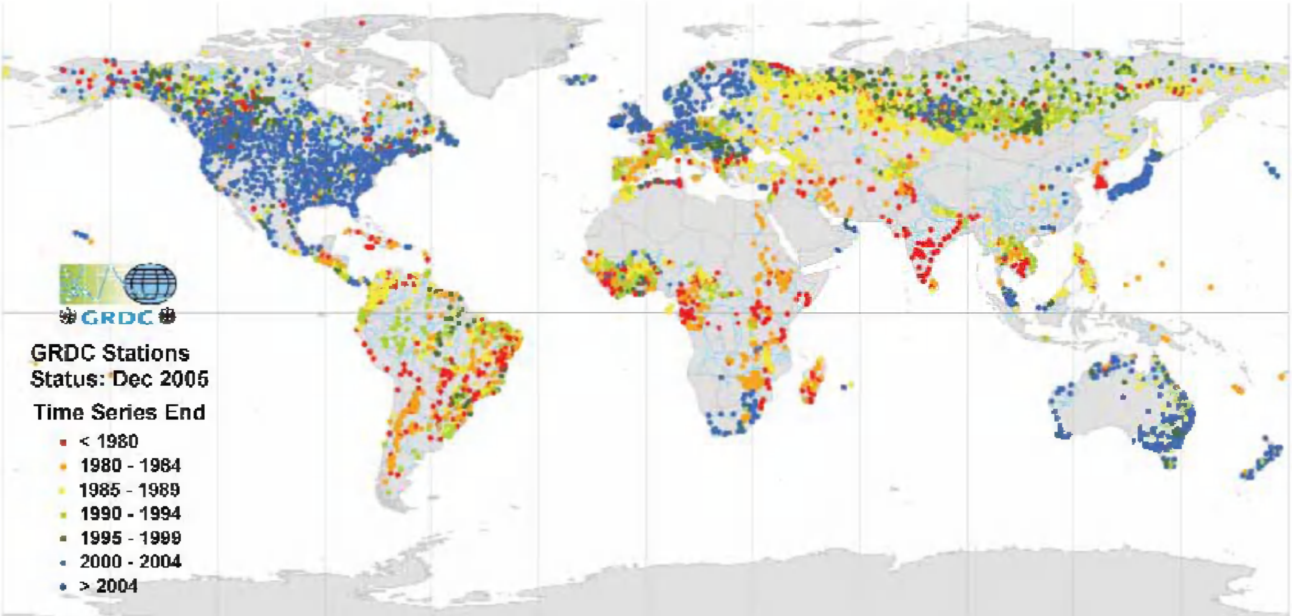
records extend back 200 years in Europe and 100 to 150 years on other continents, in many developing nations the data record is generally of insufficient length and quality to carry out either reliable water resources assessments or cost-effective project designs. As a result, for these regions, data is rarely compiled or distributed effectively on a global scale (WMO, 2005).

2e. Wetlands

Wetlands are water-saturated environments and are commonly characterized as swamps, bogs, marshes, mires and lagoons. Wetlands cover an area about four times greater than the world's lakes. However, they contain only 10 percent of the water found in lakes and other surface waters. During the last century, an extensive number of wetlands were destroyed or converted to other forms of land-use. The role they play in terms of ecosystems and water services are more fully described in **Chapter 5**. However, because they total about 6 percent of the Earth's land surface (OECD, 1996), they are critical areas to consider and protect in terms of surface water and, in some regions, groundwater resources. Currently, extensive work is being done through the 'Wise Use' campaigns sponsored principally by Ramsar, WWF and UNEP. These campaigns seek to maintain critical services in water and related livelihood and food production areas. An important new study on variability in the role of wetlands was carried out by Bullock and Acreman (2003), wherein they assess the differences in wetland water quantity functions based on 169 worldwide studies conducted from 1930 to 2002. They believe this new review 'provides the first step towards a more scientifically defensible functional assessment system (of wetlands)' and establishes 'a benchmark for the aggregated knowledge of wetland influences upon downstream river flows and aquifers'. They conclude that

Everglades National Park, United States, is 1 of the 1,558 wetland sites currently protected under the Ramsar Convention

Map 4.1: Distribution of GRDC water measurement stations, March 2005



'there is only limited support to the generalized model of flood control, recharge promotion and flow maintenance portrayed throughout the 1990s as one component of the basis of wetland policy formulation', noting that support is confined largely to floodplain wetlands. They also note that: 'Less recognized are the many examples where wetlands increase floods, act as a barrier to recharge or reduce low flows' and that 'generalized and simplified statements of wetland function are discouraged because they demonstrably have little practical value'. Overall they conclude that wetlands cannot be considered to have the same role in every hydrological setting. They recommend that future water management actions for both basins and aquifers carefully evaluate each wetland's characteristics as they will exhibit different performance and functional roles according to their location in the watershed, their climate, and the extent of other development features.

2f. Groundwater

Global groundwater volume stored beneath the Earth's surface represents 96 percent of the Earth's unfrozen freshwater (Shiklomanov and Rodda, 2003). Groundwater provides useful functions and services to humans and the environment. It feeds springs and streams, supports wetlands, maintains land surface stability in areas of unstable ground, and acts as an overall critical water resource serving our water needs.

UNESCO and WMO support the International Groundwater Resources Assessment Centre (IGRAC, hosted in Utrecht, The Netherlands). IGRAC estimates that about 60 percent of withdrawn groundwater is used to support agriculture in arid and semi-arid climates. Morris et al. (2003) report that groundwater systems globally provide 25 to 40 percent of the world's drinking water. Today, half the world's megacities and hundreds of other major cities on all continents rely upon or make significant use of groundwater. Small towns and rural communities particularly rely on it for domestic supplies. Even where groundwater provides lower percentages of total water used, it still can serve local areas with relatively low-cost good-quality water where no other accessible supply exists. Finally, groundwater can bridge water supply gaps during long dry seasons and during droughts.

Occurrence and renewability

Recent, globally focused groundwater publications (Zekster and Everett, UNESCO Groundwater Series, 2004; UNEP, 2003), point out that large variations in groundwater exist in terms of occurrence, rate of renewal and volumes stored in different types of aquifers. Geological characteristics are also an important factor. While shallow basement aquifers contain limited storage, large volumes of groundwater are stored in thick sedimentary basins. Aquifers in folded mountain zones tend to be fragmented, while volcanic rock environments have unique hydraulic conditions. Shallow aquifer systems have near-surface water tables that are strongly linked to and interchange with surface water bodies. **Map 4.2** illustrates the thirty-six Global Groundwater Regions identified by IGRAC (2004), which compares predominant hydrogeological environments found around the world. The UNESCO-led World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) also contributes to mapping aquifer systems, collecting and disseminating information related to groundwater at a global scale (see **Chapter 13**).

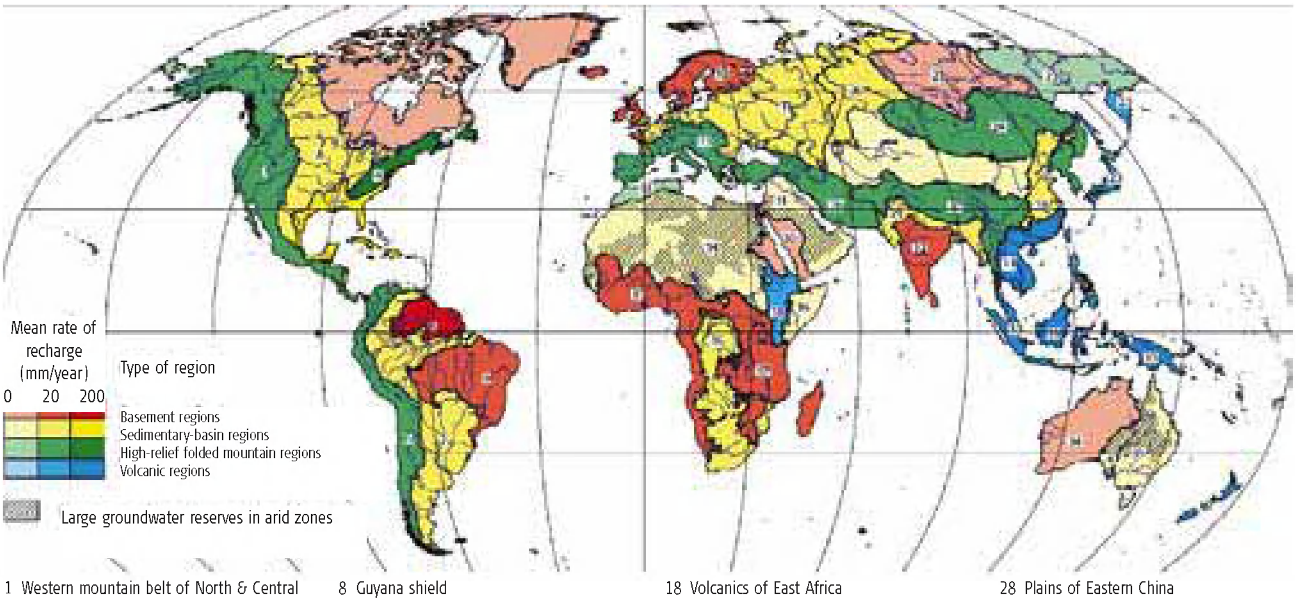
Groundwater, as a potential resource, can be characterized by two main variables: its rate of renewal and its volume in storage. Much of groundwater is derived from recharge events that occurred during past climatic conditions and is referred to as 'non-renewable groundwater' (IAEA). The actual recharge of these aquifer systems is negligible. The world's largest non-renewable groundwater systems (**Table 4.2**) are located in arid locations of Northern Africa, the Arabian Peninsula and Australia, as well as under permafrost in Western Siberia. Their exploitation will result in a reduction in stored volumes. A debate has arisen about how and when to use these groundwater resources as sustainable groundwater development is understood as 'exploitation under conditions of dynamic equilibrium leaving reserves undiminished'. However, nations may decide that the exploitation of such reserves is justified where undesired side-effects would not be produced (Abderrahman, 2003). UNESCO and the World Bank have jointly prepared the publication *Non-renewable groundwater resources, a guidebook on socially-sustainable management for policy makers* (forthcoming, 2006).

Transboundary groundwater

In terms of shared water resources, groundwater does not respect administrative boundaries. Most of the large non-renewable reserves in **Table 4.2** are shared. However, in addition to these aquifer systems, there are numerous smaller renewable transboundary aquifers located worldwide. Attention to shared groundwater resources management is increasing with strong support from

Groundwater, as a potential resource, can be characterized by two main variables: its rate of renewal and its volume in storage

Map 4.2: Global groundwater regions: predominant mode of groundwater occurrence and mean rate of renewal



1 Western mountain belt of North & Central America
2 Central plains of North & Central America
3 Canadian shield
4 Appalachian highlands
5 Caribbean islands and costal plains of North & Central America
6 Andean belt
7 Lowlands of South America
8 Guyana shield
9 Brazillian shield and associated basins
10 Baltic and Celtic shields
11 Lowlands of Europe
12 Mountains of Central & Southern Europe
13 Atlas Mountains
14 Saharan basins
15 West African basement
16 Subsaharan basins
17 East African basement & Madagascar
18 Volcanics of East Africa
19 Horn of Africa basins
20 West Siberian platform
21 Central Siberian plateau
22 East Siberian highlands
23 Northwestern Pacific margin
24 Mountain belt of Central & Eastern Asia
25 Basins of West & Central Asia
26 Mountain belt of West Asia
27 Himalayas & associated highlands
28 Plains of Eastern China
29 Indo-Gangelic-Brahmaputra Plain
30 Nubian & Arabian shields
31 Levant & Arabian platform
32 Peninsular India & Sri Lanka
33 Peninsulars & islands of South-East Asia
34 Western Australia
35 Eastern Australia
36 Islands of the Pacific

Note: Small-scale world map showing 36 Global Groundwater Regions depicting predominant hydrogeological setting (Basement (red), Sedimentary Basin (yellow), High-Relief Folded Mountain (green) and Volcanic (blue). Higher groundwater renewal rates, as averaged over each of the mentioned Global Groundwater Regions, are reflected in the figure by higher colour intensities. The hatched zones depict areas of limited groundwater renewal that contain extensive (non-renewable) groundwater reserves which were created in the past.

Source: IGRAC, 2004.

Most renewable groundwater is of a high quality, is adequate for domestic use, irrigation and other uses, and does not require treatment

Table 4.2: Selected large aquifer systems with non-renewable groundwater resources

Countries	Aquifer system	Area (km^2)	Estimated total volume (km^3)	Estimated exploitable volume (km^3)	Estimated annual recharge (km^3)	Estimated annual abstraction (km^3)
Egypt, Libya, Sudan, Chad	Nubian Sandstone Aquifer System	2,200,000	150,000 to 457,000	> 6,500	13	1.6
Algeria, Libya, Tunisia	NW Sahara Aquifer System	1,000,000	60,000	1,280	14	2.5
Algeria, Libya, Niger	Murzuk Basin	450,000	> 4,800	> 60 to 80	n.a.	1.75
Mali, Niger, Nigeria	Iullemeden Aquifer System	500,000	10,000 to 15,000	250 to 550	50 to 80	n.a.
Niger, Nigeria, Chad, Cameroon	Chad Basin Aquifer	600,000	n.a.	>170 to 350	n.a.	n.a.
S.Arabia, UAR, Bahrain, Qatar	Multilayer Aquifer Arabian Platform	250,000	n.a.	500?	30	13.9
Australia	Great Artesian Basin	1,700,000	20,000	170	50	0.6
Russia	West Siberian Artesian Basin	3,200,000	1,000,000	n.a.	55	n.a.

Source: Jean Margat, personal communication, 2004.
(Adapted from the UNESCO Working Group on Non-Renewable Groundwater Resources, 2004).

several international organizations that are addressing sustainable management strategies which would enable shared socio-economic development of such aquifers. At present, the UNESCO Internationally Shared Aquifer Resources Management (ISARM) project is compiling an inventory of transboundary aquifers.

Natural groundwater quality

Most renewable groundwater is of a high quality, is adequate for domestic use, irrigation and other uses, and does not require treatment. However, it should be noted that uncontrolled development of groundwater resources, without analysis of the chemical and biological content, is an unacceptable practice that can (as in the example of fluoride and arsenic problems in Southeast Asia) lead to serious health problems. Some waters have beneficial uses owing to naturally high temperatures and levels of minerals and gas. This is the case for thermal waters where these properties have been created by high geothermal gradients, volcanic settings or natural radioactive decay. In most cases, these groundwaters are highly developed and used for health and recreation (spa) and geothermal energy services.

Groundwater monitoring networks

Groundwater monitoring networks, as with surface water systems, operate differently at national, regional and local levels. Groundwater levels constitute the most observed parameter, whereas widespread and continuous water quality and natural groundwater discharge and abstraction networks are operational in only a few countries (Jousma and Roelofson, 2003). Several large-scale efforts are underway to upgrade monitoring and networks, for example, in Europe (Proposal for new Directive on Groundwater Protection [EC 2003] and in India [World Bank, 2005]). However, groundwater assessment, monitoring and data management activities are for the most part minimal or ineffective in many developing countries and are being downsized and reduced in many developed counties (see **Chapter 13**). Lack of data and institutional capacity is endemic, making adequate groundwater development and management difficult. GEMS/Water (a UNEP programme) is currently adding national groundwater data to its international water quality database (described in Part 3). This will supplement the current global knowledge of groundwater quality information collected and displayed by IGRAC on its website, which includes special reports on both arsenic and fluorides in groundwater (IGRAC, 2005a, 2005b).

2g. Water availability

Efforts to characterize the volume of water available to a given nation have been ongoing for several decades. The primary input for many of these estimates is an information database (AQUASTAT) that has historically been developed and maintained by FAO. It is based on data related to the quantity of water resources and uses a water-balance approach for each nation (FAO, 2003a). This database has become a common reference tool used to estimate each nation's renewable water resources. FAO has compiled an Index of Total Actual Renewable Water Resources (TARWR). The details of how the TARWR Index and its national Per Capita Equivalent of 'Availability' (PCA) are determined and some of the considerations that should be taken into account when using the database index are explained in **Box 4.1**. The TARWR and PCA results for most nations from the latest 2005 update of the FAO AQUASTAT database are found in **Table 4.3**.

BOX 4.1: INDEX OF WATER RESOURCES AVAILABILITY – TOTAL ACTUAL RENEWABLE WATER RESOURCES (TARWR)

Total Actual Renewable Water Resources (TARWR) is an index that reflects the water resources theoretically available for development from all sources within a country. It is a calculated volume expressed in km^3/year. Divided by the nation's population and adjusted to m^3/yr, it is expressed as a per capita volume more readily allowing a relative evaluation of the resource available to its inhabitants. It estimates the total available water resources per person in each nation taking into account a number of individual component indicators by:

- adding all internally generated surface water annual runoff and groundwater recharge derived from precipitation falling within the nation's boundaries,
- adding external flow entering from other nations which contributes to both surface water and groundwater,
- subtracting any potential resource volumes shared by the same water which comes from surface and groundwater system interactions, and
- subtracting, where one or more treaty exists, any flow volume required by that treaty to leave the country.

It gives the maximum theoretical amount of water actually available for the country on a per capita basis. Beginning in about 1989, TARWR has been used to make evaluations of water scarcity and water stress.

Considerations related to availability in the TARWR index

It is important to note that the FAO estimates are maximum theoretical volumes of water renewed annually as surface water runoff and groundwater recharge, taking into consideration what is shared in both the surface and groundwater settings. These volumes, however, do not factor in the socio-economic criteria that are potentially and differentially applied by societies, nations or regions to develop those resources. Costs can vary considerably when developing different water sources. Therefore, whatever the reported 'actual' renewable volume of water, it is a theoretical maximum, and the extent to which it can be developed will be less for a variety of economic and technical reasons. For example, Falkenmark and Rockstrom (2004) point out that, globally, approximately 27 percent of the world's surface water runoff occurs as floods. That is not considered a usable water resource even though it would be counted as part of the annual renewable surface water runoff component of TARWR. Therefore, the usable volumes available as resources to meet societal demands will be considerably less than the maximum number given as a nation's TARWR.

Four additional limitations are inherent in the TARWR information. First, seasonal variability in precipitation, runoff and recharge, which is important to regional and basin-level decision making and water storage strategies, is not well reflected in annualized quantities. Second, many large countries have several climatic settings as well as highly disparate population concentrations and the TARWR does not reflect the ranges that can occur within nations. The recently developed small-scale Relative Stress Index Map (Vörösmarty) could assist in overcoming this oversight. Third, there is no data in TARWR that identifies the volumes of 'green' water that sustain ecosystems – the volumes that provide water resources for direct rain-fed agriculture, grazing, grasslands and forests – nor does it account for the volumes of water that are potentially available from non-conventional sources (reuse, desalination, non-renewable groundwater). Finally, while the accounting-based method for a nation's TARWR adds all water that enters from upstream countries, it does not subtract any part of the water that leaves the nation in the TARWR number although estimates of those volumes are available for each country from the database.

Source: FAO, 2003a; FAO-AQUASTAT, 2005.

Table 4.3: Water availability information by country (AQUASTAT, FAO 2005)

Country	Population (1,000,000s)	Precip Rate[1] (mm/yr)	TARWR Volume 2005 (km^2/yr)	TARWR Per Capita 2000 (m^3/yr)	TARWR Per Capita 2005 (m^3/yr)	Surface water % TARWR	Ground-water % TARWR	Overlap[2] % TARWR	Incoming Waters % TARWR	Outgoing[3] Waters % TARWR	Total Use % TARWR
1 Afghanistan	24,926	300	65	2,986	2,610				15%	77%	36%
2 Albania	3,194	1,000	42	13,306	13,060	55%	15%	6%	35%	0%	4%
3 Algeria	32,339	100	14	478	440	12%	92%	6%	3%	3%	42%
4 Angola	14,078	1,000	148	14,009	10,510	98%	39%	21%	0%	80%	0.2%
5 Antigua and Barbuda	73	2,400	0.1	800	710				0%	0%	
6 Argentina	38,871	600	814	21,981	20,940	34%	16%	16%	66%	14%	4%
7 Armenia	3,052	600	10	2780	3,450	60%	40%	13%	14%	31%	28%
8 Aruba	101										
9 Australia	19,913	500	492	25,708	24,710	89%	15%	4%	0%	0%	5%
10 Austria	8,120	1,100	78	9,616	9,570	71%	8%	8%	29%	100%	3%
11 Azerbaijan	8,447	400	30	3,765	3,580	20%	22%	14%	73%		57%
12 Bahamas	317	1,300	0.02	66	63	nd	nd	nd	0%	0%	
13 Bahrain	739	100	0.1	181	157	3%	0%	0%	97%	0%	258%
14 Bangladesh	149,664	2,700	1,211	8,809	8,090	7%	2%	0%	91%	0%	7%
15 Barbados	271	2,100	0.1	307	296	10%	92%	2%	0%	0%	105%
16 Belarus	9,852	600	58	5,694	5,890	64%	31%	31%	36%	96%	5%
17 Belgium	10,340	800	18	1,786	1,770	66%	5%	5%	34%	60%	
18 Belize	261	2,200	19	82,102	71,090				14%	0%	1%
19 Benin	6,918	1,000	26	3,954	3,820	38%	7%	6%	61%	22%	1%
20 Bermuda	82	1,500									
21 Bhutan	2,325	1,700	95	45,564	40,860	100%	0%	95%	0.4%		
22 Bolivia	8,973	1,100	623	74,743	69,380	45%	21%	17%	51%	93%	0.2%
23 Bosnia and Herzegovina	4,186	1,000	38	9,429	8,960					100%	
24 Botswana	1,795	400	12	9,345	6,820	7%	14%	1%	80%	5%	1%
25 Brazil	180,654	1,800	8,233	48,314	45,570	66%	23%	23%	34%	6%	1%
26 Brunei Darussalam	366	2,700	9	25,915	23,220	100%	1%	1%	0%	0%	
27 Bulgaria	7,829	600	21	2,680	2,720	94%	30%	26%	1%	92%	49%
28 Burkina Faso	13,393	700	13	1,084	930	64%	76%	40%	0%	100%	6%
29 Burundi	7,068	1,200	15	566	2,190	65%	48%	48%	35%	14%	2%
30 Cambodia	14,482	1,900	476	36,333	32,880	24%	4%	3%	75%	99%	1%
31 Cameroon	16,296	1,600	286	19,192	17,520	94%	35%	33%	4%	14%	0.3%
32 Canada	31,744	500	2,902	94,353	91,420	98%	13%	12%	2%	5%	2%
33 Cape Verde	473	400	0.3	703	630	60%	40%	0%	0%	0%	9%
34 Central African Rep.	3,912	1,300	144	38,849	36,910	98%	39%	39%	2%	98%	0.02%
35 Chad	8,854	300	43	5,453	4,860	31%	27%	23%	65%	9%	0.5%
36 Chile	15,996	700	922	60,614	57,640	96%	15%	15%	4%	0%	1.4%
37 China	1,320,892	600	2,830	2,259	2,140	96%	29%	26%	1%	25%	
38 China, Taiwan Prov.	22,894	2,400	67		2,930	94%	6%	0%	0%		
39 Colombia	44,914	2,600	2,132	50,635	47,470	99%	24%	24%	1%	50%	1%
40 Comoros	790	1,800	1.2	1,700	1,520	17%	83%	0%	0%	0%	
41 Congo, Dem Rep.	54,417	1,500	1,283	25,183	23,580	70%	33%	33%	30%	0%	0.03%
42 Congo	3,818	1,600	832	275,679	217,920	27%	24%	24%	73%	23%	0.005%
43 Costa Rica	4,250	2,900	112	27,932	26,450	67%	33%	0%	0%	7%	2%
44 Côte d'Ivoire	16,897	1,300	81	5,058	4,790	91%	47%	43%	5%	15%	1%
45 Croatia	4,416	1,100	106	22,669	23,890	26%	10%	0%	64%	38%	
46 Cuba	11,328	1,300	38	3,404	3,370	83%	17%	0%	0%	0%	22%
47 Cyprus	808	500	0.8	995	970	72%	53%	24%	0%	0%	31%
48 Czech Rep	10,226	700	13	1,280	1,290	100%	11%	11%	0%	100%	20%

Table 4.3: *continued*

	Country	Population (1,000,000s)	Precip Rate[1] (mm/yr)	TARWR Volume 2005 (km^3/yr)	TARWR Per Capita 2000 (m^3/yr)	TARWR Per Capita 2005 (m^3/yr)	Surface water % TARWR	Ground-water % TARWR	Overlap[2] % TARWR	Incoming Waters % TARWR	Outgoing[3] Waters % TARWR	Total Use % TARWR
49	Denmark	5,375	700	6	1,128	1120	62%	72%	33%	0%	0%	21%
50	Djibouti	712	200	0.3	475	420	100%	5%	5%	0%	0%	3%
51	Dominica	79	3,400									
52	Dominican Republic	8,872	1,400	21	2,507	2,370	100%	56%	56%	0%	5%	16%
53	Ecuador	13,192	2,100	424	34,161	32,170	102%	32%	32%	0%	36%	4%
54	Egypt	73,390	100	58	859	790	1%	2%	0%	97%	0%	118%
55	El Salvador	6,614	1,700	25	4,024	3,810	70%	24%	24%	30%	0%	5%
56	Equatorial Guinea	507	2,200	26	56,893	51,280	96%	38%	35%	0%	0%	0.4%
57	Eritrea	4,297	400	6	1,722	1,470				56%	35%	5%
58	Estonia	1,308	600	13	9,195	9,790	91%	31%	23%	1%	3%	1%
59	Ethiopia	72,420	800	122	1,749	1,680	16%	100%	16%	0%	80%	2%
60	Fiji	847	2,600	29	35,074	33,710				0%	0%	0.2%
61	Finland	5,215	500	110	21,268	21,090	97%	2%	2%	3%	25%	2%
62	France	60,434	900	204	3439	3,370	87%	49%	48%	12%	7%	20%
63	French Guiana	182	2,900	134	812,121	736,260				0%	0%	
64	French Polynesia	248										
65	Gabon	1,351	1,800	164	133,333	121,390	99%	38%	37%	0%	0%	0.1%
66	Gambia	1,462	800	10	6,140	5,470	38%	6%	6%	63%	0%	0.4%
67	Gaza Strip, Palestinian Territories	1,376	300	0	52	41	0%	82%	0%	18%	0%	
68	Georgia	5,074	1,000	63	12,035	12,480	90%	27%	25%	8%	19%	6%
69	Germany	82,526	700	154	1,878	1,870	69%	30%	29%	31%	59%	31%
70	Ghana	21,377	1,200	50	2,756	2,490	55%	49%	47%	43%	0%	1%
71	Greece	10,977	700	74	6,998	6,760	75%	14%	11%	22%	2%	10%
72	Greenland	57	600	603	10,767,857	10,578,950				0%	0%	
73	Grenada	80	1,500									
74	Guadeloupe	443	200									
75	Guatemala	12,661	2,700	111	9,773	8,790	91%	30%	23%	2%	47%	2%
76	Guinea	8,620	1,700	226	27,716	26,220	100%	17%	17%	0%	45%	1%
77	Guinea-Bissau	1,538	1,600	31	25,855	20,160	39%	45%	32%	48%	0%	0.4%
78	Guyana	767	2,400	241	316,689	314,210	100%	43%	43%	0%	0%	1%
79	Haiti	8,437	1,400	14	1,723	1,660	77%	15%	0%	7%	0%	7%
80	Honduras	7,099	2,000	96	14,949	13,510	91%	41%	31%	0%	0%	1%
81	Hungary	9,831	600	104	10,433	10,580	6%	6%	6%	94%	100%	7%
82	Iceland	292	1,000	170	609,319	582,190	98%	14%	12%	0%	0%	0.1%
83	India	1,081,229	1,100	1,897	1,880	1,750	64%	22%	20%	34%	68%	34%
84	Indonesia	222,611	2,700	2,838	13,381	12,750	98%	16%	14%	0%	0%	3%
85	Iran, Islamic Rep.	69,788	200	138	1,955	1,970	71%	36%	13%	7%	7%	53%
86	Iraq	25,856	200	75	3,287	2,920	45%	2%	0%	53%		57%
87	Ireland	3,999	1,100	52	13,673	13,000	93%	21%	19%	6%	0%	2%
88	Israel	6,560	400	2	276	250	15%	30%	0%	55%		122%
89	Italy	57,346	800	191	3,325	3,340	89%	22%	16%	5%	0%	23%
90	Jamaica	2,676	2,100	10	3,651	3,510	59%	41%	0%	0%	0%	4%
91	Japan	127,800	1,700	430	3,383	3,360	98%	6%	4%	0%	0%	21%
92	Jordan	5,614	100	1	179	160	45%	57%	25%	23%		115%
93	Kazakhstan	15,403	200	110	6,778	7,120	63%	6%	0%	31%		32%
94	Kenya	32,420	700	30	985	930	57%	10%	0%	33%	30%	5%
95	Korea, Dem. People's Rep.	22,776	1,400	77	3,464	3,390	86%	17%	16%	13%	6%	12%
96	Korea, Rep.	47,951	1,100	70	1,491	1,450	89%	19%	15%	7%		27%

Table 4.3: *continued*

Country	Population (1,000,000s)	Precip Rate[1] (mm/yr)	TARWR Volume 2005 (km²/yr)	TARWR Per Capita 2000 (m³/yr)	TARWR Per Capita 2005 (m³/yr)	Surface water % TARWR	Ground-water % TARWR	Overlap[2] % TARWR	Incoming Waters % TARWR	Outgoing[3] Waters % TARWR	Total Use % TARWR
97 Kuwait	2,595	100	0.02	10	8	0%	0%	0%	100%	0%	2,227%
98 Kyrgyzstan	5,208	400	21	4,182	3,950	214%	66%	54%	0%	36%	49%
99 Lao Peoples Dem. Rep.	5,787	1,800	334	63,184	57,640	57%	11%	11%	43%	100%	1%
100 Latvia	2,286	600	35	14,642	15,510	47%	6%	6%	53%	2%	1%
101 Lebanon	3,708	700	4	1,261	1,190	93%	73%	57%	1%	11%	31%
102 Lesotho	1,800	800	3	1,485	1,680	173%	17%	17%	0%	57%	2%
103 Liberia	3,487	2,400	232	79,643	66,530	86%	26%	26%	14%	0%	0.05%
104 Libyan Arab Jamahiriya	5,659	100	1	113	106	33%	83%	17%	0%	117%	802%
105 Lithuania	3,422	700	25	6,737	7,280	62%	5%	4%	38%	20%	1%
106 Luxemburg	459	900	3	7,094	6,750	32%	3%	3%	68%	100%	
107 Macedonia, Fr Yugoslav Rep.	2,066	600	6	3,147	3,100	84%	0%	0	16%	100%	
108 Madagascar	17,901	1,500	337	21,102	18,830	99%	16%	15%	0%	0%	4%
109 Malawi	12,337	1,200	17	1,528	1,400	93%	8%	8%	7%	93%	6%
110 Malaysia	24,876	2,900	580	26,105	23,320	98%	11%	9%	0%	0%	2%
111 Maldives	328	2,000	0.03	103	91	0%	100%	0%	0%	0%	
112 Mali	13,409	300	100	8,810	7,460	50%	20%	10%	40%	52%	7%
113 Malta	396	400	0.1	129	130	1%	99%	0%	0%	0%	110%
114 Martinique	395	2,600	nd								
115 Mauritania	2,980	100	11	4,278	3,830	1%	3%	0%	96%	0%	15%
116 Mauritius	1,233	2,000	3	1,904	2,230	86%	32%	18%	0%	0%	22%
117 Mexico	104,931	800	457	4,624	4,360	79%	30%	20%	11%	0%	17%
118 Moldova, Rep.	4,263	600	12	2,712	2,730	9%	3%	3%	91%	85%	20%
119 Mongolia	2,630	200	35	13,739	13,230	94%	18%	11%	0%	76%	1%
120 Morocco	31,064	300	29	971	930	76%	34%	10%	0%	1%	44%
121 Mozambique	19,182	1,000	217	11,814	11,320	45%	8%	6%	54%	0%	0.3%
122 Myanmar	50,101	2,100	1,046	21,898	20,870	84%	15%	14%	16%	5%	3%
123 Namibia	2,011	300	18	10,211	8,810	23%	12%	0%	66%	72%	2%
124 Nepal	25,725	1,300	210	9,122	8,170	94%	10%	10%	6%	100%	5%
125 Netherlands	16,227	800	91	5,736	5,610	12%	5%	5%	88%	0%	9%
126 New Caledonia	233	1,500									
127 New Zealand	3,904	1,700	327	86,554	83,760	0%	0%	1%			
128 Nicaragua	5,597	2,400	197	38,787	35,140	94%	30%	28%	4%	0%	1%
129 Niger	12,415	200	34	3,107	2,710	3%	7%	0%	90%	96%	6%
130 Nigeria	127,117	1,200	286	2,514	2,250	75%	30%	28%	23%	0%	3%
131 Norway	4,552	1,100	382	85,478	83,920	98%	25%	24%	0%	3%	1%
132 Oman	2,935	100	1	388	340	94%	97%	91%	0%	0%	137%
133 Pakistan	157,315	300	223	2961	1,420	21%	25%	22%	76%	3%	76%
134 Panama	3,177	2,700	148	51,814	46,580	97%	14%	12%	0%	0%	1%
135 Papua New Guinea	5,836	3,100	801	166,563	137,250	100%			0%	0%	0.01%
136 Paraguay	6,018	1,100	336	61,135	55,830	28%	12%	12%	72%	99%	0.1%
137 Peru	27,567	1,500	1,913	74,546	69,390	84%	16%	16%	16%	94%	1%
138 Philippines	81,408	2,300	479	6,332	5,880	93%	38%	30%	0%	0%	6%
139 Poland	38,551	600	62	1,596	1,600	86%	20%	19%	13%	3%	26%
140 Portugal	10,072	900	69	6,859	6,820	55%	6%	6%	45%	0%	16%
141 Puerto Rico	3,898	2,100	7	1,814	1,820				0%	0%	
142 Qatar	619	100	0.1	94	86	2%	94%	0%	4%	0%	554%
143 Reunion	767	2,100	5	6,935	6,520	90%	56%	46%	0%	0%	
144 Romania	22,280	600	212	9,445	9,510	20%	4%	4%	80%	0%	11%

Table 4.3: *continued*

Country	Population (1,000,000s)	Precip Rate[1] (mm/yr)	TARWR Volume 2005 (km^2/yr)	TARWR Per Capita 2000 (m^3/yr)	TARWR Per Capita 2005 (m^3/yr)	Surface water % TARWR	Ground-water % TARWR	Overlap[2] % TARWR	Incoming Waters % TARWR	Outgoing[3] Waters % TARWR	Total Use % TARWR
145 Russian Federation	142,397	500	4,507	30,980	3,1650	90%	17%	11%	4%	0%	2%
146 Rwanda	8,481	1,200	5	683	610	100%	69%	69%	0%	81%	1%
147 Saint Helena	5	800									
148 Saint Kitts and Nevis	42	2,100	0.0	621	560	15%	85%	0%	0%	0%	
149 Saint Lucia	150	2,300									
150 Saint Vincent and the Grenadines	121	1,600									
151 Samoa	180	3,000									
152 Sao Tome and Principe	165	2,200	2.2	15,797	13,210				0%	0%	
153 Saudi Arabia	24,919	100	2.4	118	96	92%	92%	83%	0%	6%	722%
154 Senegal	10,339	700	39	4,182	3,810	60%	19%	13%	33%	14%	4%
155 Serbia and Montenegro	10,519				19,820	20%	1%	1%	79%		
156 Seychelles	82	2,000									
157 Sierra Leone	5,168	2,500	160	36,322	30,960	94%	31%	25%	0%	0%	0.2%
158 Singapore	4,315	2,500	0.6	149	139				0%	0%	
159 Slovakia	5,407	800	50	9,279	9,270	25%	3%	3%	75%	27%	
160 Slovenia	1,982	1,200	32	16,031	16,080	58%	42%	42%	41%	60%	
161 Solomon Islands	491	3,000	45	100,000	91,040				0%	0%	
162 Somalia	10,312	300	14	1,538	1,380	40%	23%	21%	56%	0%	23%
163 South Africa	45,214	500	50	1,154	1,110	86%	10%	6%	10%	19%	31%
164 Spain	41,128	600	112	2,794	2,710	98%	27%	25%	0%	31%	32%
165 Sri Lanka	19,218	1,700	50	2,642	2,600	98%	16%	14%	0%	0%	25%
166 Sudan	34,333	400	65	2,074	1,880	43%	11%	8%	77%	30%	58%
167 Suriname	439	2,300	122	292,566	277,900	72%	66%	66%	28%	0%	1%
168 Swaziland	1,083	800	4.5	4,876	4,160				41%	100%	18%
169 Sweden	8,886	600	174	19,679	19,580	98%	11%	11%	2%	2%	2%
170 Switzerland	7,164	1,500	54	7,462	7,470	76%	5%	5%	24%	76%	5%
171 Syrian Arab Rep.	18,223	300	26	1,622	1,440	18%	16%	8%	80%	119%	76%
172 Tajikistan	6,298	500	16	2,625	2,540	396%	38%	19%	17%		75%
173 Tanzania	37,671	1,100	91	2,591	2,420	88%	33%	31%	10%	14%	2%
174 Thailand	63,465	1,600	410	6,527	6,460	48%	10%	7%	49%	79%	21%
175 Togo	5,017	1,200	15	3,247	2,930	73%	39%	34%	22%	54%	1%
176 Tonga	105	2,000								0%	
177 Trinidad and Tobago	1,307	1,800	3.8	2,968	2,940				0%	0%	8%
178 Tunisia	9,937	300	4.6	482	460	68%	32%	9%	9%	4%	60%
179 Turkey	72,320	600	214	3,439	2,950	87%	32%	13%	1%	29%	18%
180 Turkmenistan	4,940	200	25	5,218	5,000	4%	1%	0%	97%		100%
181 Uganda	26,699	1,200	66	2,833	2,470	59%	44%	44%	41%	56%	0%
182 Ukraine	48,151	600	140	2,815	2,900	36%	14%	12%	62%	22%	27%
183 United Arab Emirates	3,051	100	0.2	58	49	100%	80%	80%	0%	0%	1,538%
184 United Kingdom	59,648	1,200	147	2,465	2,460	98%	7%	6%	1%	0%	6%
185 United States of America	297,043	700	3,051	10,837	10,270				8%		16%
186 Uruguay	3,439	1,300	139	41,654	40,420	42%	17%	17%	58%	0%	2%
187 Uzbekistan	26,479	200	50	2,026	1,900	19%	17%	4%	77%		116%
188 Venezuela, Bolivarian Rep.	26,170	1,900	1,233	51,021	47,120	57%	18%	17%	41%	6%	1%

Table 4.3: *continued*

Country	Population (1,000,000s)	Precip Rate[1] (mm/yr)	TARWR Volume 2005 (km^3/yr)	TARWR Per Capita 2000 (m^3/yr)	TARWR Per Capita 2005 (m^3/yr)	Surface water % TARWR	Ground-water % TARWR	Overlap[2] % TARWR	Incoming Waters % TARWR	Outgoing[3] Waters % TARWR	Total Use % TARWR
189 Viet Nam	82,481	1,800	891	11,406	10,810	40%	5%	4%	59%	4%	8%
190 West Bank, Palestinian Territories	2,386		0.8		320	10%	90%	0%	0%	28%	
191 Yemen	20,733	200	4	223	198	98%	37%	34%	0%	0%	162%
192 Zambia	10,924	1,000	105	10,095	9,630	76%	45%	45%	24%	100%	2%
193 Zimbabwe	12,932	700	20	1,584	1,550	66%	25%	20%	39%	71%	13%

Source: FAO-AQUASTAT, 2005.

Notes:
1. Average precipitation (1961–90 from IPCC (mm/year). As in the FAO-AQUASTAT Database, for some countries large discrepancies exist between national and IPCC data on rainfall average. In these cases, IPCC data were modified to ensure consistency with water resources data.
2. Overlap is the water that is shared by both the surface water and groundwater systems.
3. Outflow – Sep. 2004 for surface water and Aug. 2005 for groundwater.

...each type of landscape change will have its own specific impact, usually directly on ecosystems and directly or indirectly on water resources...

Part 3. Human Impacts

A number of forces continue to seriously affect our natural water resources. Many of these are primarily the result of human actions and include ecosystem and landscape changes, sedimentation, pollution, over-abstraction and climate change.

The removal, destruction or impairment of natural ecosystems are among the greatest causes of critical impacts on the sustainability of our natural water resources. This issue is dealt with more broadly in **Chapter 5**. However, it should be emphasized that the ecosystems with which we interact are directly linked to the well-being of our natural water resources. Although it is difficult to integrate the intricacies of ecosystems into traditional and more hydrologically-based water assessment and management processes, this approach is being strongly advocated in some sectors and scientific domains (e.g. Falkenmark and Rockström, 2004; Figueras et al., 2003; Bergkamp et al., 2003). The basis of this approach is the recognition that each type of landscape change will have its own specific impact, usually directly on ecosystems and directly or indirectly on water resources. The magnitude of the impacts will vary according to the setting's conditions with a wide range of possible landscape changes. Changes that can occur to landscapes include: forest clearance, crop- or grazing lands replacing grasslands or other natural terrestrial ecosystems, urbanization (leading to changes in infiltration and runoff patterns as well to pollution), wetlands removal or reduction, new roadwork for transportation, and mining in quarries or large-scale open pits.

3a. Sedimentation

Sediments occur in water bodies both naturally and as a result of various human actions. When they occur excessively, they can dramatically change our water resources. Sediments occur in water mainly as a direct response to land-use changes and agricultural practices, although sediment loads can occur naturally in poorly vegetated terrains and most commonly in arid and semi-arid climates following high intensity rainfall. **Table 4.4** summarizes the principal sources of excessive sediment loads and identifies the major impacts that this degree of sediment loading can have on aquatic systems and the services that water resources can provide. A recently documented and increasing source of high sediment loads is the construction of new roads in developing countries where little consideration is given to the impacts of such actions on aquatic systems and downstream water supplies. Globally, the effects of excessive sedimentation commonly extend beyond our freshwater systems and threaten coastal habitats, wetlands, fish and coral reefs in marine environments (see **Chapter 5**). The importance of sediment control should be an integral consideration in any water resources development and protection strategy. UNESCO's International Sediment Initiative (ISI) project will attempt to improve the understanding of sediment phenomena, and provide better protection of the aquatic and terrestrial environments.

3b. Pollution

Humans have long used air, land and water resources as 'sinks' into which we dispose of the wastes we generate. These disposal practices leave most wastes inadequately treated, thereby causing pollution. This in turn affects precipitation (**Box 4.2**), surface waters (**Box 4.3**), and groundwater (**Box 4.4**), as well as degrading ecosystems (see **Chapter 5**). The sources of pollution that impact our water resources can develop at different scales (local, regional and global) but can generally be categorized (**Table 4.5**) according to nine types. Identification of source types and level of pollution is a prerequisite to assessing the risk of the pollution being created to both

Table 4.4: Major principal sources and impacts of sedimentation

Pertinence	Sector	Action or mechanism	Impacts
SOURCES			
Agriculture areas, downstream catchments	Agriculture	■ poor farming with excessive soil loss	■ increase soil erosion ■ add toxic chemicals to the environment ■ sediment and pollutants are added to streams ■ irrigation systems maintenance cost increased
Forest and development access areas,downstream catchments	Forestry, Road Building, Construction, Construction, Mining	■ extensive tree cutting ■ lack of terrain reforestation ■ lack of runoff control in steep terrain	■ increase natural water runoff ■ accelerated soil erosion creating more sediment
MAJOR IMPACTS			
Major rivers and navigable waterways	Navigation	■ deposition in rivers or lakes ■ dredging (streams, reservoirs, lakes or harbors)	■ decreases water depth making navigation difficult or impossible. ■ releases toxic chemicals into the aquatic or land environment.
Aquatic ecosystems	Fisheries / Aquatic habitat	■ decreased light penetration ■ higher suspended solids concentrations ■ absorbed solar energy increases water temperature ■ carrying toxic agricultural and industrial compounds ■ settling and settled sediment	■ affects fish feeding and schooling practices; can reduce fish survival ■ irritate gills of fish, can cause death, destroy protective mucous covering on fish eyes and scales ■ dislodge plants, invertebrates, and insects in stream beds affecting fish food sources resulting in smaller and fewer fish, increased infection and disease susceptibility ■ stress to some fish species ■ release to habitat causes fish abnormalities or death ■ buries and suffocates eggs ■ reduces reproduction
Lakes, rivers, reservoirs as water supplies	Water supply	■ increased pump/turbine wear ■ reduced water supply usability for certain purposes ■ additional treatment for usability required	■ affects water delivery, increases maintenance costs ■ reduces water resource value and volume ■ increased costs
Hydroelectric facilities	Hydropower	■ dams trap sediment carried downstream ■ increased pump/turbine wear	■ diminished reservoir capacity ■ shortened power generation lifecycle ■ higher maintenance, capital costs.
All waterways and their ecosystems	Toxic chemicals	■ become attached or adsorbed to sediment particles	■ transported to and deposited in, other areas ■ later release into the environment.

Source: Adapted from Environment Canada (2005a), www.atl.ec.gc.ca/udo/mem.html

Note: Water transforms landscapes and moves large amounts of soil and fine-grained materials in the form of *sediment*.
Sediment is: 1) eroded from the landscape, 2) transported by river systems and eventually 3) deposited in a riverbed, wetland, lake, reservoir or the ocean. Particles or fragments are eroded naturally by water, wind, glaciers, or plant and animal activities with geological (natural) erosion taking place slowly over centuries or millennia. Human activity may accelerate the erosion. Material dislodged is transported when exposed to fluvial erosion in streams and rivers. Deposition occurs as on flood plains, bars and islands in channels and deltas while considerable amounts end up in lakes, reservoirs and deep river beds.

BOX 4.2: ACID RAIN IMPACTS ON WATER RESOURCES

Atmospheric contamination from industrial plants and vehicle emissions leads to dry and wet deposition. This causes acidic conditions to develop in surface water and groundwater sources and at the same time leads to the destruction of ecosystems. Acid deposition impairs the water quality of lakes and streams by lowering pH levels (i.e. increasing acidity), decreasing acid-neutralizing capacity, and increasing aluminum concentrations. High concentrations of aluminium and increased acidity reduce species diversity and the abundance of aquatic life in many lakes and streams. While fish have received most attention to date, entire food webs are often negatively affected. Despite improvements, it still remains a critical situation that impacts water resources and ecosystems in some developed regions of Europe and in North America. The situation remains an important issue in several developing countries (for example in China, India, Korea, Mexico, South Africa and Viet Nam) where there are typically lower emission controls and inadequate monitoring and evaluation (Bashkin and Radojevic, 2001). In recognition of this, UNEP and the Stockholm Environmental Institute are sponsoring programmes such as RAPIDC (Rapid Air Pollution in Developing Countries) with the aim of identifying sources and sensitive areas and measuring levels of acid rain. Extensive funding from ADB is now being used to source reductions in several Asian nations. The problem has broad transboundary implications as acid rain can get carried over long distances from polluting areas to other countries. For example, Japan is impacted by Korean and Chinese emissions, while Canada, in addition to its own sources, receives substantive emissions from the US.

As reported by Driscoll et al. (2001), there are still impacts to water quality in northeastern US and eastern Canada, even though improved conditions developed after the introduction of the Clean Air Act and its amendments (1992).

> 41 percent of lakes in the Adirondacks of New York and 15 percent of all lakes in New England exhibit signs of chronic and/or episodic acidification. Only modest improvements in acid-neutralizing capacity have occurred in New England with none in the Adirondacks or Catskills of New York. Elevated concentrations of aluminum have been measured in acid-impacted surface waters throughout the Northeast.

Figure 4.6: Acid rain and its deposition processes

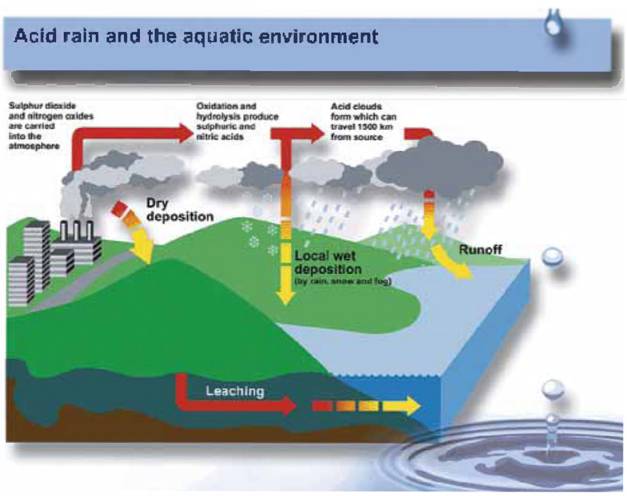
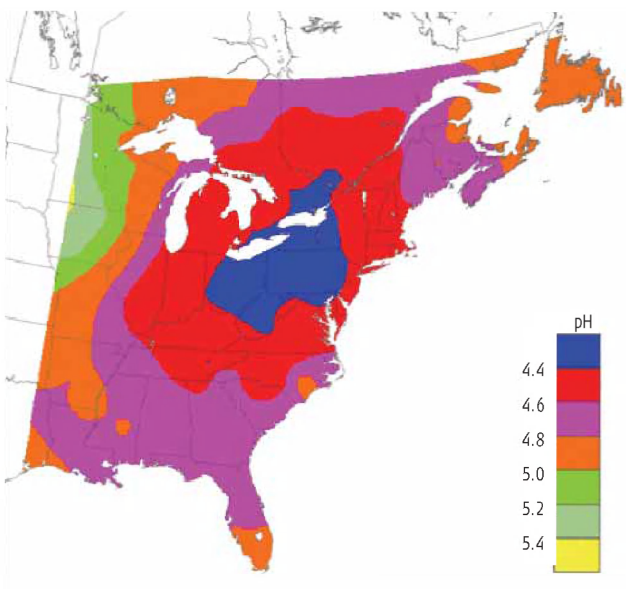


Figure 4.7: Five-year mean of the pH level in rainfall in the eastern regions of Canada and the US



Source: Environment Canada, 2005c.

BOX 4.3: IMPACTS TO SURFACE WATER QUALITY FROM HUMAN ACTIVITY

The challenge of how to improve water quality by rehabilitation and protection of lakes, streams, reservoirs, wetlands and related surface water bodies is a growing global concern, typified by the recent European Commission Water Framework Directive (EC, 2000). However, surface water pollution risks, particularly in developing nations, remain relatively widespread. A valuable initial step in identifying the nature and extent of water quality impacts linked to pollution is to distinguish their point (PS) and non-point sources (NPS). PS pollution is commonly linked directly to end-of-pipe releases from industry and municipal wastes. Its control is more direct and quantifiable and in many developed countries its mitigation has been linked to treatment achieving lower contaminant concentrations before discharge. NPS pollution occurs when contaminants from diverse and widely spread sources are transported by runoff into rivers, lakes, wetlands, groundwater and coastal areas. This type of pollution is more difficult to address as there are a large number of sources, for example, varied agricultural areas all of which are using pesticides and nutrients. Today, however, NPS pollution is receiving more attention as its impacts are becoming evident over large areas in lakes, streams and groundwater and can also be linked to the degradation of aquatic freshwater and marine ecosystems.

Further detail on pollution impacts are found in the chapters on human settlements (**Chapter 3**), agriculture (**Chapter 7**) and industry (**Chapter 8**).

Emerging Issues

Only a small percentage of chemicals are regulated locally, nationally or internationally (Daughton 2004). An emerging concern is contaminants in high population settings that are neither traditionally measured nor regulated, for example pharmaceuticals (Wiegel et al. 2004). Reynolds (2003) reports:

> Scientists are becoming increasingly concerned about the potential public health impact of environmental contaminants originating from industrial, agricultural, medical and common household practices, i.e., cosmetics, detergents and toiletries. A variety of pharmaceuticals including painkillers, tranquilizers, anti-depressants, antibiotics, birth control pills, estrogen replacement therapies, chemotherapy agents, anti-seizure medications, etc., are finding their way into the environment via human and animal excreta from disposal into the sewage system and from landfill leachate that may impact groundwater supplies. Agricultural practices are a major source and 40 percent of antibiotics manufactured are fed to livestock as growth enhancers. Manure, containing traces of pharmaceuticals, is often spread on land as fertilizer from which it can leach into local streams and rivers.

Reynolds further notes that conventional wastewater treatment is not effective in eliminating the majority of pharmaceutical compounds. Since various contaminants do not always have coincident pollution patterns, single indicators for all contaminants are not effective. Reynolds (2003) suggests that 'pharmaceutical contamination in the environment will involve both advanced waste and water treatment technologies and source control at the point of entry into the environment ... all of which are issues of ongoing scientific research'.

the aquatic systems and, through that system, to humans and the environment. With the knowledge of the principal sources of the pollution, the appropriate mitigation strategy can be identified to reduce the impact on the water resources.

The potential impacts from the different pollution types based on the area (scale) affected, the time it takes to contaminate, the time needed to clean up (remediate) a contaminated area, and the links to the major controlling factors are illustrated in **Table 4.6** (Peters and Meybeck, 2000). With the exception of pathogenic contaminants, all other forms of pollution can extend to a regional scale. The fact that it takes considerably longer to remediate a contaminated area than to pollute it clearly highlights the need for adopting the precautionary principle and prioritizing protection strategies rather than costly ad-hoc restoration measures.

Developed countries have historically experienced a succession of water quality problems relating to pathogens, eutrophication, heavy metals, acidification, organic compounds and micro-pollutants and sediments from municipal, industrial and agricultural waste sources (Webb, 1999; Meybeck et al., 1989; Revenga and Mock, 2000). In rapidly developing countries – such as Brazil, China and India – similar sequences of water problems have emerged over the last few decades. In other developing countries, water pollution still remains problematic and is one of the single leading causes of poor livelihood and bad health (Lenton, 2004; and see **Chapter 6**).

Global water quality and pollution information

Assessing water quality enables the natural characteristics of the water to be documented and the extent of the pollution to be determined; however, today monitoring is

BOX 4.4: IMPACTS TO GROUNDWATER QUALITY FROM HUMAN ACTIVITY

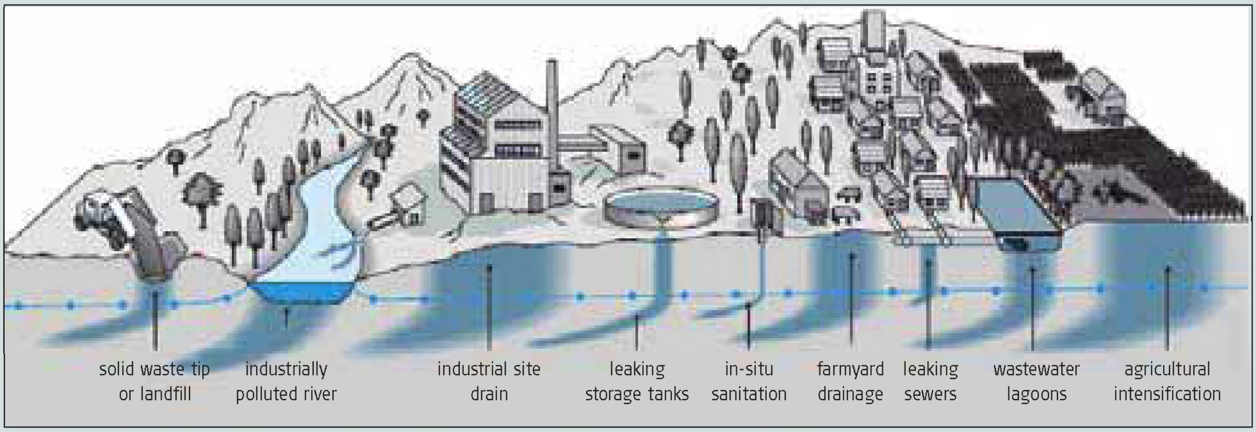
Protection of groundwater sources is becoming a more widespread global concern as typified by the recent European Commission directive which focuses on preventing rather than cleaning up pollution (EC 2003). Incidents of groundwater pollution arising from human actions, particularly in developing nations, remain relatively widespread and its impacts in terms of degraded water quality are summarized in Zektser and Everett (2004). Throughout the world, most countries' practices of urbanization, industrial development, agricultural activities and mining enterprises have caused groundwater contamination and its most typical sources are illustrated in **Figure 4.8**. A 2002 joint World Bank, GWP, WHO and UNESCO online guidance document (Foster et al. 2002) states '*There is growing evidence of increasing pollution threats to groundwater and some well documented cases of irreversible damage to important aquifers, following many years of widespread public policy neglect*'. This guide is supplemented by recommendations in a 2003 joint FAO, UNDESA, IAEA and UNESCO report directly addressing the universal changes needed in groundwater management practice (FAO 2003b) to arrive at more sustainable water development and use.

Groundwater pollution contrasts markedly in terms of the activities and compounds that most commonly cause surface water pollution. In addition, there are completely different controls that govern the contaminant mobility and persistence in the two water systems' settings. Foster and Kemper (2004), UNEP (2003), FAO (2003b) and Burke and Moench (2000) point out that groundwater management commonly involves a wide range of instruments and measures (technical, process, incentive, legal and enforcement actions/sanctions and awareness raising) to deal with resources that are less visible than those in our surface water bodies.

Mapping groundwater vulnerability

Groundwater is less vulnerable to human impacts than surface water. However, once polluted, cleaning it up (remediation) takes a relatively long time (years), is more technically demanding, and can be much more costly. While this has been recognized for several decades (Vrba 1985), this important message has not been adequately or consistently conveyed to the policy-makers or the public. To address this gap, groundwater vulnerability assessment methods are being developed. These emerging 'vulnerability maps' have historically been applied to other risks such as flooding and landslides and they can now be used as direct input to water resources and land planning (Vrba and Zaporozek 1994). Results of such studies are absolutely critical where aquifers are used for water supplies and have sensitive ecosystem dependencies. In conjunction with other environmental input, they have become effective instruments used to regulate, manage and take decisions related to impacts from existing and proposed changes in land use, ecosystems and sources of water supplies. Large-scale groundwater vulnerability maps (e.g. France, Germany, Spain, Italy, The Czech Republic, Poland, Russia and Australia) serve as guidelines for land use zoning at national or regional levels.

Figure 4.8: Primary sources of groundwater pollution



Note: This figure illustrates the type of sources that should be inventoried for cataloging potential sources of groundwater contamination.

Source: Foster et al., 2002.

Table 4.5: Freshwater pollution sources, effects and constituents of concern

Pollution type	Primary sources	Effects[1]	Constituents of concern[2]
1 Organic matter	Industrial wastewater and domestic sewage.	Depletion of oxygen from the water column as it decomposes, stress or suffocating aquatic life.	Biological Oxygen Demand (BOD), Dissolved Organic Carbon (DOC), Dissolved Oxygen (DO)
2 Pathogens and microbial contaminants	Domestic sewage, cattle and other livestock, natural sources.	Spreads infectious diseases through contaminated drinking water supplies leading to diarrhoeal disease and intestinal parasites, increased childhood mortality in developing countries.	Shigella, Salmonella, Cryptosporidium, Fecal coliform (Coliform), Escherichia coli (mammal faeces – E. Coli)
3 Nutrients	Principally runoff from agricultural lands and urban areas but also from some industrial discharge.	Over-stimulates growth of algae (eutrophication) which then decomposes, robbing water of oxygen and harming aquatic life. High levels of nitrate in drinking water lead to illness in humans.	Total N (organic + inorganic), total P (organic + inorganic) For eutrophication: (Dissolved Oxygen, Individual N species (NH4, NO2, NO3, Organic N), Orthophosphate)
4 Salinization	Leached from alkaline soils by over irrigation or by over-pumping coastal aquifers resulting in saltwater intrusion.	Salt build-up in soils which kills crops or reduces yields. Renders freshwater supplies undrinkable.	Electrical conductivity, Chloride (followed, post characterization by full suite of major cations (Ca, Mg), anions
5 Acidification (precipitation or runoff)	Sulphur, Nitrogen oxides and particulates from electric power generation, industrial stack and auto/truck emissions (wet and dry deposition). Acid mine drainage from tailings as well as mines.	Acidifies lakes and streams which negatively impacts aquatic organisms and leaches heavy metals such as aluminium from soils into water bodies.	pH
6 Heavy metals	Industries and mining sites.	Persists in freshwater environments such as river sediments and wetlands for long periods. Accumulates in the tissues of fish and shellfish. Can be toxic to both aquatic organisms and humans who consume them.	Pb, Cd, Zn, Cu, Ni, Cr, Hg, As (particularly groundwater)
7 Toxic organic compounds and micro-organic pollutants.[3]	Wide variety of sources from industrial sites, automobiles, farmers, home gardeners, municipal wastewaters.	A range of toxic effects in aquatic fauna and humans from mild immune suppression to acute poisoning or reproductive failure.	PAHs, PCBs, pesticides (lindane, DDT, PCP, Aldrin, Dieldrin, Endrin, Isodrin, hexachlorobenzene)
8 Thermal	Fragmentation of rivers by dams and reservoirs slowing water and allowing it to warm. Industry from cooling towers and other end-of-pipe above-ambient temperature discharges	Changes in oxygen levels and decomposition rate of organic matter in the water column. May shift the species composition of the receiving water body.	Temperature
9 Silt and suspended particles	Natural soil erosion, agriculture, road building, deforestation, construction and other land use changes.	Reduces water quality for drinking and recreation and degrades aquatic habitats by smothering them with silt, disrupting spawning and interfering with feeding.	Total suspended solids, turbidity

Other pollutants include Radioactivity, Fluoride, Selenium.

Sources and notes:

1 Principally from Revenga and Mock, 2000. Their compilation from Taylor and Smith, 1997; Shiklomanov, 1997; UNEP/GEMS, 1995.

2 From R. Peters, W. Beck, personal communication, 2004.

3 Micro-organic pollutant list now includes a suite of endocrin disrupters, antioxidants, plasticizers, fire retardants, insect repellents, solvents, insecticides, herbicides, fragrances, food additives, prescription drugs and pharmaceuticals (e.g., birth control, antibiotics, etc.), non-prescription drugs (e.g., caffeine, nicotine and derivatives, stimulants).

Table 4.6: Spatial and time scales within which pollution occurs and can be remediated

Major Causes / Issues	Major Related Issues [1]	Scale [2]			Time to Pollute [3]			Time to Remediate[4]			Major Controlling Factors	
		Local	Region	Global	<1	1 to 10	10 to 100	<1	1 to 10	10 to =>100	Biophysical	Human
Population	Pathogens											Density & Treatment
	Eutrophication (*)											Treatment
	Micro-pollutants											Various
Water Management [4]	Eutrophication (*)										Hydrodynamics	Flow
	Salinization											Water Balance
	Parasites									> 100		Hydrology
Land Management	Pesticides											Agrochemicals
	Nutrients											Fertilizer
	Suspended Solids (*)											Construction/clearing
	Physical Changes									> 100		Cultivation, Mining, Construction, Clearing
Atmospheric Transport	Acidification (*)											Cities, melting and fossil fuel emissions
	Micro-pollutants											Cities
	Radionuclides									>> 100		Industry
	Mega Cities: Pathogens											Population & Treatment
	Mega Cities: Micro-pollutants											
	Mines: Salinization											Types of Mines
	Mines: Metals											
	Nulcear-Radionuclides									> 100		
Global Climate Change	Salinization										Temperature & Precipitation	Fossil fuel emissions & Greenhouse gases
Natural Ecology	Parasites (*)					Permanent				Permanent	Climate, Hydrology	
Natural Geochemistry	Salts										Climate, Lithology	
	Fluoride (**)					Permanent				Permanent		
	Arsenic, Metals (**)										Lithology	

Notes:
The nutritional status of most regions of the world has improved in all developing regions. Sub-Saharan Africa and South Asia have also improved their nutritional level, but they lag behind and are host to the majority of the undernourished people in the world.
1 Relevant primarily to * surface water, ** groundwater,
2 Local < 10000 km^2, region- >10^4 to 10^6 km^2, global- >10^6 to 10^8 km^2.
3 Lag between cause and effect.
4 Longest time scale is for groundwater, followed by lakes, and shortest for rivers and streams.

Category Shading:
Scale – the colour intensity increases as impact dimension becomes greater.
Time to pollute and Time to remediate are highlighted in red for most critical, orange for moderately critical, and yellow for the least critical situations. Green is shown for the situation where remedial actions could be less than one year (pathogens).

Source: Modified from Peters and Meybeck, 2000.

Food remains in the Mekong River after the daily market activities, Viet Nam

a more holistic process relating to health and other socio-economic issues. The international compilation of surface water and groundwater quality data sets at a global scale is still in its relative infancy as compared to precipitation or surface water runoff data. Although some facilities have existed for several decades to collect and disseminate this type of data, it has been historically difficult to collect. This is attributable to several reasons. National centres have not always been linked to institutional networks. Most nations are simply not used to providing this information to anyone other than their immediate institutions and users for either national or specific project purposes. In addition, data in many developing countries is not extensive and even where it has been collected, making it publicly available as a data set is frequently not a priority for the already overloaded and meagrely resourced national and subnational water resource institutions. However, progress has been made in the past three years in this area. The GEMS/Water international water quality database[4] went online in March 2005 and now has begun to work with a broad range of agencies, NGOs and data quality groups to harmonize the reporting of water data and information. They have established a QA/QC (quality assurance/quality control) programme that includes laboratory evaluations

4. See www.gemstat.org for more information

based on a freely available published set of methods that are used by most of the laboratories that report their data to GEMS/Water. GEMS/Water (2005) reports that data is now received from about 1,500 stations globally, including about 100 for lakes and groundwater.

Increased awareness of the need for water quality data to evaluate impacts and design improved water use and reuse strategies in order to meet quality and quantity demands is emerging at national and river-basin levels. Moreover, there is increasing use and future development of shared aquifers and river basins – many of which are being supported extensively by programmes of the GEF (Global Environment Facility) and UNESCO.

3c. Over-abstraction

The problems of over-abstraction in surface water bodies and groundwater, sometimes tied directly to upstream diversions, reservoirs and deforestation, are well documented. The problems commonly become exacerbated when combined with extended natural dry periods. Notable examples of substantive reductions in large major river flows can be found around the world. Some of the basins suffering from this reduction are: Niger, Nile, Rwizi, Zayandeh-Rud (Africa); Amu Darya, Ganges, Jordan, Lijiang, Syr Darya, Tigris and Euphrates, Yangtze and Yellow (Asia); Murray-Darling (Australia); and Columbia, Colorado, Rio Grande and San Pedro (North America). Examples of lakes and inland sea areas decreasing dramatically in size and volume include: Lakes Balkhash, Drigh, Hamoun, Manchar, and the Aral and Dead Seas (Asia); Lakes Chad, Nakivale and in the Eastern Rift Valley Area, e.g. Nakuru (Africa); Lake Chapala (North America); and Mono Lake and the Salton Sea (North America). Dramatically lowered water levels in aquifers are increasingly reported, for example in the Mexico City and the Floridian and Ogallala aquifers (North America), as well as in China, India, Iran, Pakistan and Yemen (Asia).

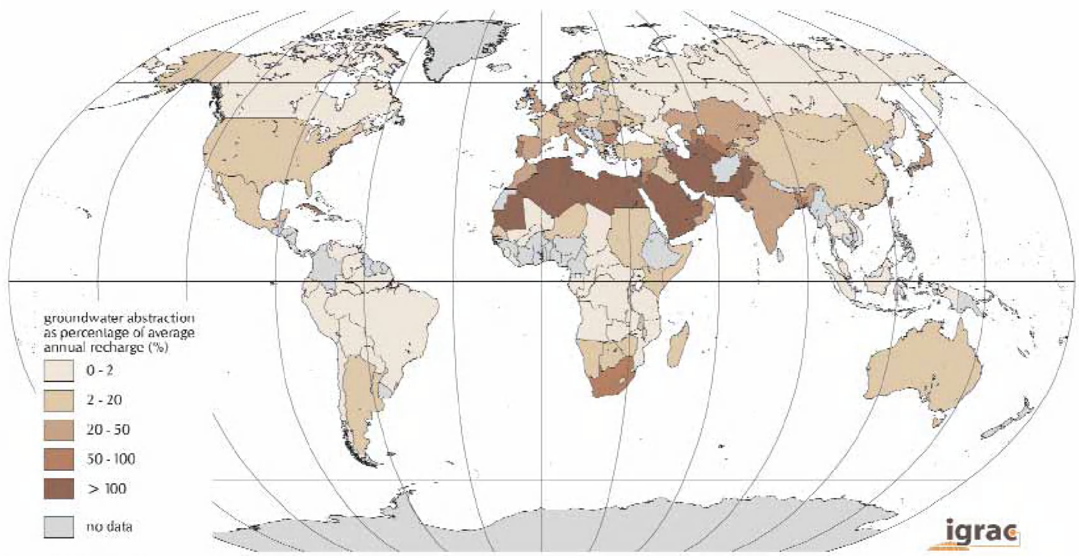
Despite years of clear over-use with evident changes in both water and related ecosystem conditions, many of the same causes persist. Among the most prominent are the highly inefficient water supply provisioning practices for agriculture and municipal use, deforestation, and the basic lack of control over exploitation of the actual surface and groundwater sources. Inappropriate development of reservoirs and diversions combined with inadequate considerations of alternatives in conservation and use minimization (demand management) have further complicated and increased the impacts on existing water resources. While there are some hopeful signs of change emerging in selected local actions (see **Chapters 5** and **7**), these are few in comparison to the broad-based and fundamental modifications needed in national, regional and subnational practices to reverse and counteract these ongoing substantive impacts.

Groundwater over-abstraction represents a special situation as the visual evidence is typically less obvious and the effects are more difficult to recognize and react to. Increased pumping from aquifers has increased globally, particularly during the second half of the twentieth century. While this has produced a number of important benefits, some have been sustainable over only relatively short periods and have had significant negative side-effects (UNEP, 2003; FAO, 2003b; Burke and Moench, 2000). We see, for example, that an initially impressive benefit was experienced in India where shallow groundwater development allowed irrigated land area to be essentially doubled, thereby dramatically increasing food production. However, it also caused momentous changes to local water regimes that resulted in a variety of impacts, including lowered water tables and entirely depleted groundwater resources in some areas. Similar cases from all climatic regions of the world illustrate that over-abstracting groundwater is relatively common. The results of groundwater over-abstraction can be seen in: reduced spring yields; rivers drying up and having poorer water quality because of lowered base-flow contributions; intrusion of saline waters or other poor quality water into the freshwater zones of aquifers; lowered or abandoned productivity as water levels decline in wells; higher production costs from wells or the need to extend underground aqueducts (qanats) as inflow rates decrease; and diminished groundwater-dependent ecosystems, including wetlands, as they become stressed or lose resilience from inadequate water sources. Subsidence is another particularly widespread impact that occurs from excessive over-pumping, with some notable examples in a number of major cities in China, Japan, Mexico and the US. However, this type of impact can be stopped when the over-pumping of the aquifer is discontinued, although the effects are not usually reversible. Llamas and Custodio (2003) provide a recently updated compilation of papers that illustrate the wide-ranging impacts of intensive groundwater exploitation by identifying examples of criteria that have led to over-abstraction actions and by explaining how these criteria can be part of sustainable development strategies.

Tigris River, Iraq

Groundwater over-abstraction represents a special situation as the visual evidence is typically less obvious and the effects are more difficult to recognize and react to

Map 4.3: Groundwater abstraction rate as a percentage of mean recharge



Note: Low percentages indicate underdeveloped groundwater resources, high percentages point to development stress or eventually overexploitation.

Source: IGRAC, 2004.

High levels of exploitation are currently taking place in many countries in the Middle East, Southern and Northern Africa, Asia, selected countries in Europe, and in Cuba

Map 4.3 introduces a groundwater development indicator that compares the degree of groundwater use in each nation to the volume of estimated recharge. Exploitation, for example of more than 50 percent of recharge, will likely result in particular stress on the aquifer sustainability of groundwater systems. High levels of exploitation are currently taking place in many countries in the Middle East, Southern and Northern Africa, Asia, selected countries in Europe, and in Cuba. In addition, as noted above, parts of China, India, Mexico, Pakistan and the US are also being overexploited in selected regions where there is high aridity and population density. Tracking groundwater use as compared to recharge volumes at national and subnational levels – and particularly for individual aquifers – should be practised and implemented to identify and take corrective action as needed to maintain groundwater development sustainability.

3d. Global warming and climate change

As noted above, there is empirical evidence of impacts on water resources from global warming. The IPCC, in cooperation with new partners, has begun to address this issue in addition to their more traditional focus on greenhouse gases and temperature changes. A recent IPCC expert meeting (IPCC, 2004, p. 27) identified two issues related to water and the impacts from global warming: one related to impacts and the other to knowledge gaps. These two issues, as taken from the IPCC report, are as follows:

- 'The extreme event frequency and magnitude will increase even with a small increase in temperature and will become greater at higher temperatures. The impacts of such events are often large locally and could strongly affect specific sectors and regions. Increased extreme events can cause critical design values or natural thresholds to be exceeded, beyond which the impacts' magnitudes increase rapidly.'

- Knowledge gaps related to the water sector were identified as:
  (1) Insufficient knowledge of impacts in different parts of the world (especially in developing countries),
  (2) Almost complete lack of information on impacts under different development pathways and under different amounts of mitigation,
  (3) No clear relationship between climate change and impacts on water resources,
  (4) Little analysis of the capacity and cost of adaptation, and
  (5) Lack of understanding of how changes in variability affect the water environment.

Arnell (2004) also assessed predicted impacts of both population and climate on water-stressed regions, based on population growth scenarios and climate change models. He concludes:

> Climate change increases water resources stresses … where runoff decreases, including around the

Mediterranean, in parts of Europe, central and southern America, and southern Africa. In other water-stressed parts of the world – particularly in southern and eastern Asia – climate change increases runoff, but this may not be very beneficial in practice because increases tend to come during the wet season and extra water may not be available during the dry season.

However, he further points out that model results differ by up to four times in terms of persons impacted according to different population and climate scenarios.

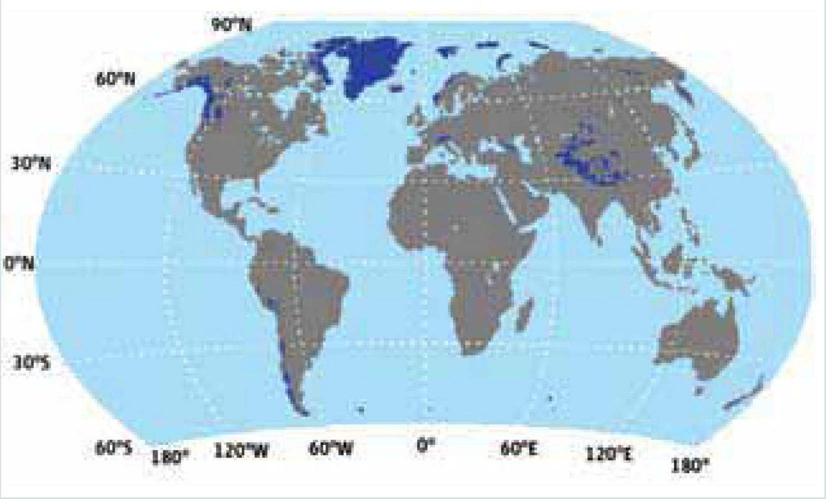
Shiklamanov and Rodda (2003) conclude that only general predictions and observations have been developed based on the assessments of global warming impacts on water resources to date. They agree with Arnell (2004) that assessments of future water resources can only be obtained by using estimates of possible regional (rather than global) changes in climate (primarily precipitation and temperature by seasons and months). They specify that the existing climate change estimates are extremely unreliable even for the largest regions and river basins. Furthermore, they suggest that the gap in knowledge related to the specific impacts of global warming on water resources is one of the largest scientific challenges in hydrology today.

BOX 4.5: ACCELERATING GLACIAL DECLINE

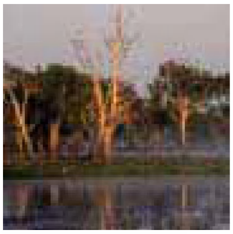
Land-based and mountain glaciers have generally experienced a worldwide retreat and thinning during the last century. Notably, glacier decline has considerably accelerated on a global basis during recent years (Arendt et al. 2002; Dyurgerov 2003). The mean mass balance decrease that took place during the period 1990–99 was three times greater than that of the previous decade (Frauenfelder et al. 2005). Data for this figure are based on measured changes in glacier mass balance made at thirty glaciers located in nine high mountain regions of Asia, Europe and North and South America.

As a specific country example we can look to China. In 2004, AFP (L'Agence France-Presse) cites renewed concerns of disappearing glaciers being broadcast in Asia, notably in China and Nepal. Yao Tangdong, China's foremost glaciologist, was quoted in state media as saying, 'An ecological catastrophe is developing in Tibet because of global warming and that most glaciers in the region could melt away by 2100'. His conclusion was based on the results of a forty-month study by a group of twenty Sino-American scientists which showed separated ice islands that used to be connected with the glaciers at levels above 7,500 m. While Tibet's glaciers have been receding for the past four decades due to global warming, the rate of decline has increased dramatically since the early 1990s. It was initially thought that the water from the melting glaciers could provide additional water for China's arid north and west. However, this hope has not been realized as much of the glacier runoff evaporates long before it reaches the country's drought-stricken farmers. 'The human cost could be immense' states AFP (2004), as 300 million Chinese live in the country's arid west and depend on the water flowing from the glaciers for their livelihoods.

Map 4.4: Principal regions of land-based and mountain glaciers



Source: GLIMS, 2005 (Global Land Ice Measurements from Space nsidc.org/data/glims/ lvOct05).



Part 4. Matching Demands to Supply

Numerous responses have been put forward to meet the ever-increasing demand for water. In some cases, the response focuses on how to compensate for the natural variability in the hydrological cycle in order to provide a continuously available resource. In other circumstances, the response focuses on overcoming the reduced availability in water quantity or quality that results from human and development impacts, from a demand management perspective.

Most water-short regions of the world with dry climates have long-standing water conservation traditions. These are being maintained or supplemented with demand-management practices. To meet increased demands, water resource management practitioners are augmenting the limited natural water supply with desalination, water reuse, enhanced groundwater recharge and inter-basin transfers.

However, regions with abundant water (tropical and cold climates) are accustomed to water supply schemes and tend to adopt management practices that are particularly adapted to those specific settings. It is often taken for granted that resources will remain relatively abundant and could be readily treated or replaced if polluted; that any disruption in ecosystem balance could be remedied; and that adequate water could be diverted and stored to overcome the inconvenience of seasonal flow variations. However, in these regions, impacts from human development have been more severe than anticipated. Water resources have been diminished in quantity and quality, and ecosystem habitats have become endangered to a point below their resilience levels. As a result, responses are emerging that include some of the same practices in demand management used in dry climates. In both water settings, it is increasingly recognized that maintaining and, where possible, restoring the state of the environment by keeping both aquatic and terrestrial aquatic ecosystems above resilience levels can provide substantial long-term benefits to a region's water resources.

4a. Environmental flows for preserving ecosystems and increasing water resources

The heightened awareness of the important role played by ecosystems in terms of water resources and sustainability is a result of the recent focus on 'environmental' or 'in-stream' flows. Dyson et al. (2003) define environmental flows as follows:

> the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits. They provide critical contributions to river health, economic development and poverty alleviation.

BOX 4.6: MANAGEMENT OF AQUIFER RECHARGE (MAR) – AN EXAMPLE FROM VIET NAM

The Binh Thuan province is located along the coastal plain in the lower part of central eastern Viet Nam; its principal city is Phan Tiet, 200 km East of Ho Chi Minh City. The area of the province is approximately 8,000 km^2, with a total population of 1 million.

Before 1975, the area was covered by a dense tropical forest, which was cleared to make room for rice fields and resulted in massive desertification. Due to an uneven rainfall distribution and a four-month period (from December to March) of very little precipitation, the area suffers from considerable water shortage during the dry season.

In order to combat desertification, improved practices in ecosystem rehabilitation as well as remediation techniques to restore aquifer systems and groundwater storage capacity are being developed. In particular, these techniques are being used in the Hong Phong sub-district (Bac Binh district), located about 25 km northeast of Phan Tiet, with an area of approximately 300 km^2 encompassing three villages.

The geo-hydrological assessment of the area, consisting of a semi-permeable bedrock and porous material (sand dunes) with a thickness of up to 150 m, allows for the use of SAR (storage and aquifer recovery) techniques by redirecting rainfall during the rainy season and making use of the resource during the dry period (December–March).

The project's implementation by UNESCO is ongoing and the results achieved thus far have allowed for the selection of the site for the Aquifer Recharge Project in the morphological depression of Nuoc Noi, where the aquifer water table is very close to the ground level. The use of the bank filtration technique is already producing satisfactory results as water quality increases. Groundwater can be abstracted and used, after natural filtration, for different purposes (human and agricultural).

The means for maintaining and restoring these flows under multi-use and competing demand situations are increasingly being considered in detail in many nations and basins. In some regions, environmental flow considerations are being integrated into water policy, legislation and regulations, and water management practices. South Africa (1997), Australia (CSIRO, 2004) and several USA states (e.g. Connecticut, Texas), among others, already have broadly encompassing legislation and in-field practices that take into account environmental flows. More research is needed to understand the water volumes, levels and quality needed to keep ecosystems resilient during seasonal variations and periods of climatic stress. Furthermore, a recognized additional challenge is how to introduce and embed this concept in the predominantly engineering-driven water management agencies of many developing countries so that the resilience of their basin- and watershed ecosystem is less at risk (see **Chapter 5**).

4b. Combating natural variability

Dealing with variability in water runoff in particular has led to centuries-old practices of intercepting, diverting and storing water so that adequate volumes would be available to match the needs and demands of the users.

Rainwater harvesting

Rainwater management, also known as harvesting, is receiving renewed attention as an alternative to or a means of augmenting water sources. Intercepting and collecting rainwater where it falls is a practice that extends back to pre-biblical times (Pereira et al., 2002). It was used 4,000 years ago in Palestine and Greece; in South Asia over the last 8,000 years (Pandey et al., 2003); in ancient Roman residences where cisterns and paved courtyards captured rain that supplemented the city's supply from aqueducts; and as early as 3000 BC in Baluchistan where farming communities impounded rainwater for irrigation. Recently in India, it has been used extensively to directly recharge groundwater at rates exceeding natural recharge conditions (UNESCO, 2000; Mahnot et al., 2003). Reports from other international organizations focusing on this area[5] indicate that eleven recent projects across Delhi resulted in groundwater level increases of from 5 to 10 metres in just two years. In fact, the application of rainwater management in India is likely to be one of the most updated and modern in the world. The site www.rainwaterharvesting.org provides links to cases where rainwater management has been successfully applied in different nations in both urban and rural settings. An advantage of the technique is that its costs are relatively modest and that individual or community programmes can locally develop and manage the required infrastructures (collection devices, basins, storage tanks, surface or below-ground recharge structures or wells). Larger rain harvesting schemes, which intercept runoff using low-height berms or spreading dikes to increase infiltration, have also been introduced in upstream catchments where deforestation has decreased water availability. The various methods of rainwater harvesting that have the potential to satisfy local community and crop demands are described in UNEP (2005).

Water diversions

Diverting surface waters into nearby spreading basins/infiltration lagoons, ditches, recharge pits or injection wells to recharge alluvial or other types of aquifers are techniques used to deal with natural variability in flow, reduce evaporative losses, and obtain better quality water. Water diversion programmes being established around the globe are referred to as ASR (artificial storage and recovery) or MAR (managed aquifer recharge) (see **Box 4.6**). This practice is being applied in arid and semi-arid locations throughout the Middle East and Mediterranean regions. Runoff in 'wadis' (dry riverbeds that only contain water during times of heavy rain) that otherwise would discharge into the sea or evaporate, is collected behind earthen berms following infrequent but heavy rainfall. The water infiltrates into the underlying alluvial gravel thereby remaining available for substantively longer periods without the excessively evaporative losses that would typically occur from surface storage. In wetter areas, diversions into alluvium are used as a means not only to store and maintain groundwater-dependent ecosystems, but also to reduce the treatment needed for the water supplies systems taken from the alluvium further downstream.

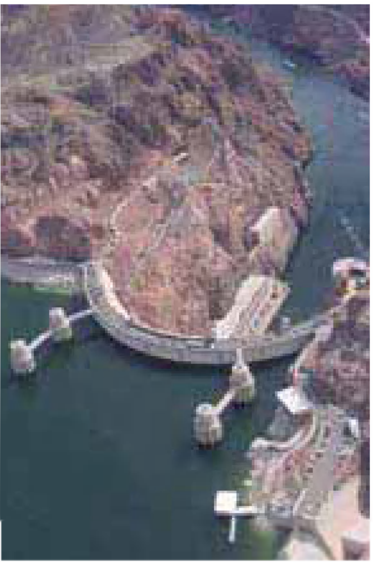
Professional associations such as the US National Ground Water Association (US NGWA) and the IAH (International Association of Hydrogeologists) Commission on Managing Aquifer Recharge (MAR)[6] in cooperation with UNESCO and other international donors, are actively supporting MAR with applied research, capacity-building and pilot projects. MAR programmes, some including injection of treated wastewaters, are being carried out in both developed and developing countries (e.g. in Australia, China, Germany, Hungary, India, Kenya, Mexico, Oman, Pakistan, the southern Africa region, Switzerland and the US).

Kakadu National Park, Australia. Most predictions indicate that precipitations will increase in Australia due to climate change

Intercepting and collecting rainwater where it falls is a practice that extends back to pre-biblical times...

5. See www.irha-h2o.org for more information.
6. www.iah.org/recharge/MAR.html

...the major hydrological challenge will be to achieve more equilibrium between the stored volumes needed to meet users' demands and the incoming and outgoing flow...



Storing water in reservoirs

The construction of dams to create reservoirs has frequently been our response to growing demands for water to provide hydropower, irrigation, potable supplies, fishing and recreation, as well as to lower the impacts and risks to our well-being from high-intensity events such as floods and droughts. These facilities collect natural runoff, frequently quite variable in its location, duration and magnitude, and store it so that its availability is more constant and reliable. Good information on the number and capacity of dams is essential to assess impacts and responses at the local, national and regional levels in order to optimize water resources management, but it is also needed to address issues related to global climate and water availability scenarios (see **Chapter 5**).

Though the creation of reservoirs enables higher water availability when and where it is needed, the construction of these facilities has had a considerable impact, both positive and negative, on the Earth's ecosystems and landscapes and has resulted in modifications to the interactions among the components of the hydrological cycle. Despite increased benefits derived from the services reservoirs provide, there is ongoing debate about how to prevent and reduce the social and environmental consequences that come from building dams and creating reservoirs. Following considerable media attention and local actions some practices are changing. Large dam construction rates have slowed, at least temporarily, and there have been advances in the reconsideration of alternatives and design criteria. Some existing dams that no longer provide extensive services have been decommissioned. Lastly, existing reservoir operations and structures have been modified to allow releases. A balance between what enters and what is released is required to have a site's upstream and downstream hydrological settings and supporting ecosystems sustained. When such a balance is achieved, the results are substantial. There are both added benefits and potential further value to the role of reservoirs in development scenarios.

Transferring water among basins

The transfer of water from one river or aquifer basin to another basin has long been used as a way to meet water demands, particularly in arid and semi-arid regions. It occurs often when large populations or, more commonly, agricultural demands have outstripped existing water resources. Even in advanced national development stages, some basins can have surplus water resources while others face shortages. Major long-distance schemes exist in many nations and new ones are in development. Linking the Ganga-Brahmaputra-Meghna system with other rivers in India is part of the solution being offered to counteract extensive recurring droughts and floods. For example, Shao et al. (2003) present the situation in China where there are seven existing major transfers and seven more planned or under consideration. They describe a large-scale south-to-north basin transfer involving the Yangtze and Yellow Rivers' basins which, when completed, would divert 450 km^3/yr. They also point out some of the impacts of such a large scheme. Multi-disciplinary approaches allow evaluation of the feasibility and sustainability of transfer schemes. Global experience has shown that although the transfer of water among basins has been identified as a hydraulically and technically feasible response, before proceeding with such potential changes, broad social and environmental considerations must be taken into account.

4c. Water reuse

Asano and Levine (2004) recently summarized the more important challenges associated with water reclamation and reuse. They noted that the technique of water reuse is being applied in many countries including the United States, Mexico, Germany, Mediterranean and Middle Eastern countries, South Africa, Australia, Japan, China and Singapore. Its increased application is being facilitated by modern wastewater treatment processes, which advanced substantially during the twentieth century. These processes can now effectively remove biodegradable material, nutrients and pathogens so the treated waters have a wide range of potential applications (**Table 4.7**). On a global scale, non-potable water reuse is currently the dominant means of supplementing supplies for irrigation, industrial cooling, river flows and other applications (Asano, 1998). The reuse of potable waters has been an accepted global practice for centuries. Settlements downstream produced their potable water from rivers and groundwater that had circulated upstream through multiple cycles of withdrawal, treatment and discharge (Steenvorden and Endreny, 2004; Asano and Cotruvo, 2004; GW MATE, 2003). San Diego gets 90 percent of its current municipal water supply from a wholesale water provider but in future that amount will decrease to 60 percent with the supplementary supply coming from reclaimed water and desalination (USGS, 2005). Similar programmes are emerging in many other large urban centres worldwide where there are limited or less readily available freshwater supplies. Similarly, riverbeds or percolation ponds have been used to artificially recharge underlying groundwater aquifers mainly with wastewater.

Recent documents from WHO (Aertgeerts and Angelakis, 2003) and the US EPA (2004) address the state-of-the-art aspects and future trends in water use, both of which predict increased development and use of the above-mentioned practice to augment water supply sources in order to meet demands. The WHO guidelines for wastewater reuse first published in 1995 are being updated with a planned release date of 2006 (WHO, 2005). According to water reuse surveys (Lazarova, 2001; Mantovani et al., 2001), the best water reuse projects in terms of economic viability and public acceptance are those that substitute reclaimed water in lieu of potable water for use in irrigation, environmental restoration, cleaning, toilet flushing and industrial uses.

The annual reclaimed water volumes total about 2.2 billion m^3, based on 2000 and 2001 figures from the World Bank. Recent projections indicate that Israel, Australia and Tunisia will use reclaimed water to satisfy 25 percent, 11 percent and 10 percent, respectively, of their total water demand within the next few years (Lazarova et al., 2001). In Jordan, reclaimed water volumes are predicted to increase more than four times by 2010 if demands are to be met. By 2012, Spain will need to increase its reclaimed water use by 150 percent and, by 2025, Egypt will need to increase its usage by more than ten times. A number of Middle Eastern countries are planning significant increases in water reuse to meet an ultimate objective of 50 to 70 percent reuse of total wastewater volume. The growing trend of water reuse is not only occurring in water-deficient areas (Mediterranean region, Middle East and Latin America), but also in highly populated countries in temperate regions (Japan, Australia, Canada, north China, Belgium, England and Germany). This method of augmenting natural water sources is becoming an integral component to many water resources management plans and future use policies.

4d. Demand management

Conserving available water and reducing demand is a necessary measure in water-short regions, especially those in arid climates. Programmes of conservation and demand reduction are referred to as water demand management (WDM). This approach differs from the traditional supply-driven method, which makes all existing water available. WDM applies selective economic incentives to promote efficient and equitable water use. It also identifies water conservation measures that are aimed at raising society's awareness of the scarcity and finite nature of the resource.

Conservation measures have not been readily implemented, particularly where water was perceived as abundant. However, the benefits in the extended useful life of water supply and treatment plants and in the operating efficiency and duration of sewage disposal systems can be considerable in terms of higher economic return on investment. On the environmental front, conservation

At inland locations or where desalination is too costly, reclaimed water can now significantly contribute to the overall water supply used for irrigation or industry...

Table 4.7: Potential applications for reclaimed water

Application settings	Examples
Urban use	
Unrestricted	Landscape irrigation (parks, playgrounds, school yards), fire protection, construction, ornamental fountains, recreational impoundments, in-building uses (toilets, air conditioning)
Restricted-access irrigation	Irrigation of areas where public access is infrequent and controlled (golf courses, cemeteries, residential, greenbelts)
Agricultural irrigation	
Food crops	Crops grown for human consumption and consumed uncooked
Non-food crops, food crops consumed after processing	Fodder, fibre, seed crops, pastures, commercial nurseries, sod farms, commercial aquaculture
Recreational use	
Unrestricted	No limitations on body contact (lakes and ponds used for swimming, snowmaking)
Restricted	Fishing, boating, and other non-contact recreational activities
Environmental use	Artificial wetlands, enhanced natural wetlands, and sustained stream flows
Groundwater recharge	Groundwater replenishment, saltwater intrusion control, and subsidence control
Industrial reuse	Cooling system makeup water, process waters, boiler feed water, construction activities, and washdown waters
Potable reuse	Blending with municipal water supply (surface water or groundwater)

Source: Asano and Leavine, 2004.

One interesting emerging concept proposes combining desalinated water with aquifer storage and recovery...

allows for the diversion of the unused volumes to sustain ecosystems and also lowers the pollution loadings to lakes, rivers and groundwater. Such steps lead to improved protection of drinking water sources and overall ecological balance (Environment Canada, 2005b).

WDM advocates a wide range of measures that go beyond conservation to broader sustainable resource management. It applies to the protection of water quality sources; reduction of wastage both in infrastructure leakage and by users; improvement of water allocation among competing uses, and creation of appropriate pricing mechanisms. One example of a situation where conservation measures are needed is the case of 'undelivered water' – a commonly accepted result of utilities supplying water through piped distribution systems. The leakage from degraded pipes provides 'unaccounted for' water that results in both a physical shortage and reduced revenue. In terms of inefficiency of resources and operations, losses are routinely reported as 40 percent and as high as 60 to 70 percent in some major cities. Though it is an endemic problem for most water utilities, its impact on society in terms of wasted water resources is even more substantial.

Further water conservation can be achieved after delivery by improving use practices in households. Reductions in community water use after conservation measures have been applied are reported to be as high as 40 percent. These two situations illustrate to what extent the water that is currently supplied may not actually be needed. By reducing leakage and demand, substantial reductions in the source volumes could be achieved. This should be a clear message in development settings. WDM may obviate the need for some of the proposed large-scale physical or infrastructure investments and thereby provide real efficiency gains to society (GWP, 2005a).

4e. Desalination

Desalination is used mainly in water-scarce coastal arid and semi-arid areas that are located inland where the only available water source is saline or brackish groundwater. The technology has been well established since the mid-twentieth century and has evolved substantially to meet the increased demands of water-short areas. Awerbuch (2004) and Schiffler (2004) report on the global application of desalination capacity and the most recent advances and challenges. According to the latest statistics in 2002 from IDA (International Desalination Association),[7] about 50 percent of global desalination takes place in the Middle East, followed by North America (16 percent), Europe (13 percent), Asia (11 percent) Africa (5 percent) and the Caribbean (3 percent). South America and Australia each account for about 1 percent of the global desalination volume. Globally, the contracted capacity of desalination plants is 34.2 million m^3/day converting principally seawater (59 percent) and brackish water (23 percent). In terms of the uses of desalinated water, municipalities are the largest users (63 percent), followed by substantial industry use (25 percent). The cost of producing desalinated water has fallen dramatically in the past two decades. Recently built large-scale plants produce fresh water for US$ 0.45/m^3 to US$ 0.50/m^3 using reverse osmosis (RO) systems and US$ 0.70/m^3 to US$ 1.0/m^3 using distillation systems. The energy consumed to drive the conversion is a significant part of the cost and ranges from 4 to 15kWh/m^3 depending on factors such as the technique used, the production rate of the facility, and the quality of the equipment (US NRC, 2004).

Much of the conversion is likely to continue to be heavily reliant on fossil fuels with its associated air pollution. The challenge of what to do with the brine waste by-product remains. Today it is disposed of by discharge into the ocean or surface waters, sewage treatment plants, deep-well injection, land application or further evaporation in ponds. Each of these methods has potentially adverse environmental impacts. The cost of concentrate disposal for inland locations often limits its applicability in these locations. Schiffer (2004) recommends the establishment of an internationally agreed-upon environmental assessment methodology for desalination plants to enable the impacts from different facilities to be consistently compared.

Future uses for desalination are emerging and IDA expects that, with increasing demand and the up-scaling of processes, it will continue to be applied for the development of economies in coastal areas to partially meet the demands of recreation and tourism, environmental protection, the military, and irrigated agriculture. One interesting emerging concept proposes combining desalinated water with aquifer storage and recovery (DASR) (Awerbuch, 2004; Pyne and Howard, 2004). This approach has the advantages of allowing storage and recovery of large volumes of water while minimizing facility throughput with lowered operating costs. Stored volumes could be used to meet daily or seasonal peaks in water demands while maintaining a steady desalination rate.

7. See www.idadesal.org for more information.

4f. Water Resources Assessment (WRA)

Water resources assessments (WRAs) are designed to be analyses of available water sources from the perspective of potential water use. Since Rio '92, and in particular the Dublin 2000 considerations, water resources have come to be more broadly considered within the dimensions of social equity, economics and ecosystem/ecohydrology. The modern WRA process can be adapted and updated to include these relationships (GWP, 2005b).

Hydrological data and information systems and networks provide the basic and critical input to WRA, whether the assessment is done within an IWRM perspective at the national or basin/sub-basin/aquifer level or otherwise. Factors that affect the accuracy of hydrological input to WRAs include: the number of gauging stations, station distribution within physiographic regions, duration and continuity of observations, quality of measurements, and data processing. The commonly measured parameters include precipitation, evaporation, soil moisture, river level and discharge, groundwater (well) depths, sediment and water quality data on a continuous, hourly, daily or monthly basis.

However, reliability and availability of data have declined sharply since the mid-1980s, particularly in Africa and in Eastern Europe (Rodda, 1998), and that situation has not changed substantively since the turn of the century. Investment in national networks has fallen drastically and is still decreasing. Hydrometric networks, while they are costly to maintain, provide basic WRA input that cannot be collected dependably by any other means (see **Chapter 13**).

The development of more decentralized and basin-type approaches for WRA is inherent in the internationally agreed upon IWRM principles. It is widely recognized that it will take several decades of institutional adjustment (Blomquist et al., 2005) to reorient water management practices on basins. However, such changes are beginning at the basin level and there are examples of decentralized approaches on most continents in terms of water management processes. An important element of the World Water Assessment Programme's mission is to assist partner case study countries in developing their own assessment capacity (see **Chapter 14**). Sovereignity issues and competition will always remain factors in managing the resource. However, the basic WRA scope which broadly defines the extent of available water quantity and quality, including aspects related to environment, pollution and water use, is the basis for effective management. This information can be collected and jointly developed by the nations sharing the resource (see **Chapter 11**). These will give forward-looking direction not only in water technology areas but also on how improving data, information and assessment practices for water resources will provide critical knowledge that will greatly benefit society, human livelihoods and the environment.

Many developing nations, where the demand for water is growing the fastest, have the worst capability for acquiring and managing water data

Part 5. The Challenge of Sustainable Development

Climate change and the hydrological variability of water's distribution and occurrence are natural driving forces that, when combined with the pressures from economic growth and major population change, make the sustainable development of our water resources a challenge.

5a. Driving forces and pressures

The combination of these factors commonly results in increased water use, competition and pollution in addition to highly inefficient water supply practices. These results can be traced back to the fact that most decisions in water resources management, at almost all levels, remain principally driven by short-term economic and political considerations that lack the long-term vision needed to implement sustainable development practices. Water management plans should consider the best existing practices and the most advanced scientific breakthroughs.

The scientific community has to convey more effectively its recommendations to decision-makers to enable the latter to develop and maintain multidisciplinary integrated approaches and solutions. Societies should realize that today's water-related challenges are no longer readily solved just by using last century's hydraulic schemes. Increased funding and resources need to be provided for the collection of detailed water data and information.

Overall, there are reasons to be hopeful as new water programmes are emerging that finally emphasize the application of more sustainable practices to reduce impacts

5b.State of our natural water resources

The roles and interdependencies of the different hydrological cycle components are often not fully appreciated. As a result, it is difficult to set up adequate protection and prevention strategies.

All components of the hydrological cycle should be taken into account when developing water management plans. Each component has a specific role that must be better understood. For example, rain and snow directly supply terrestrial ecosystems and soil moisture is a unique water source for both agricultural development and terrestrial ecosystems. Furthermore, glacial melting has a strong influence on water availability in many nations and as a result more comprehensive global assessments are needed.

We can substantively predict annual variability in surface runoff and have created solutions to deal with it. However, overcoming the less predictable five- to ten-year global cycles of distinctly lower and higher runoff remains a challenge. Groundwater resources could provide a valuable contribution to overcoming climate variability and meeting demands during extended dry periods. A surplus of surface water runoff during wet periods can be used to replenish aquifer systems.

However, we do not have enough data on groundwater and aquifer systems, especially in developing countries where the lack of adequate surface water resources is most extreme. This is particularly true in both Asia and Africa where there has been a dramatic reduction in water monitoring programmes.

Water quality monitoring programmes are inadequate or lacking in most developing nations; thus safeguarding human health is difficult. Despite two decades of increased international scientific attention and concern, attempts to collect, compile and gain knowledge from consumption, pollution and abstraction data and information at a global scale are still piecemeal and in relatively early stages of applicability.

5c. Impacts

Poor quality water and unsustainable supplies limit national economic development and can lead to adverse health and livelihood conditions.

Landscape modifications further complicate our understanding of and ability to predict the impacts on water resources since these changes disrupt natural hydrological and ecosystem functioning. This becomes more important when we seek to advance our understanding of the future impacts of climate change at local and regional scales. We know that detailed estimates of climate change impacts on water resources at regional or global scales are currently very problematic due to inadequate water data.

We have reached a reasonable level of knowledge towards recognizing impacts on water quality and quantity from pollution and excessive groundwater and surface water withdrawals. The focus must now be on reducing these impacts. In most developing countries, specific and well-targeted programmes should be funded to reduce impacts on water quality and quantity.

Overall, there are reasons to be hopeful as new water programmes are emerging that finally emphasize the application of more sustainable practices to reduce impacts.

5d. Responses

Prevention strategies and new technologies that augment existing natural water resources, reduce demand, and achieve higher efficiency are part of the response to meet today's increasing demands on our available water resources.

To meet current and future water demands, increased attention should be given to precautionary approaches such as innovative uses of natural supplies and new technologies. In the past we have responded by storing runoff in reservoirs, diverting flows from water-abundant to water-scarce regions, and extracting aquifer resources – methods that provided ample water where and when it was needed. These methods are likely to remain part of most water resources development strategies. Non-conventional water resources, such as water reuse and desalination, are being increasingly used and new technologies such as artificial recharge are also becoming more and more common. Capturing rain at the source through rainwater harvesting is yet another method used to increase the availability of natural water sources. In certain regions, an extreme response has been adopted. In some arid countries, where sufficient renewable water resources are not available, non-renewable groundwater reserves are being exploited to support development.

Demand management and conservation are methods that target efficiency. Conservation begins by reducing high losses from water supply distribution systems. Demand management has gone largely unaddressed since most water utilities still focus on infrastructure development rather than on conservation.

It is worth noting that industry's approach in recent years has been to reduce wastewater and minimize the quantity of processed water needed as this method has proven to be technically feasible and economically advantageous. The demand reduction and efficiency approach should be an integral part of modern water resources management. Its applicability should be promoted while recognizing that it requires a distinct change in the behavioural patterns of institutions, utilities and individuals – a change that will require education, awareness-raising and political commitment to achieve effective implementation.

Institutional responses at different levels are also needed. Some nations have implemented new laws and regulations that point the way forward toward protecting and restoring our water sources. Many nations are adapting emerging technical practices to secure and protect their existing natural water resources and use local knowledge as part of sustainable resource development.

5e. The benefits

There will be economic, social and environmental benefits from carrying out regular Water Resources Assessments (WRAs) in all basins and aquifers in individual nations as well as regionally, where transboundary shared water resources are present.

Modern approaches to WRA are rapidly emerging and now go well beyond the traditional hydraulic and supply-biased studies carried out during the last century. WRAs have been extended to take advantage of the recently recognized benefits that come from using an integrated approach (IWRM) and including ecosystems' services (ecosystem approach). WRAs continue to fundamentally require well-documented hydrological cycle component data – without this data the evaluation results are unreliable. To be comprehensive and assist in sustainable practices, WRAs should include well-documented user consumption and water quality requirements, accurate use data, estimates of the environmental flow volumes needed to maintain ecosystem resilience, characterization of both point and non-point sources of pollution and the quality of the receiving waters, and the extensive engagement of all water users and other pertinent stakeholders.

Providing incentives to improve demand management efficiencies has proven highly effective in augmenting natural water supplies. WRAs should consider new capacities to use non-conventional water supplies and new technologies to augment existing supplies. A comprehensive WRA must also include social and economic considerations as well as ecosystem needs and contributions.

If climate change follows the projected scenarios, we can expect more erratic weather in the future, including increased variability in precipitation, which will threaten crop yields in both developed and developing countries, while placing more than 2.8 billion people at risk of water shortage. Understanding all aspects of the hydrological cycle is critical if our society is to be able to cope with the many changes we observe.

Many nations are adapting emerging technical practices to secure and protect their existing natural water resources and use local knowledge as part of sustainable resource development

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