2 World Water Resources, Water Use and Water Management

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2.1 INTRODUCTION

Freshwater is the most important natural resource, without which human activity and life would be impossible because there is no substitute for water. It is also an integral and important component of the environment. Like water scarcity, water over-abundance can be a hazard that can lead to great damage and calamity. People consume and conserve water because they cannot survive without it but, at the same time, they must maintain the environmental balance and protect themselves from the hazards of water. This variable relationship with water gives rise to difficult interactions between water and people that are characterized differently in different regions, and have also changed over time as societies have developed.

Each stage of human society is closely associated with water problems. The history of each country is a process of a gradual transition from the simplest ways of using rivers and lakes (in their undisturbed states) to an intensive transformation of their regimes through various hydraulic structures, such as irrigation and drainage canals, hydroelectric power plants and large constructed reservoirs. However, in recent years, there has been a greater evaluation of the need for new large hydraulic structures (e.g. the Report of the World Commission on Dams, 2000) and dams have been decommissioned in some parts of the world. Economic development and higher living standards generally lead to ever-growing water use. From a historical point of view, the current water situation in the world is a product of social, economic, and ideological developments stemming from the advent of industry approximately 200 years ago. Industrialization was accompanied by trends that have led to an unprecedented increase in water use: the greater needs of industrial and agricultural production, an expansion in world population, an explosive rate of urbanization, and a pronounced increase in ecological impact including landscape change, pollution, and resource depletion. Consequently the measures required to solve diverse water problems may differ greatly in various regions of the world, depending on the physiography and level of socio-economic development.

Being limited and vulnerable, freshwater still restricts socio-economic development in many countries and regions of the world. The results of many water resource assessments indicate that in the coming decades water supply problems may become acute for most of the population on the planet, exacerbated by the effects of anthropogenic global climate change. This chapter begins by discussing the importance of global hydrology and new concepts relevant to global water resource assessments, such as “virtual water”. The next section presents current and future assessments of water resource availability, use and management in different natural-economic regions in the world to provide a background to the contemporary water issues that are examined in detail in Chapter 3. This is followed by a short section that emphasizes the necessity of addressing the land degradation and soil erosion that often occur as a result of hydrological processes. Finally, water resources management is discussed as a means of reconciling conflicting demands for water resources.

2.2 THE IMPORTANCE OF GLOBAL HYDROLOGY

2.2.1 Hydrology as an important part of Earth System Science

Why is global hydrology highlighted now? It is because water, as one of the major components of the global climate system, is one of the major cross-cutting axes in Earth System Science. The water cycle transports various materials, such as sediments and nutrients, from land to the oceans. Water resources are closely related to energy, industry and agricultural production. Of course, water is indispensable for life and supports health. Water issues are related to poverty, and providing access to safe drinking water is one of the key necessities for sustainable development. In the past, water issues were local issues. However, due to the increase in international trade and mutual interdependence among countries, water issues now often need to be dealt with at the global scale and require information on global hydrology for their resolution. Sharing hydrological information relating to transboundary river basins and shared aquifers will help reduce conflict between relevant countries, and quantitative estimates of recharge amounts or potentially available water resources will assist in implementing sustainable water use.

Global hydrology is not only concerned with global monitoring, modelling, and world water resources assessment. Owing to recent advancements in global earth observation technology and macro-scale modelling capacity, global hydrology can now provide basic information on regional hydrological cycles which may support the decision making process in integrated water resources management. Practically speaking, any flood forecasting with a lead time longer than the flood concentration time requires meteorological or climatological forecasts. Even the latest, sophisticated, physically-based, distributed, and (likely) complicated basin model cannot forecast a river discharge with a drainage area of less than 1000 km^2 beyond two days without meteorological forecasts. It is also impossible to predict monthly discharge half a year in advance without seasonal forecast information. Of course, surface fluxes, such as sensible, latent, and momentum fluxes, determine boundary conditions for atmospheric circulation and there are interactions between surface hydrology and meteorology. Surface hydrological conditions have a significant role in seasonal predictions, at least in some “hotspots” in the world (Koster *et al.*, 2004). Therefore, even regional scale hydrology should consider the implications of global Earth System Science.

2.2.2 Global hydrological observations

The contribution of hydrological science to resolving local water problems and stimulating people’s interest in water issues in their immediate environment has been hampered by the lack of systematic collection of observational data on the global water cycle. The history of global observational networks of hydrological variables established after World War II, from the International Geophysical Year (1958), the International Hydrological Decade (1965–1974) and the Global Atmospheric Research Project (GARP), to the Global Precipitation Climatology and Runoff Data Centres (GPCC and GRDC) established in the 1980s and 1990s, is well known and will not be repeated here. The amount of river discharge data available worldwide peaked around 1979 when the First GARP Global Experiment (FGGE) was implemented and river discharge data were intensively collected and assembled under international collaborations.

The FGGE initiated "4-dimensional data assimilation" (4DDA), which merges the products of numerical weather forecasts and satellite/*in situ* observations considering the uncertainties in each estimate. Satellite and *in situ* monitoring networks generally do not hold observational data at regular temporal and spatial intervals, e.g. every six hours at 2.5 degree or 1.0 degree latitudinal and longitudinal grid points. However, their accuracy may be better than that of model predictions that are available at regular temporal and spatial intervals globally. The 4DDA technology was developed to provide the initial conditions for improved weather forecasts by combining the advantages (and disadvantages) of actual observations with model predictions. However, it has been recognized that 4DDA data is also useful in climate studies and efforts to re-analyse past records (Kalney *et al.*, 1996).

Gridded datasets, such as GPCC precipitation fields or 4DDA surface meteorology fields, are handy to use and are sometimes the only hydro-meteorological information available for regional hydrological simulations and water resources assessments. However, regions with less or no real observational data are filled with model simulations or spatially-interpolated values, and thus the accuracy may not be as high as in regions with a higher density observational network. As a result, hydrological simulations conducted with these global datasets in regions with sparse *in situ* observational data tend to have poor accuracy (Oki *et al*., 1995). Remote sensing may be the only source of information on land surface properties with high resolution and large spatial coverage, but its accuracy is only known through *in situ* observations. An *in situ* observational network with the appropriate density combined with satellite remote sensing, and possibly assimilated with numerical model products, will provide the best knowledge of global and regional hydro-meteorological conditions.

In situ meteorological observational data are exchanged internationally through the Global Telecommunication System (GTS) under the framework of the World Meteorological Organization (WMO) but not river discharge data. This is an example of how key hydrological data are not being collected and assembled internationally even for research purposes, let alone management purposes. It is one of the motivations behind the Hydrology 2020 Working Group's proposal for an international water body that will manage river discharge information from every country.

It is a concern that many governments place a low priority on keeping and maintaining existing *in situ* observational networks, and thus, the number of observing stations is decreasing. Satellite remote sensing is powerful and useful but requires substantial resources and, therefore, its utility is also vulnerable to budget and network cuts. This crisis was one of the major motivations behind establishing the intergovernmental *ad hoc* Group on Earth Observations (GEO) at the first Earth Observation Summit in July 2003. The group adopted the Global Earth Observation System of

Systems (GEOSS) 10-Year Implementation Plan on 16 February 2005, and summarized the essential steps to be undertaken, over the next decade, by a global community of nations and intergovernmental, international, and regional organizations. "*Improving water resource management through better understanding of the water cycle*" is one of the nine social benefits identified in the plan. Hopefully it will help sustain current global hydrological monitoring networks, consisting of regional and local *in situ* observational stations, or develop and implement better monitoring systems.

2.2.3 Climate change awareness and global hydrology

Scientific interest in global hydrology has increased since the 1980s as awareness of global environmental issues and process interactions, such as El Niño events and anthropogenic climate change, has risen. In early publications, estimates of global river discharge were required to validate the hydrological cycle simulated by general circulation models (GCMs) (Russell & Miller, 1990; Miller *et al.*, 1994, Sausen *et al.*, 1994), but increasingly global river discharge itself has become one of the main targets of GCM simulations (Kanae *et al.*, 1995; Milly *et al.*, 2002; Manabe *et al.*, 2004) because it is another link between the atmosphere and the oceans through its effect on salinity, and ultimately, thermohaline circulation.

Awareness of climate change has changed the classical view of the hydrological cycle and how it is treated. For example, stationary stochastic processes have been assumed for classical statistical analysis in hydrology, but now it is widely accepted that there are decadal or longer oscillations in the natural climate system and the statistical characteristics of hydrological quantities are changing accordingly. Climate change, particularly global warming due to anthropogenic activity, is recognized even among policy makers and the anticipated impacts of such a change to the hydrological cycle in the future tends to be reflected in the current design of facilities for water resources management. The influence of climatic anomaly fields was unknown in the past, and the relationship between global climatic variations, such as the El Niño–Southern Oscillation (ENSO), and regional anomalous weather were not considered, or a concern. However, owing to the implementation of an enhanced observational network in the 1980s through to the 1990s and a better understanding of process interactions, events such as ENSO are predicted more than a year in advance and this information is utilized for adapting to anomalous weather associated with ENSO, such as droughts or long rainy seasons.

2.2.4 Global hydrology for world water resources assessment

Global water resources assessments have been increasingly emphasized since the late 1990s with the recognition of the impending "global water crisis" in the 21st century. Shiklomanov (1997) assembled information on past, current, and future water resources across the world. Assessments of future water resources that take into account changes in climate and society were made by various authors (e.g. Alcamo *et al.*, 2000; Vörösmarty *et al.*, 2000; Wallace, 2002; Oki *et al.*, 2003; Arnell, 2004). The former results (Shiklomanov, 1997) should be suitable for current assessments because the approach is based on statistics and reports published by each country and/or researchers and all the basic information are based on observations. In contrast, the latter approach utilizes model estimates based on knowledge of the global hydrological cycle. Model estimates are not always accurate because numerical models, input data, and the necessary physical and non-physical parameters are never without errors. However, the approach of using numerical models to estimate the global distribution of availability and demand, or withdrawal of water resources, has the advantage of being able to estimate water demand and availability within national boundaries incorporating future hydrological cycles modified by climate change. Moreover, human activities, such as changing land cover, storing water in artificial reservoirs, and withdrawing water for irrigation, domestic water usage, and industrial purposes, have been altering water cycles on a global scale, and the feedback to climatic systems can be taken into account through the modelling approach. In this era of global change—the Anthropocene (Crutzen, 2002)—it is now recognized that human activities are changing the global water system and that the prevailing hydrological cycle is not a "natural" hydrological cycle unaffected by human activity.

The ultimate purpose of global water resources assessment is not just to predict the regions that will experience severe water scarcity in the future, but to warn these regions that such a situation will be realized if no action is taken to mitigate the anticipated water problems. Ideally, suggested mitigation measures would be proposed simultaneously with the prediction of potential future hazards. Modelling approaches can incorporate cause and effect relationships and conduct sensitivity analyses of the impact of changing policies, which can assist in developing alternate plans. Basic understanding and a sufficient observational capacity of global hydrological cycles are key to achieving efficient proposals that will help mitigate global water issues in the future.

2.2.5 Virtual water trade

Although they are not really within the field of hydrology as a natural science, new concepts related to water resources management and assessment, such as *green water* (Falkenmark *et al.*, 1989; Falkenmark, 1995; discussed in more detail in Section 2.9.2) and *virtual water* (Allan, 1997, 1998) were introduced in the 1990s. Quantification and implementation of such concepts to global and local water resources assessments is required.

The concept of "virtual water trade" has been developed to explain how physical water scarcity in countries in arid and semi-arid regions is relaxed by importing water-intensive commodities (Allan, 1998). The original idea of virtual water trade is therefore, "importing food is as if importing water"; namely, food trade is virtually the trade of water because importing countries can use their own water resources for other purposes such as domestic water use.

Today the perhaps more straightforward and easier to understand concept of "virtual water content"—the water used to produce the commodity (Hoekstra & Hung, 2002)—is used. In this case, "virtual water content" is the same as the external cost of water for agricultural and livestock production processes and it has recently been called a "water footprint" (Chapagain & Hoekstra, 2004). However, the amount that was used to make the product does not necessarily reflect the amount of water which can be saved by the virtual water import. Utilizing the concept of "virtual water trade" for water resources assessment, the amount that should be estimated is the quantity of water needed if the same amount of imported goods were produced in the importing country. In this case, there will be a difference between the amount of water actually used during the production process in the exporting country, and the imported amount of virtual water. The difference explains the comparative advantage of food production and can illustrate how much water usage is saved globally (Oki & Kanae, 2004).

The confusion between these two definitions of “virtual water” most likely started from a misunderstanding in which some people regarded the trade of food as the “trade of virtual water”. Instead, originally, the food trade was regarded as the “virtual trade of water.” Since “virtual water content” is really the external cost of water usage to the environment, it may be more appropriate to call it “environmental virtual water” (Allan, 2004, personal communication). Another issue regarding virtual water trade is that the water required for the same amount of product can vary. This is partially because values differ from region to region and country to country due to differences in water use efficiency and crop yield per area. Also, the definitions of “water usage” and “per weight of crops” are sometimes unclear. Water usage may include only the amount transpired by plants, or instead, it may account for all the required water to grow the crop including the loss through the irrigation canal. The weight of crops may only include the edible portion of the food product, or instead, it may include the husk or discarded portions.

Here “virtual water” is defined as “virtually required water” in its original sense, and we may call the water used in the exporting country as “really required water” or “real water” in the same way. From this point of view, “real water” in exporting countries becomes “virtual water” in importing countries. Global “virtual water” flows associated with major cereal (wheat, rice, maize, and barley) trade were estimated for each country where statistics were available in the year 2000, and summarized as annual virtual water flows for 16 regions (Fig. 2.1). The Middle East, Northwest Africa, and East and Southeast Asia are recipients of virtual water, and the sources of virtual water are North America, Oceania and Europe.

The existence of virtual water flow demands a modified view of classical world water resources assessment. According to the classical view, 22 countries were identified as “seriously stressed” because less than 1000 m^3 $year^{-1}$ $capita^{-1}$ of water resource is available. However, if the virtual water trade, including livestock production and the major crops in Fig. 2.1, is considered for these countries (expressed as GDP per year per capita), Fig. 2.2 shows that only five countries are categorized as “seriously stressed” (Oki *et al.*, 2004). Furthermore, richer countries with available water resources exceeding 2000 m^3 $year^{-1}$ $capita^{-1}$ may even be classified as “slightly stressed” if virtual water flow is considered. This result clearly indicates the importance of considering human aspects in world water resources assessment, and the strong relationship between economic poverty and water shortages.

Generally crop yields and water efficiencies in exporting countries are higher than in importing countries. Consequently, “real water” in exporting countries tends to be smaller than “virtual water” in importing countries. For example, 1 kg of soy bean corresponds to 1.7 t of “real water” in the USA and 2.5 t of “virtual water” in Japan. In this sense, the virtual water trade of 1 kg of soy bean from the USA to Japan saves 0.8 t of global water resources. The total virtual water trade (imported virtual water) for commodities in 2000 was estimated to be approximately 1140 km^3 $year^{-1}$. However, this corresponds to only 680 km^3 $year^{-1}$ of real water suggesting a water saving of 460 km^3 $year^{-1}$ (Oki & Kanae, 2004). While the virtual water trade will not increase the total water resource, “saved” water in the importing country can be allocated

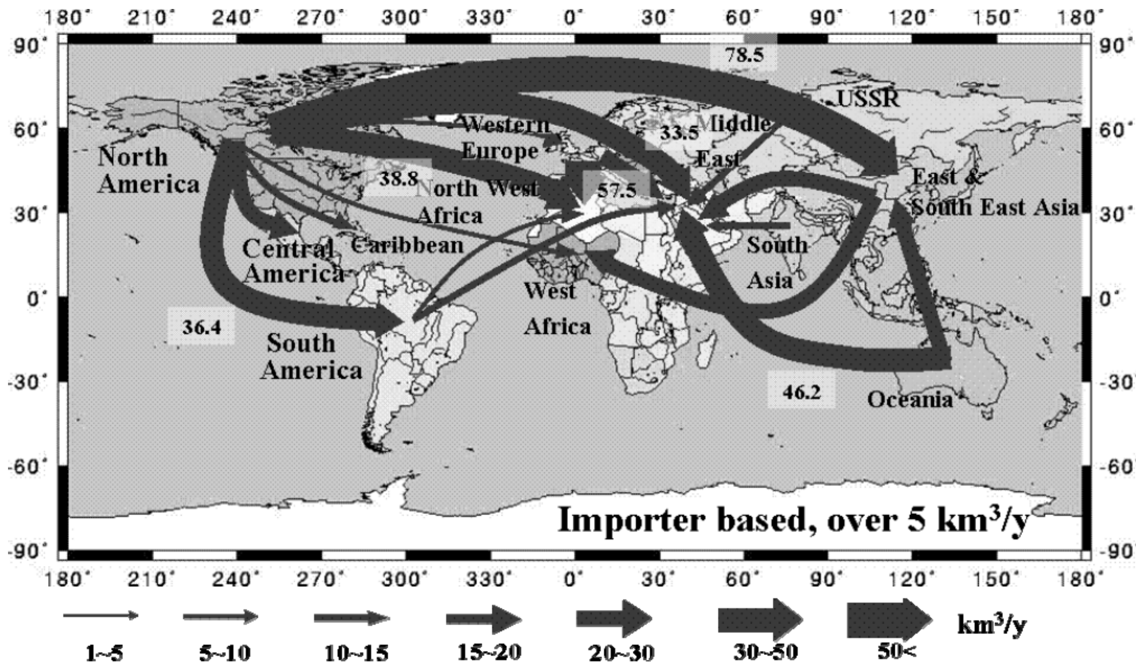

Fig. 2.1 *Annual virtually required water (virtual water) trade (km^3 $year^{-1}$) estimated for the major crops of wheat, rice, maize and barley in 2000 (after Oki et al., 2004).*

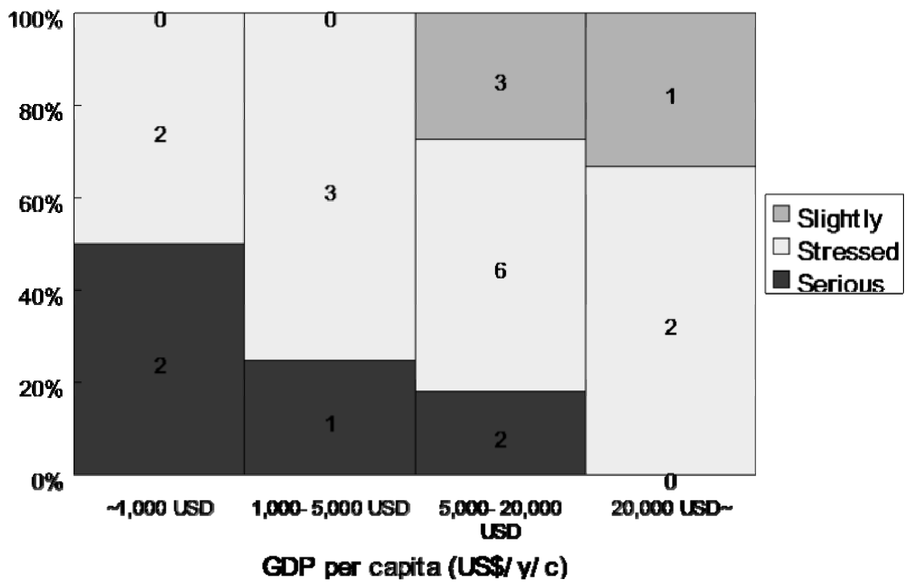

Fig. 2.2 *Country classification by water stress category according to the GDP per capita in 2000. The shading represents the water stress category taking account of virtual water trade (import). All these 22 countries were classified as "seriously water stressed" under natural conditions, but, after considering virtual water trade (assessed as GDP per capita), richer countries are actually classified as less water stressed.*

to other purposes, such as municipal and environmental uses. However, one should be careful when interpreting these results since the idea of virtual water does not consider social, cultural, and environmental implications or limiting factors other than water.

Virtual water trade is a conceptual tool that can be used to consider the inter-relationship and trade-offs among water, food, land, and energy. Further quantification and detailed investigations of virtual water trade, such as the differentiation of virtual water into categories, for example: non-sustainable water resources and rain-fed products, are required, and should be considered in the future assessment of world or even regional water resources.

2.3 RENEWABLE WATER RESOURCES: AREAL DISTRIBUTION AND DYNAMICS IN TIME

2.3.1 Assessment methodology

As indicated in Section 2.2.4, world water resources can be estimated by two methods: from observational data of surface and groundwaters, and from global hydrological models. The estimates of renewable water resources presented in this section are based on observational data. A number of detailed tables were produced for these assessments. The main findings are summarized in the text and accompanying figures; the detailed tables may be referred to in Appendix 5.

Two concepts are often used to assess the water resources of any region: static water storage and renewable waters. Static storage conventionally includes freshwater with a period of complete renewal taking place over many years or decades, such as large lakes, groundwater, or glaciers. Renewable water resources refer to waters replenished annually in the process of the water turnover of the Earth. These are mainly runoff from rivers, estimated as volume per unit of time (e.g. $m^3\ s^{-1}$, $km^3\ year^{-1}$) and formed either within a specific region or derived from external sources, including groundwater inflow to a river network. It also includes the annual renewable upper aquifer groundwater not drained by river systems. However, on the global scale, these volumes are small compared with the volume of river runoff and are of importance only for specific regions or countries. Thus, river runoff is the main component of renewable water resources; it is the most widely distributed over the land surface, and it provides the major volume of water use in the world. Hence, in practice, it is the value of river runoff that is used to estimate water resource availability and/or deficit in a particular region.

The renewable water resources of a region or river basin can be quantified using meteorological data or river runoff observations. In this case, observational data from the world's hydrological network were used to estimate renewable water resources and their dynamics at the global scale (continents, regions and countries). Although the WMO has information on 64 000 stations with measured river runoff (Rodda, 1995), using data from all of these would be impossible because the stations are very unevenly distributed throughout the world. Also, the duration of observation ranges from only a few months to more than 180 years and the data quality is highly variable. Consequently, about 2500 hydrological sites with the following characteristics were selected to estimate renewable water resources at a global scale:

– long time series of continuous observations available;
– located on large and medium rivers, preferably evenly distributed throughout a territory;
– observations reflect the natural (or close to the natural) river runoff regime.

The sites are distributed as widely as possible across all continents: about 800 in Asia, 600 in Europe, 330 in North America, 240–250 in each of Africa and South America, and about 200 in Australia and Oceania. Although more recent data are available in Europe and North America, a single 65-year study period of 1921–1985 was chosen. This enabled comparable mean values of water resources to be obtained for all regions of the world and also reliable estimates to be made of extreme values and long-term variability. The total available renewable water resources of each region were calculated as the sum of local runoff and river inflow. Local runoff is the runoff of all rivers and temporary streams within the region, while river inflow is the total volume of water imported from adjacent regions. Hydrological models, specially developed at the State Hydrological Institute, St. Petersburg, Russia, were used to estimate the renewable water resources of individual countries and natural-economic regions whose boundaries do not coincide with river basins (Shiklomanov & Rodda, 2003).

2.3.2 Water resources of the continents and natural-economic regions of the world

Renewable water resources at the global scale were assessed by dividing the Earth's land surface into 26 large natural-economic regions (Fig. 2.3) with homogeneous physiographic conditions and a similar level of economic development. The areas of

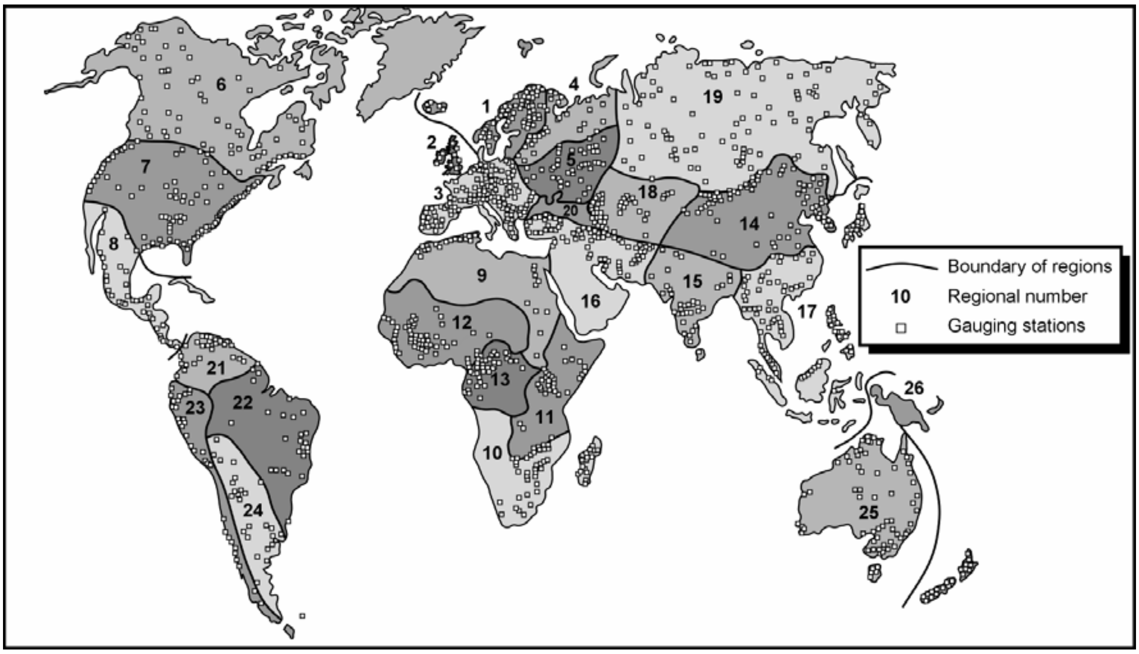

Fig. 2.3 *Natural-economic regions of the world and river gauging stations used for assessment of regional and world water resources. For names of individual numbered regions see Table A.5.1 in Appendix 5.*

the selected regions vary widely from 0.19 to 13×10^6 km^2, though most are $1–8 \times 10^6$ km^2 in area. Dynamics of the renewable water resources of the continents and the world were determined by summing the data for natural-economic regions.

The mean value of renewable global water resources for 1921–1985 was estimated at 42 700 km^3 $year^{-1}$ and it is very variable with space and time (Shiklomanov & Balonishnikova, 2003; see Table A.5.1 in Appendix 5). The mean annual potential water availability per capita worldwide is 7000 m^3, varying from 3600 m^3 in Asia to 34 800 m^3 in South America and 77 200 m^3 in Australia and Oceania. In most regions the majority of water resources are formed internally, whereas in northern Africa and central South America, water inflow equals or exceeds local runoff. The quantity of water resources varies greatly between different regions but potential water availability per capita differs even more, by up to 100 times. Long-term variability, as expressed by the coefficient of variation (CV), is an important characteristic of regional water resources, especially for arid and semi-arid regions where the quantities of water resources are small. Here, in individual years water resources can be 150–200% less than the long-term average, whereas for wet regions this difference is within 15–25%.

The possibilities of using water resources for economic needs are determined not only by their year-to-year variability, but also by their seasonal and monthly variability. Significant monthly and seasonal variations in runoff cause great difficulties in water use during dry seasons. Therefore, in the absence of control structures, a sustainable base runoff subject to slight variations is important for water use. Base runoff is estimated to be 37% of total (global) runoff on average, or about 16 000 km^3 $year^{-1}$. Reservoirs constructed all over the world have a total effective capacity of 4000 km^3 $year^{-1}$, increasing global base runoff by 25% to about 20 000 km^3 $year^{-1}$. Many regions are characterized by an extremely uneven river runoff distribution throughout the year (see Table A.5.2 in Appendix 5). In some regions 60–80% of annual runoff occurs during the three- to four-month wet season and less than 10% during the dry season.

Consequently, storage of river runoff in reservoirs is often an important component of water resource management to provide a sustainable water supply during dry seasons and even dry years. The coefficient of control is a measure of the availability of storage for river runoff and is calculated as the ratio between the effective reservoir capacity and annual river runoff and expressed as a percentage. Coefficient values of 20–40% normally indicate that there is sufficient reservoir capacity to provide a sustainable water supply. The highest control coefficients, greater than 40%, are in the southern European territory of the former Soviet Union, the USA (without Alaska), West Asia, Transcaucasia, and Central Asia and Kazakhstan (Balonishnikova, 2004; and see Table A.5.1 in Appendix 5). High control coefficients also occur in parts of Africa but this is mainly due to the presence of one or two very large reservoirs in each region. In many regions the effective reservoir capacity is small and can only store less than 10% of annual runoff. These regions usually have either high water availability or lack suitable physiographic and ecological features for constructing reservoirs of great capacity (e.g. Central Europe).

2.4 MODERN AND FUTURE TRENDS OF FRESHWATER USE IN THE WORLD

Global and regional trends in water use in the 20th century and in the coming decades were assessed for the 26 natural-economic regions of the world by Shiklomanov *et al.*

(2004). For every region the total water withdrawal and consumption for urban population needs (domestic or municipal water use), industry (including thermal power), irrigated farming and agriculture were estimated, as well as water loss by evaporation from reservoir water surfaces.

2.4.1 Methodology for prediction of water use in the nearest future

There are several basic factors that determine water use in large regions and countries of the world: the level of socio-economic development, population number and characteristics, physiographic features (including climate) and political and institutional water-related aspects. Estimates of all these factors are required to assess the volume, structure and dynamics of water use in the present and future.

Areas suitable for agriculture and irrigation, climate characteristics (annual and monthly precipitation, air temperature, and soil moisture content indices), the amount of renewable water resources and their space–time distribution may be used as indicators of physiographic and climatic conditions. Population number and dynamics is one of the main factors affecting future water use development. The population number not only directly determines domestic water supply volumes but also affects agriculture (irrigation in particular), industry, transport and trade and thereby the water uses of these sectors. Furthermore, it is important to know the proportions of urban and rural populations as these determine total water withdrawal and consumption in rural areas and in cities. The level of socio-economic development is also an important factor which controls the amount of total water use in any region. The value of the annual gross national product expressed in US dollars per capita is usually taken as an indicator of socio-economic development. Political and institutional water-related aspects are also very important, particularly for assessments of future water resources and water use, when it is necessary to take into account the actions of decision makers in developing strategies for the use and protection of water resources.

All the above factors are extremely variable in time and space so that prediction of the factors themselves, and of water use in the future, is subject to many uncertainties. As a result, forecasts of future global water use in the latter part of the 20th century tended to be influenced by the prevailing socio-economic, political and environmental conditions. Forecasts published before 1990 tended to overestimate future water use, mainly because of the extrapolation of the increased rates of water use observed in the 1970s and 1980s in many countries. Forecasts during the 1990s give more moderate estimates for water use in the coming decades because they are based to a certain extent on the present trends and new approaches to freshwater use in the world. During the last 10–15 years there have been fewer plans for enlargement of irrigated lands, construction of large reservoirs in inhabited regions or new large-scale water transfers. Instead, planning institutions have focussed more on improving the efficiency of water use in industry, irrigation and municipal water supply, and on protecting the environment.

In the framework of the World Water Vision Project, three scenarios of world freshwater use for the period of 1995 to 2010–2025 were developed and presented in March 2000 to the Second World Water Forum at The Hague, in The Netherlands. The three scenarios: Business-As-Usual (BAU), Technology, Economics and the Private Sector (TEC), and Values and Lifestyles (VAL), are fully described in Rijsberman (2000). However there may be difficulties using the scenarios for planning water management projects as some of the underlying assumptions are unrealistic. For example, present daily per capita municipal water use is about 600–700 litres in the USA and Canada and 330 litres in Japan. The VAL scenario assumes that these figures will fall to 177 litres in North America and 77 litres in Japan. Such values last occurred in the USA and Canada in the early 20th century. Although measures have been taken in the USA since the 1980s to reduce municipal water use (Gleick, 1998), water use per capita increased by about 4.5%. A similar situation is observed in Canada and in the majority of developed countries. Therefore, it is may be unrealistic to incorporate large reductions in municipal water use in future water resource assessments.

2.4.2 New water use scenarios

In recent years, two alternative scenarios for world water use during the period 2000–2025 have been developed: a Conventional Scenario (CS) and a Sustainable Development Scenario (SDS) (Shiklomanov & Balonishnikova, 2003). These scenarios use the same basic data as the scenarios developed for the World Water Vision Project but reflect fundamentally different approaches to freshwater use in the coming decades.

The CS assumes that attitudes toward freshwater use will not change in the near future so water use for the next 25–30 years will develop in the same manner as during previous decades. This is the most realistic situation as it does not require additional effort and investment to find solutions to water problems. In contrast, under the SDS it is assumed that measures will be taken to save water in every possible way and to achieve the most effective water use. The following changes from 2000 to 2025 were assumed in the SDS:

– *World population* will reach 7.9 billion in 2025.
– *Irrigated lands* will increase in area by 20% worldwide, varying in individual regions from increases of 10% (highly developed countries) to 30–40% (countries with transient economies and some developing countries in Africa and South America).
– *Efficiency of water use in irrigation* will attain 15% on average worldwide, with variations in individual regions from 20% (highly developed countries) to 10%. One third of the efficiency would be attained during the first half of the period, and the other two thirds during the second half.
– In Europe and North America, *domestic water use* (L day^{-1} per capita) will decrease by 10–20% and 40%, respectively. Two thirds of this decrease will occur during the second half of the period. In Africa, water use will increase by 10–20% (in northern and southern Africa) to 100–120% (other regions), mainly during the first half of the period. In southern Asia, an increase in domestic water use of 50% is expected, but in other regions of Asia, there would be no change or a decrease of 10–20%. In 2025, water use would not be less than 50 L day^{-1} per capita in the poorest countries of Africa and Asia and would not exceed 300 L day^{-1} per capita in the richest countries of Asia. In South America and Australia, domestic water use would either decrease by 10–25% or remain unchanged.
– In regions with highly developed countries, *industrial water use* accounted for 0.5–0.6 of the total water use observed in 1995. By 2025, this value will be 0.8 in the regions of the former Soviet Union. In Asia, South and Central America,

northern and southern Africa and Oceania, industrial water use is expected to increase by 1.2–2.0 times. In other regions of Africa, industrial water use would be 6–7 times higher. Increased water withdrawal for industrial use would be accompanied by decreased water consumption.

– *Water losses by evaporation from reservoir surfaces* will increase by 5–10% in the regions of North America, Europe, the former Soviet Union and Australia, and by 20–30% in other regions.

Water use for 2010 and 2025 was forecast for each region using the Conventional and Sustainable Development Scenarios and then the results were aggregated for continents and for the world as a whole.

2.4.3 Past, current and future trends in world water use using the Conventional and Sustainable Development Scenarios

Worldwide changes in water withdrawal and consumption by sector assessed for the period 1900–1995 and forecast for 2010 and 2025 are shown in Fig. 2.4 (see Table A.5.3 in Appendix 5 for detailed figures). The present total annual global water withdrawal is about 4000 km^3 and the total annual water consumption equals 2200 km^3. Worldwide water withdrawal intensified in the second half of the 20th century. From 1900 to 1950, annual water withdrawal increased by about 800 km^3, i.e. by 160 km^3 each decade, whereas from 1950 to 1980 the rate of increase in water withdrawal rose four-fold to 550–650 km^3 per decade. This increase in water withdrawal rates can be explained by the rapid growth in human population number, the expansion of irrigated lands and more intensive industrial development. Although the rate of increase in global water withdrawal slowed after 1980 because of the reduced expansion of irrigated land area and higher efficiency of freshwater use in many countries, particularly in developed countries, global water withdrawal has remained very high. According to the CS, future world water withdrawal would rise by about 10–12% each decade and by 2025 it would be about 5240 km^3 $year^{-1}$ (1.39 times higher than in 1995). The rise in water consumption would be slightly smaller, increasing by 1.33 times over the same time period. In contrast, forecasts made using the SDS show that the total water withdrawal would stabilize in the near future, equalling 3890 km^3 $year^{-1}$ in 2025, i.e. only 2.9% higher than in 1995.

With regards to water use by sector of economic activity, at present, water use for agriculture accounts for 66% of total water withdrawal and 85% of water consumption in the world. At the start of the 20th century agriculture dominated water use even more and these figures were 89% and 97%, respectively. The changing proportion of water use and consumption in agriculture can be explained by changes in the area of irrigated land per capita and water use efficiency in agriculture. Before 1970 the increase in area of irrigated land exceeded the increment in the population number. After 1970 the opposite situation occurred and the area of irrigated land per capita decreased gradually. From 1950 to 1995 the average annual volume of water used to irrigate 1 ha of land decreased slightly from 10 700 to 9900 m^3. By 2025 both scenarios forecast an increase in irrigated land area to 329 million ha (CS) and 306 million ha (SDS), representing increases of 30% and 21% from 1995, respectively. Specific water use per hectare in agriculture is forecast to decrease over the same time period to 9660 m^3 (CS) or 8270 m^3 (SDS), representing decreases of 2% and 16% from 1995,

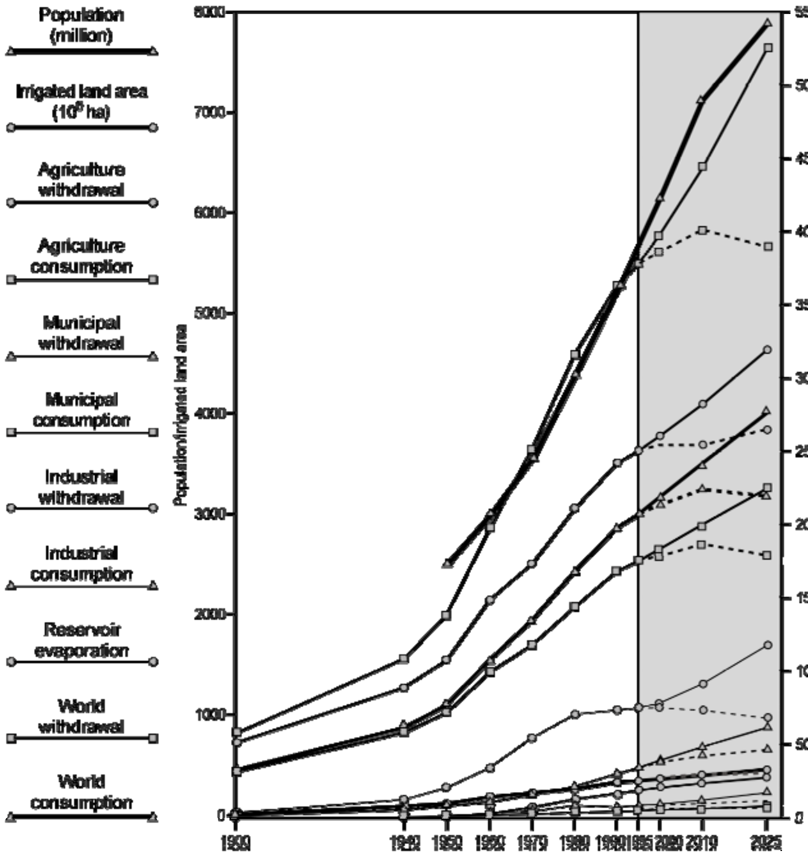

__Fig. 2.4__ Dynamics of water use in the world by sector of economic activity for 1900–1995 (assessment) and 2010 and 2025 (forecast) (km^3 year^{-1}). Forecast water use is shown as a solid line and a dashed line for the Conventional and Sustainable Development Scenarios, respectively, as defined in Section 2.4.2. Water use was assessed by the State Hydrological Institute (SHI), St. Petersburg, Russia. FAO yearbooks and FAO Water Reports (FAO, 1995, 1999, 2000) were used to estimate irrigated land area.

respectively. Overall, in the SDS water use is forecast to decrease in all sectors by 2025 compared to the CS, particularly in industry. Industrial water use in 2025 is forecast to be 10% lower than in 1995 in the SDS but will increase by 56% in the CS.

The distribution of past and current water use and forecast water use by continent is shown in Fig. 2.5 (for detailed data see Table A.5.4 in Appendix 5). At present about 60% of the global water withdrawal and 70% of water consumption occur in Asia which has the largest irrigated areas and the majority of the world population. On most continents the intensive increase in water use since 1950 is continuing, but, since 1980, water withdrawal has begun to stabilize and even decrease in Europe and North America, mainly due to more efficient water use in industry.

According to the CS, water withdrawal is forecast to increase by 2025 on every continent, by 1.5–1.6 times in Africa and South America, and 1.1–1.2 times in North America and Europe, compared to 1995 values. In contrast, under the SDS, water

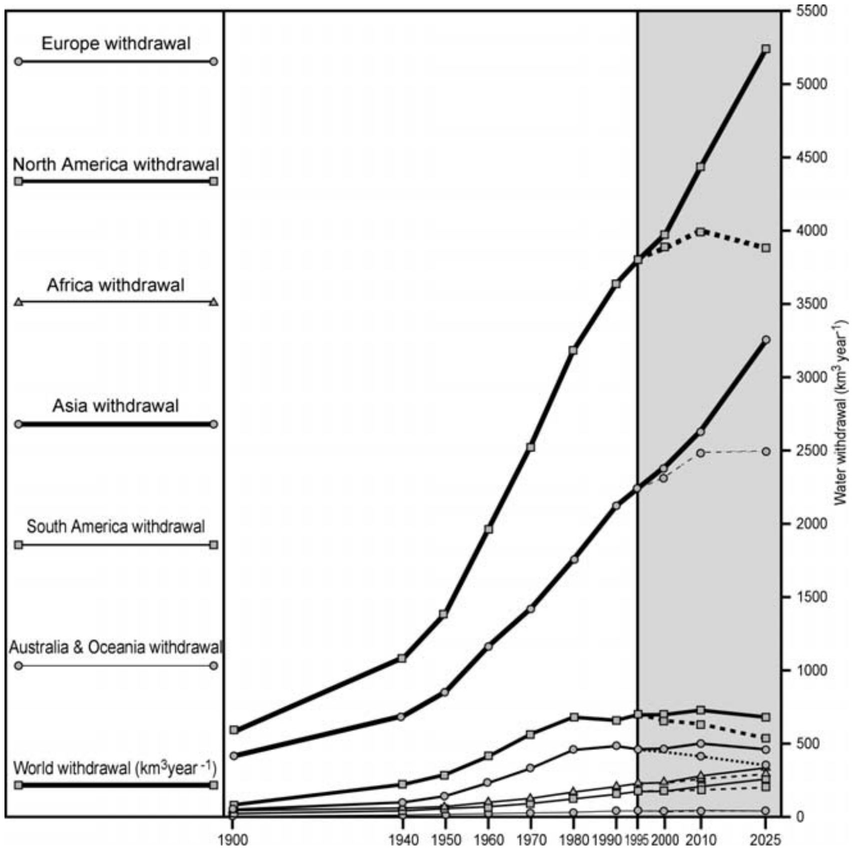

Fig. 2.5 *Dynamics of water use in the world, by continent, for 1900–1995 (assessment) and 2010 and 2025 (forecast) (km^3 year^{-1}). Forecast water use is shown as a solid line and a dashed line for Conventional and Sustainable Development Scenarios, respectively, as defined in Section 2.4.2. Water use was assessed by the State Hydrological Institute (SHI), St. Petersburg, Russia.*

withdrawal in 2025 would be 23% lower in Europe and North America, and 4% lower in Australia and Oceania, compared to 1995. On the other continents water use would increase slightly compared to 1995: by 33% in Africa, 21% in South America, and 12% in Asia. Forecasts of the spatial variation in water use by sector in 2025 (data not shown) demonstrate that, under the CS, water use would increase from 1995 values in all sectors on all continents, albeit with regional variability in the magnitude of increase. In contrast, under the SDS, water use would decrease in all sectors in Europe and North America and most sectors in Australia and Oceania, and increase in Asia, Africa and South America, although the increase is forecast to be smaller than under the CS. For example, municipal water use would increase by 10–15% (Europe, North America) to 3–5 times the 1995 values (some regions in Africa) in the CS. According to the SDS, in Europe and North America the volume of municipal water use would decrease by 12–20%, while in Africa it is expected to be more than three times greater than in 1995.

2.5 WATER RESOURCES AND WATER USE

2.5.1 Load on water resources

To estimate the condition of water resources in any region, the coefficient of water resources use (K_w) is usually calculated; K_w is the ratio of total water withdrawal to renewable water resources and is usually expressed as a percentage. Renewable water resources involve not only local water resources but river water inflow from adjacent areas. In the present evaluation, renewable water resources were defined as the sum of the minimum annual local water resources for the period 1921–1985 and half of the water inflow from the adjacent territory. This value is known as the “real water resources”. The value of K_w was calculated for each region in 1950, 1995 and for 2025 (according to the CS and SDS). The K_w values vary widely over time and between continents and regions. In 1995, K_w values for continents ranged from 1.5–1.6% in South America and Australia and Oceania to 20% in Europe and Asia, and for individual regions from 0.2% to 100%. The worldwide average value of K_w increased from 3.5% in 1950 to 10.3% in 1995 and was forecast by 2025 to reach 14% (CS) or to stabilize at the present value (SDS). For detailed values see Table A.5.5 in Appendix 5.

The following classification of K_w values is widely accepted for assessing the load on water resources:

$K_w < 10\%$	low load
$K_w = 11–20\%$	average load
$K_w = 21–40\%$	high load
$K_w = 41–60\%$	very high load
$K_w > 60\%$	catastrophically high load

In 1950, one region (Northern Africa) had a very high load on water resources and only three regions (Southern and Western Asia and Central Asia & Kazakhstan) had high loads. By 1995, five regions had very high or catastrophically high loads on water resources. Within each continent (except for South America) there is currently considerable variability in the load on water resources. For instance, in Southern and Central Europe, water withdrawal amounts to 30–40% of renewable water resources, but the K_w value for Northern Europe is only 1.9%. In Northern Africa renewable water resources are totally withdrawn but in other regions of Africa, especially Central Africa, the load on water resources is low. If the future water resources situation follows the Conventional Scenario, by 2025 more countries and regions will have very high and catastrophically high loads on water resources which will hinder their socio-economic development. Urgent measures will be required to control available water resources and meet water demands.

To evaluate the impact in human terms of water resource loadings, the populations living in regions with different loads on water resources were estimated in 1950, 1995 and 2025 (according to the two scenarios of water use). The details are given in Table 2.1. In 1950 only 24% of the world population (631 million) lived in regions with a high or very high load on water resources. By 1995, however, more than 40% of the world population (2360 billion) lived in regions with very high or catastrophically high loads. In the future, according to the CS, a freshwater catastrophe would be evident on the global scale with 40% of the global population (3118 billion) living

Table 2.1 *Number and percentage of the world's population inhabiting regions with different loads on water resources, 1950, 1995 (assessment) and 2025 (forecast). Forecasts were made under the Conventional Scenario (CS) and Sustainable Development Scenario (SDS), as defined in Section 2.4.2.*

K_w (%)	Population number (millions) and %							
	1950		1995		2025			
					Conventional Scenario		Sustainable Development Scenario	
	Number	%	Number	%	Number	%	Number	%
≤ 10 low	1197	46.4	1032	18.1	1236	15.7	1412	17.9
11–20 average	752	29.1	1582	27.7	2587	32.8	2411	30.6
21–40 high	580	22.5	722	12.7	426	5.4	936	11.9
41–60 very high	51.4	2.0	1914	33.6	510	6.5	2363	30.0
>60 catastrophically high	0	0	451	7.9	3118	39.6	755	9.6

in regions with catastrophically high loads by 2025. This situation would be even worse than it appears because the adverse effects of very high water load conditions are not restricted to just the quantitative aspects of water resources. Under such conditions water quality usually deteriorates because of pollution, resulting in environmental degradation and increased morbidity and mortality rates as a result of water transmitted diseases. It is therefore of the utmost importance that decision makers, politicians, scientists and the public avoid the development of water resources according to the Conventional Scenario and try to develop water resources according to the Sustainable Development Scenario. According to the latter scenario, the world water resources situation in 2025 would be similar to that of 1995 and may even improve in some regions compared to the present.

2.5.2 Water availability per capita

The load on water resources cannot fully characterize the water resources deficit in any region because it does not take into account the population number. The amount of freshwater available per capita is known as the Specific Water Resource Availability (SWRA) and is calculated for a region or country as:

$$\mathrm{SWRA} = \frac{(\text{real water resources} - \text{water consumption})}{\text{population number}} \tag{2.1}$$

SWRA values for all natural-economic regions and selected countries were calculated (in 10^3 m^3 $year^{-1}$ $capita^{-1}$) for 1950 and 1995 and forecast for 2025 (according to the CS and SDS) based on the data in Tables A.5.1, A.5.3 and A.5.5. The results (data not shown) varied considerably between different regions of the world. The highest current SWRA values of 160 000–170 000 m^3 $year^{-1}$ $capita^{-1}$ occur in Canada with Alaska, and Oceania regions. In densely populated regions of Asia and Central and Southern Europe the present water resource availability is 1000–4000 m^3 $year^{-1}$ per capita, whilst in North Africa and the countries of the Arabian Peninsula it does not exceed 100–300.

The following classification has been widely accepted for assessing SWRA values (in 10^3 m^3 $year^{-1}$ $capita^{-1}$):

<1	catastrophically low
1.01–2.0	very low
2.01–5.0	low
5.01–10.0	average
10.01–20.0	high
> 20	very high

The regional distribution of water availability in 1950, 1995 and in 2025 (according to the CS and SDS) is shown in Fig. 2.6. In 1950, catastrophically low water availability did not occur anywhere in the world. Only in Northern Africa was water availability very low and most regions had average water availability or higher. By 1995 the situation had changed drastically: 47% of the world's population now had very low or catastrophically low water availability. Both scenarios forecast a worse situation in 2025 since population number is the major control on water availability and is assumed to be the same in both scenarios. Although higher water availability is calculated in the SDS compared to the CS, it does not alter the distribution of the world's population between the different SWRA categories in 2025. Consequently, even in the Sustainable Development Scenario, by 2025 the greater part of the world's population (58%) is forecast to live in conditions of low and catastrophically low water availability. At the same time high specific water availability is forecast in Northern Europe, Canada, South America (apart from Mexico and Central America), central Africa, Siberia and the Far East, and Australia and Oceania.

2.6 GROUNDWATER AND RIVER RUNOFF

The above assessments of renewable water resources in natural-economic regions and continents have been calculated from the total river runoff. River runoff comprises water directly flowing into the hydrographic network as the result of rainfall or snow melt and also the groundwater that provides river baseflow more or less constantly during the year. However, some groundwater does not contribute to river recharge, discharging directly to seas and oceans or evaporating to the atmosphere, yet this is also a component of renewable water resources. Consequently assessments based only on river runoff data tend to underestimate renewable water resources.

Assessment of renewable groundwater resources is of great applied importance because groundwater is the most reliable source of potable water in areas where river runoff is low, for example in flat plains in arid and semi-arid climates. It is difficult to make a reliable assessment of such groundwater for any region and country in the world because of inadequate data. FAO (2003) published an approximate assessment of groundwater (including groundwater not contributing to river runoff) for all countries of the world. On average, renewable groundwater resources not connected with river runoff represent 5.5% of the local river runoff and are less than 10% in most countries (see Table A.5.6 in Appendix 5 for figures for selected countries). However, in some countries, particularly in arid and semi-arid regions, the renewable groundwater resources not drained by river systems are of similar magnitude to the water resources derived from river runoff and should be taken into account when analysing water availability.

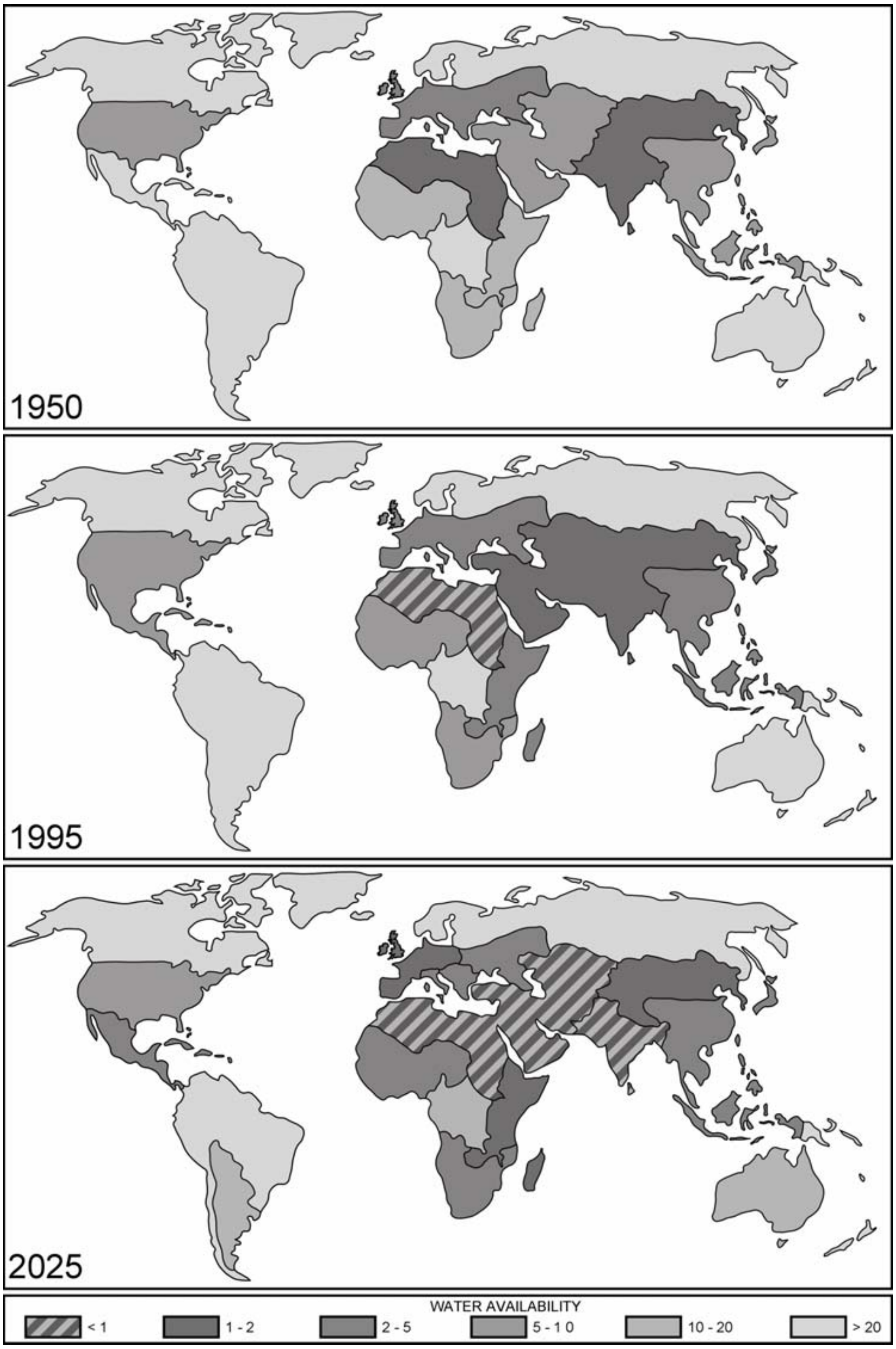

Fig. 2.6 *Regional distribution of water availability (in units of 10^3 m^3 $year^{-1}$ $capita^{-1}$) in the world in 1950, 1995 and 2025 (under Conventional and Sustainable Development scenarios, as defined in Section 2.4.2).*

During recent decades, groundwater withdrawal has provided undisputed socio-economic benefits. It is a major source of potable drinking water, particularly in developing countries, with 50% of municipal water supplies worldwide depending on it, as do many rural and dispersed populations. Irrigation with groundwater has made it possible to increase food production at a greater rate than population growth. Some 70% of all groundwater withdrawals are used for this purpose, particularly in arid or semi-arid regions (Delli Priscoli *et al.*, 2004). Most countries consider that groundwater use should not exceed renewable resources. Others, mainly the most arid ones, find that groundwater use is an acceptable policy, as long as available data indicate that it can be economically maintained for some time (for example, more than 50 years) and that ecological costs are compensated by socio-economic benefits. With careful management, many arid countries will be able to utilize resources beyond the foreseeable future without major restructuring.

In addition to the scientific difficulties in estimating the availability of groundwater resources, social and economic issues have to be considered when trying to achieve sustainable, reasonable groundwater use. For example, the subsidies (some hidden and some open) that have traditionally been a part of large hydraulic works projects for surface water irrigation have encouraged the neglect of groundwater resources by water managers and decision makers. More careful consideration of cost and benefit could reveal that many proposed surface water projects are economically unsound, thus fostering serious consideration of groundwater planning, control and management. The question of public, private or common groundwater ownership is also important. Some consider that the legal declaration of groundwater as a public domain is the necessary foundation for acceptable groundwater development. However there are examples where groundwater, which has been in public ownership for many decades, has been subject to somewhat chaotic management. Nevertheless, it cannot be disputed that promoting solidarity in the use of groundwater as a common good is vital, particularly in view of the fact that thousands of stakeholders may exist for a single aquifer of medium to large size. Groundwater management should be in the hands of these stakeholders, under the supervision of a corresponding water authority. Availability and consistency of information is a prerequisite to successful groundwater management. Development of adequate hydrological knowledge has to be a continuous process in which technology and education improve stakeholder participation and a more efficient use of the resource. There is an urgent need to create appropriate institutions to manage aquifers so that all who benefit from them are made aware that if they continue to pump in excess of the renewable recharge of groundwater, they may incur serious problems for themselves and for their children and grandchildren. Considering the aquifer as a shared common good brings with it the obligation to manage it in a participatory and responsible way.

2.7 MEASURES TO REDRESS THE BALANCE BETWEEN WATER RESOURCE AVAILABILITY AND USE

It has been demonstrated above that the load on water resources in the world is increasing while water availability in many regions is decreasing rapidly. If the management of water resources continues in the same way as during the past decades then, by 2025, 40% of the world's population is forecast to live in regions with catastrophically high loads on water resources. Urgent measures to improve the efficiency of water use, as incorporated in the Sustainable Development Scenario, would stabilize world water use and greatly reduce the load on water resources.

There are great opportunities to reduce the present specific water use in each region of the world and in every sphere of freshwater use. In thermal power generation and in industry, water may be recirculated and in some industries “dry” production may be introduced to greatly reduce the volumes of freshwater withdrawal and waste discharges to rivers and lakes. Effective treatment of industrial wastes would make it possible to retain much freshwater which is at present required to dilute untreated wastes. In arid regions it is very important to save water during irrigation, which is the main use of water in the world. In some regions specific water use for irrigation is very high; 20 000–50 000 m^3 of water per ha of irrigated land may be lost, which is three to seven times the actual crop water requirements. Inefficient use of water in irrigation occurs due to water losses in canals, addition of water in excess of the crop requirements and low levels of technical knowledge and technology in irrigation systems. For example, transition from direct-flow irrigation to sprinkling provides a two-fold water saving and the use of droplets and finely dispersed irrigation minimizes water use and at the same time provides increased crop yields.

However, even if measures are taken to increase the efficiency of water use, it is forecast under the Sustainable Development Scenario that by 2025, water availability in the world will be very low: 40% of the world’s population will have less than 1000 m^3 $year^{-1}$ $capita^{-1}$ which is considered as a catastrophically low water availability. Thus, decreasing water use will not be enough to increase water availability in the future; it is necessary to discover opportunities for a simultaneous increase in the available water resources.

The following measures may be applied to increase the available water resources in a water-stressed region (Shiklomanov *et al.*, 2004):

– *Long-term and seasonal river runoff control* In many regions of the world water supply difficulties arise not because of insufficient total water resources but because of the extremely uneven distribution of streamflow within and between years. Consequently reservoirs have been constructed for seasonal and long-term runoff control in many parts of the world. Ideally reservoirs should be constructed in mountainous or poorly populated regions to reduce water losses by evaporation and to protect fertile lands from flooding.

– *Use of “natural” freshwater storage* In regions with water deficit it may be possible to utilize freshwater from other stores within the hydrological cycle, for example, by the artificial intensive melting of glaciers to increase runoff in rivers downstream. Another idea is to use deep non-renewable groundwater for water supply in arid and semi-arid regions. For many decades, such water has been widely used in North Africa and the Arabian Peninsula, and in India and some other countries, where it is of great importance for municipal water supply and for irrigation. Nevertheless concerns have been expressed about the ecological impact and long-term sustainability of these methods.

– *Desalination of saline and brackish water* Desalination is normally only economically viable in regions where the water deficit is very high and/or where energy costs are low.

– *Artificial increase in precipitation* The potential capacity to increase water resources over large areas by cloud-seeding to increase precipitation is not high, only about 5%. Moreover, the major portion of any additional precipitation generated would fall during natural precipitation events rather than when required for human activity. Even if cloud-seeding would produce some additional precipitation which contributed to additional river runoff, the benefits would only be realized in highly developed water resource management systems.

– *Water transfers* The justification for using water transfers to increase water availability is that the global resources of river runoff are quite sufficient in general to satisfy population demands for many dozens of years. However, the problem is that the spatial distribution of these resources is extremely uneven and this variability is exacerbated by human activity.

The possible methods outlined above to obtain additional water resources and save freshwater have many different features and each is more suitable for some locations than others. The common feature of all these methods is that they require great investment. Although more desirable from an ecological viewpoint, methods to reduce water consumption are expensive. Reservoir construction and the stimulation of glacier melting in mountainous regions are the cheapest methods to obtain additional water resources. Although runoff control using reservoirs is widely practised throughout the world, it merely provides a more complete use of the local river runoff without increasing the total water resources of the region and, in fact, will decrease them due to additional evaporation from reservoir surfaces. There are also a number of difficulties relating to the use of freshwater from glaciers. This method is only applicable in a limited number of areas, there are concerns about the ecological consequences of such projects and the volumes of additional water resources generated are likely to be small and unsustainable in the long-term, particularly as many glaciers throughout the world are shrinking rapidly as the result of rising temperatures.

The other methods for obtaining additional water resources and saving freshwater are more suitable in terms of their costs and scales of application for solving the problems of water supply. It is anticipated that these methods will sooner or later be applied in the regions where they will be most cost effective and advantageous according to the local physiographic features and nature of water use. Amongst all the methods described above, water transfers are considered the most advantageous, because they may be developed in any region and provide substantial additional water resources. At present the volume of the transferred water resource is an order of magnitude greater than the total water volume generated by desalination, and it is still increasing. Water transfers, in combination with a wide use of updated technologies in water use and waste treatment, may become a realistic basis in the future for reducing the load on water resources and stabilizing water availability in many regions of the world.

2.8 LAND DEGRADATION AND SOIL EROSION

For agricultural production in particular, soil resources are of equal importance to water resource quantity. The degradation of lands has become a real threat for all

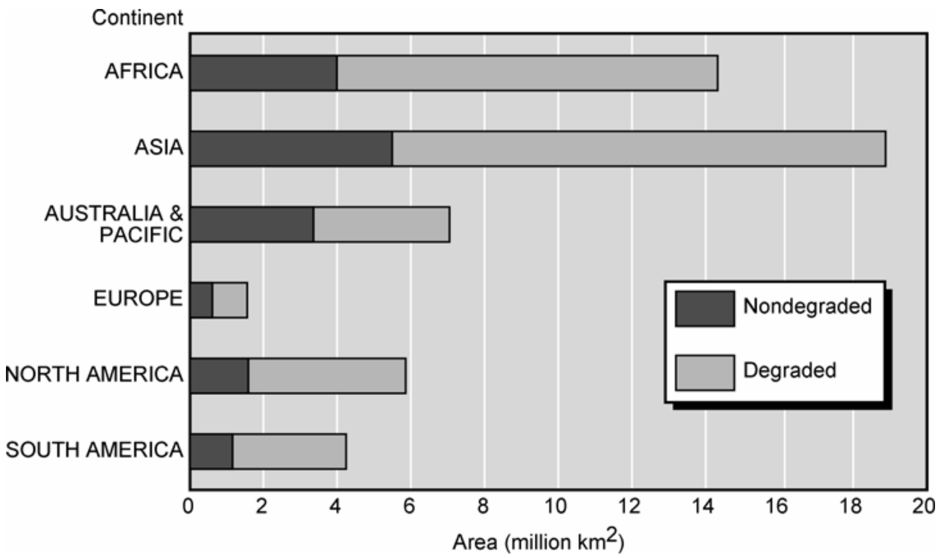

Fig. 2.7 *Area estimates of degraded and non-degraded lands within the drylands of each continent (after data from Dregne & Chou, 1994). Dryland refers to arid, semi-arid and dry subhumid regions as shown on the UNESCO (1977) map of the World Distribution of Arid Regions.*

nations, but in particular for semi-arid and arid countries where soil resources are limited and rainfall is increasingly erratic. For a long time, land degradation was overlooked but it is now a major concern for agriculture and the environment, because of the impacts on significant issues such as food security, the struggle against poverty, biodiversity, climate change and integrated water resources management. Figure 2.7 shows that degraded land accounts for a large proportion of the total dryland area on all continents.

Land degradation can be defined as the loss of actual or potential productivity or utility of soils as a result of natural or anthropogenic factors; it is the decline in land quality or reduction in its productivity and environmental regulatory capacity (Eswaran *et al.*, 2001). Mechanisms of land degradation include physical processes (such as soil crusting, compaction, erosion, desertification, anaerobiosis, pollution), chemical processes (such as acidification, leaching, salinization, decrease in cation retention capacity, fertility depletion) and biological processes (for instance reduction in total and biomass carbon, decline in land biodiversity) (Lal, 1994; Eswaran *et al.*, 2001). This degradation affects the quality, not only of upstream production zones (loss of material generally fertile for agriculture), but also of transit (a combination between loss and deposition of material) and downstream deposition zones (deposition of sediment, especially in reservoirs).

The consequences of land degradation are disastrous and will be aggravated more and more by world population growth and climate change, particularly in developing countries. By 2020, land degradation may pose a serious threat to food production and rural livelihoods in poor and densely populated areas of the developing world (Scherr & Satya, 1996). In Africa, it is estimated that the productivity of some lands has declined by more than 50% due to soil erosion and desertification since the 1970s.

Yield reduction in Africa due to soil erosion is on average 8.2% for the entire continent (Lal, 1995) and if accelerated erosion continues unabated, may rise to 16.5% by 2020 (Eswaran *et al.*, 2001). In South Asia serious productivity losses (about 20%) caused by erosion correspond to an annual loss in productivity of 36 million t of cereal equivalent valued at US$5400 million due to water erosion and US$1800 million due to wind erosion (UNDP, 1994). At the global scale, the annual loss of 75 billion t of soil costs the world about US$400 billion per year, or approximately US$70 per person per year (Lal, 1998).

Land degradation is a complex phenomenon involving natural, human, economic and political factors and therefore requires addressing through an interdisciplinary approach. Though land degradation remains a serious global threat, the underpinning science is still composed of myths and facts (Eswaran *et al.*, 2001). In order to cope with food security and achieve sustainable development, particularly in developing countries, it is crucial that barriers associated with land degradation assessment methodologies and criteria, its economic cost evaluation, and land management policies are overcome in the coming years. According to Eswaran *et al.* (2001), important requirements for addressing land degradation are to:

– Mobilize the scientific community to mount an integrated programme to develop methods, standards, data collection, and research networks for assessment and monitoring of soil and land degradation.
– Develop land use models that incorporate both natural and human-induced factors that contribute to land degradation and that could be used for land-use planning and management.
– Develop information systems that link environmental monitoring, accounting, and impact assessment to land degradation.
– Help develop policies that encourage sustainable land use and management and assist in the greater use of land resource information for sustainable agriculture.
– Develop economic instruments for the assessment of land degradation and encourage the sustainable use of land resources.

The above challenges emphasize the need to improve our understanding of the physical hydrological processes underlying land degradation. Addressing land degradation is of vital importance to ensuring world food production but understanding of the underlying physics is not sufficiently developed to devise effective water resources management tools to mitigate erosion and land degradation.

2.9 WATER RESOURCES MANAGEMENT

So far this chapter has outlined some of the water resource issues at the global scale and presented grim assessments of the likely future imbalance between water resource availability and demand, and the increasingly widespread occurrence of land degradation. The next and final section of the chapter provides a brief overview of the field of water resources management which has developed to try and resolve imbalances between water supply and demand. Water resources management is not a new field, but the increasing conflict between the accelerated demands for the development of freshwater resources and the limited availability of freshwater of a suitable quality means that water resources management is now a field of major importance in the world. Water resources management is a scientific and applied field with the ultimate goal of ensuring the availability of water in sufficient quantity and quality at the right location and the right time (Szolgay & Gottschalk, 1987). It is without doubt that water resources management has played an important role not only in the economic development, but also in the ecological environment, in every country of the world during recent decades. Governments, experts, professors, mass media, managers, lawyers, and the public are paying more and more attention to water resources management and this is only likely to increase in the future with the forecast world water crisis.

Water resources management has some features in common with the management of other natural resources but water has some characteristics which differ from other natural resources. These characteristics, described below, will, in large measure, determine how the resource can be used and they will affect, too, the nature of jurisdiction over the resource and the ways in which its use can be monitored (Young *et al.*, 1994).

1. Water is a renewable resource. Although the hydrological cycle implies that water is renewable there are two possibilities with regard to its "renewable" nature. If water is used properly, it will be replenished and will remain available for other uses. However, if it is not used properly, the hydrological cycle will be affected and either the amount of renewable water will decrease or the length of time for the completion of the cycle will be prolonged.

2. Water is mobile and can move from one political jurisdiction to another through air, the land surface (river) and even underground (groundwater). Compared to static natural resources, such as mineral resources, the ownership and jurisdiction over water are much more complicated. For example, at the local scale a stream may flow from one person's property to another, while at intermediate scales, flow can occur from one local or provincial jurisdiction to another, and at international scales from one country to another (Young *et al.*, 1994). How to coordinate the relationship between upper and lower reaches is an important component of the management of river water resources and is a complex issue. The situation is even more complicated in the management of groundwater resources in which the subsurface basin may not correspond to the surface drainage basin and there is often very little information about the volume and dynamics of the groundwater store.

3. Water resources can be re-used, unlike most natural resources; for example, once a mineral resource is used it is gone. The re-use of water resources has many meanings and it is understood in different ways by different people. Water re-use has at least four aspects: (a) water has a self-purification capacity, which means that water quality can recover by itself if the water pollution does not exceed its self-purification capacity; (b) water can be re-used if the water quality is still satisfactory after it is used, for example, water used for cooling in some industries can be re-used again and again; (c) water used in one sector can be re-used in another sector, for example, some water can be used for irrigation in agriculture after domestic usage; (d) wastewater can be treated and then re-used. Wastewater

treatment not only mitigates environmental pollution, but can also produce new sources of water. The main barriers to re-using water are investment and public perceptions of water re-use. Effective water resources management aims to maximize the amount of water available for re-use after its primary use.

4. Water resources are required in appropriate amounts at the right times in specific locations. This contrasts with most other natural resources, such as minerals, forests, oil, where the larger the quantities of the resource in the region, the better the prospects are for regional economic development. However, for water, excess amounts at a location cause flooding, one of the most serious natural disasters for humans, while if the water resources are much less than expected, drought results. These dual aspects of water resources make its management more difficult and complicated.

5. As well as forming a natural resource, water is life. Every life form on earth cannot survive without water and life prospers and declines according to the abundance of water. As water is so all-pervasive and of such importance in so many ways for life, it is not surprising that in many cultures it is regarded with spiritual reverence (Young *et al.*, 1994).

6. Water is basic to human activities and is fundamental to virtually every economic activity (Young *et al.*, 1994). If a region is deficient in mineral, oil, or forest resources, it can still have a highly-developed economy, yet, if it is deficient in water resources, it is impossible to have a prosperous economy unless water resources management infrastructure is constructed or sufficient wealth exists to import virtual water from elsewhere (see Section 2.2.5). For example, water resources are very limited on the Arabian Peninsula, but some of its countries are amongst the richest in the world because extremely complicated and advanced water supply facilities have been constructed, funded by the income received from oil sales. However, such facilities are extremely expensive and are not affordable for many developing countries.

7. Water is an active element in nature, transporting solutes, sediments and organisms and is required to maintain the biophysical environment (Young *et al.*, 1994). It moulds the landscape, rivers and ecosystems. Water resource development is often beneficial to the environment, but it may also be harmful (Whipple *et al.*, 2000), especially in developing countries where environmental protection is weaker. Pollution and changes in the hydraulic regime of rivers, lakes and aquifers can alter the landscape and result in the degeneration of ecosystems and the resources that they provide.

The unique characteristics of water described above not only demonstrate the importance of water resources management, but also make the management of water resources more difficult than that of other natural resources.

2.9.1 The development and nature of water resources management

The origin of water resources management can be traced back thousands of years to when people started to irrigate land. This management was very simple in terms of technology and extent compared to the advanced and complicated management of water resources that occurs today.

Three major eras have been identified by Mar (1998) in the development of water resources management, based on a comprehensive review of the management of freshwater resources at the national level in the United States for the last two centuries (Viessman & Welty, 1985): "*The first era can be described as an exploitation era where the water resources were viewed as unlimited compared to the demand, and the basic function of a water agency was to provide no cost or low cost water for a specific purpose such as navigation, water supply, or hydropower. During an exploitation era, technology is the primary concern. The second era began in the 1930s and continues today in many regions. This era can be described as the management era where conflicting uses for the same body of water exist, and the various water oriented institutions must share the water resources with competing users. This need to optimize multiple uses stimulated economists to participate with the technologists to develop strategies and facilities to meet the growing needs of many different types of water users. The third and final era in the evolution of water resource management is the protection era. If the demands for the water resources become so great that a small increase in demand can destroy the supply, it is time to seek an alternative source and preserve what remains of the natural ecosystem, or continue to destroy the resource.*" (Mar, 1998).

Although based on a case study in the United States, the stages identified above occur in the general evolution of water resources management in most regions of the world. This classification also reflects the general processes of flooding control and drought relief because flood control and drought relief have developed from building large flood defences (exploitation) to multi-purpose reservoirs (management) to planning controls and acceptance of some flooding (protection).

The importance of the link between water resource management and sustainable development was recognized at the United Nations Conference on Environment and Development (United Nations, 1992), in particular in Chapter 18 of Agenda 21, entitled "Protection of the Quality and Supply of Freshwater Resources: Application of Integrated Approaches to the Development, Management and Use of Water Resources". Effective water resources management should solve the key problems inherent in the control and utilization of water—conflicting demands and too little or too much water—while taking account of equity considerations and environmental and economic sustainability, and attempting to maximize economic and social benefits (Young *et al.*, 1994). It can operate either at the global scale or at national and regional scales. Water resources development and management should be planned in an integrated manner, taking into account long-term planning needs as well as those with narrower horizons.

Inputs to water resources management should include both the physical (e.g. geography, geology, climatology, meteorology, ecology) and social (e.g. politics, economics, sociology, law, institutions) sciences, with hydrology at the core (Fig. 2.8). The outputs from water resources management are implemented through both hard (control) and soft (adaptation) technologies. Hard technologies are used to construct hydrological and hydraulic engineering projects and some auxiliary facilities, for example, commutation devices. The classical use of hard technologies is to capture water at its source in the uplands and to use gravity to facilitate distribution to the

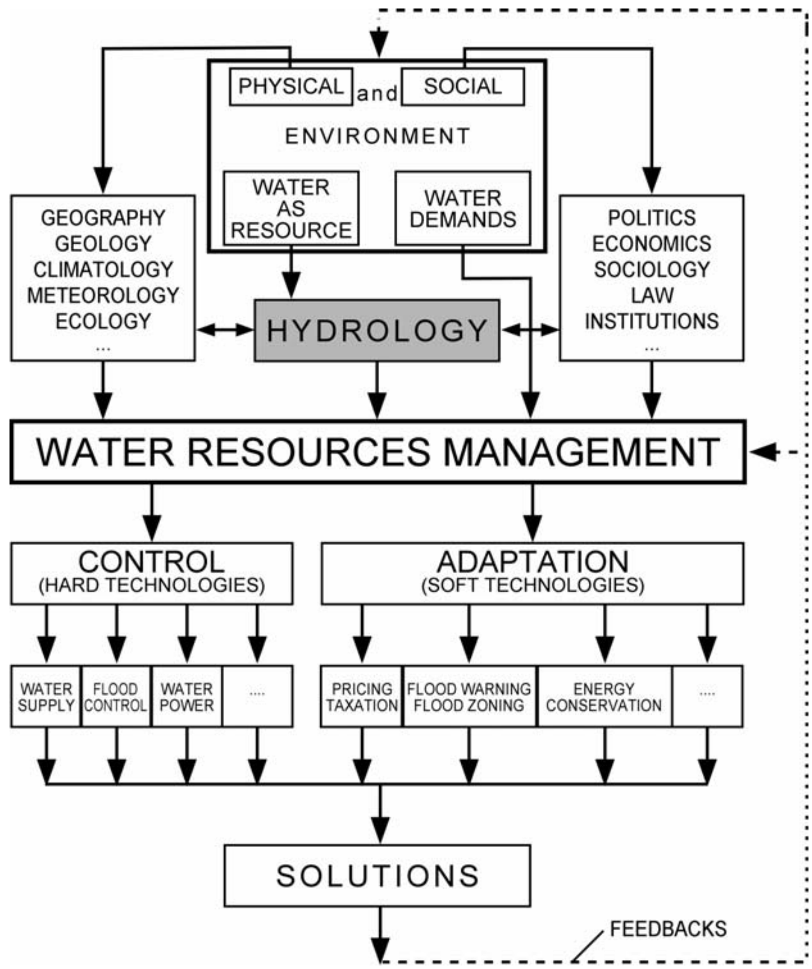

Fig. 2.8 *Schematic relationship between hydrology and water resources management and its inputs and outputs (adapted from Mar, 1998).*

lowlands. Siphons transport water over lower land and reservoirs provide pressure heads for urban water supply systems and to generate hydropower (Mar, 1998). Hard technologies can also be used to draw water uphill from lower channels, to transfer water between basins, and to construct water-saving hardware to increase water use efficiency. The application of chemical engineering processes and technologies for the treatment and conservation of water and wastewater are further examples of the utilization of hard technologies in water resource management. Soft technologies refer to non-physical measures, such as planning controls, water pricing and taxation, and public education, whose importance is increasingly recognized. Although the management of water resources is sometimes regarded more as a political and economic problem than a technical problem (Mar, 1998), both physical and social inputs and hard and soft technological solutions are of equal importance and neither aspect should be prioritized.

2.9.2 New trends in water resources management

As water problems are becoming more critical in many parts of the world, society requires better water resources management. Some new technologies, concepts and methods have recently been developed in the field of water resources management and are outlined below. A few of these have already been applied in practice, while others are still new ideas which will influence water resources management in the future.

Integrated water resources management There are many and sometimes conflicting uses of water resources. Table 2.2 presents a variety of water uses and their ideal hydrological requirements, which are often in conflict with each other. For example, high flows are preferred when water is used for waste assimilation but flows below flood levels are optimal for flood control. Because of the different perceptions of water as an integral part of the ecosystem, a natural resource and a social and economic good, an integrated approach to its management is essential. Hence integrated water resources management is defined as "a framework for planning, organizing and controlling water systems … balancing views and goals of stakeholders (social interdependence) in the context of managing water systems (ecological interdependences)" (Grigg, 1999).

Table 2.2 *The differing requirements of various water uses (adapted from Mar, 1998).*

Water use	Requirements of different water uses			
	Flow	Quality	Water level	Other requirements
Navigation	No current	No large debris	Deep enough for boat traffic	No blockage, dredge to maintain depth
Power	Flows match energy demand	No debris to damage turbines	Maximum head	None
Irrigation	No flows required after irrigation season, maximum flow during season	Low salts and herbicides	Store as much as possible	Groundwater is also used
Manufacturing & industrial	No release unless demands met	Variable depending on nature of industry	Store as much as possible	Groundwater is also used
Drainage	No flow	Not applicable	No water	Drain land for alternative use
Flood control	Regulate flows below flood levels	Sediment and debris can worsen flooding	Where reservoir keep empty	Channelize watercourses to increase releases to oceans
Waste assimilation	Maximum flow	Maximize use of assimilative capacity	Increase minimum flows	Store water for waste assimilation
Protect habitat	Maintain natural flows	Maintain natural habitats	Preserve natural fluctuations	Water not available for other uses
Fish and wildlife	Maintain natural flows	Maintain natural habitats, populations, diversity and community dynamics	Preserve natural fluctuations	Hatchery fish not a substitute
Recreation	Conflict between white and flat water needs	Meet health standards	Constant level	Conflict between wild and scenic needs and high density use

Sustainable water resources systems The concept of sustainability has grown in importance because of the increasing awareness of the global scale of the environmental impacts of economic development (Loucks & Gladwell, 1999) and also of the inter-relationships between economic development and the environment. Sustainable development has been defined in many ways and from many perspectives but all definitions emphasise a balance between development and the environment and the need to consider future as well as present benefits. Water resources are scarce and their utilization and management should fall under the framework of sustainability, i.e. with consideration of the future economy and environmental protection, not only current economic development.

New technological applications in water resources management With the development of science and technology, more and novel technologies have been, and will continue to be, applied in the field of water resources management. One of these is systems theories and methodologies, which have made great progress in recent years. Though hydrological models have served as a valuable tool in water resources management for many years (Xu *et al.*, 2001), progress in Geographic Information Systems (GIS) and remote sensing has led to significant advances in different types of physically-based hydrological models (Warwick & Haness, 1994; Kite & Pietroniro, 1996), which could assist the water manager by providing more hydrological information and tools for predicting the effects of different management systems.

Basin carrying capacity—developing the resilience concept The prosperity of human society is intimately linked to the capacity of the biosphere to generate ecosystem services. Human activities have in many places decreased the capacity of ecosystems to sustain these services, in particular as ecosystems become more fragile and less capable of coping with disturbance and change. The importance of change, disturbance and dynamics in both ecosystems and society has intrigued scientists in recent decades, resulting in new interdisciplinary theories of the resilience of socio-ecological systems. Resilience can be understood from three different dimensions: (a) the magnitude of shock that the system can absorb and remain within a given state; (b) the degree to which the system is capable of self-organization; and (c) the degree to which the system can build capacity for learning and adaptation. Management can destroy or build resilience, depending on how the socio-ecological system organizes itself in response to management actions. Emerging theories focusing on resilience in socio-ecological systems can be of great importance in improving freshwater management. Thus, there is a need for hydrologists to synthesize and communicate theories on resilience and ensure that they become operational within water policy and river basin management.

Redefining water scarcity The concept of water scarcity has commonly been synonymous with physical water scarcity, but the situation is more complex. Water scarcity can indeed be caused by a physical lack of the resource. It is also, however, often caused by a lack of appropriate infrastructure (for water treatment or to handle variability or transport water to where it is needed) or poor management structures and governance. Hence water scarcity includes physical water scarcity, managerial water scarcity and infrastructure water scarcity. Achieving a wider international understanding of the factors behind water scarcity will be important in order to manage the complex interactions behind the driving forces for scarcity.

The blue-green water concept (see Fig. 2.9) Taking a global perspective, the water transpired by vegetation, *green* water, amounts to twice as much water as that, which passes through rivers and groundwater. Almost two thirds of the precipitation over the continents is therefore consumed as green water flow from the land. Most of the global green water flow is consumptive use by natural ecosystems, while about 10% is water consumed in crop production. Out of this 10%, about 3.5% originates from irrigation and the remaining 6.5% from rainfed agriculture. As Falkenmark (1995) pointed out, only irrigated water, either withdrawn from surface water or pumped up from groundwater, had been considered in the field of water resources management, and water consumed in rain-fed agriculture had not been taken into account, even though more than 80% of cropland is not irrigated and approximately 60% of crop production is obtained this way. One third of the precipitation over the continents therefore remains to recharge rivers and groundwater and this is known as *blue water*. Only 10% of that water, i.e. less than 4% of the continental precipitation, is used for societal purposes for domestic use, industry and irrigation. All this means that the whole water debate focuses on less than 4% of the total amount of water that passes through the continents, two thirds of which is literally consumed in irrigated crop production as evaporative loss to the atmosphere. In other words, most of the blue water withdrawn from rivers and aquifers is turned into green water. Most attention in water resources management has tended to focus on obtaining more water to meet increasing water demands, neglecting the consumptive use of water (what happens to water after use in terms of quantity and quality) (Rockström *et al.*, 1999).

More disciplines and people involved in water resources management Water resources management requires more people to be involved from different disciplines because it requires input not only from the natural sciences, such as hydrology, meteorology, ecology, and geology, but also from the social sciences, such as politics, economics, sociology, and law. In addition to expert contributions, there is a need for

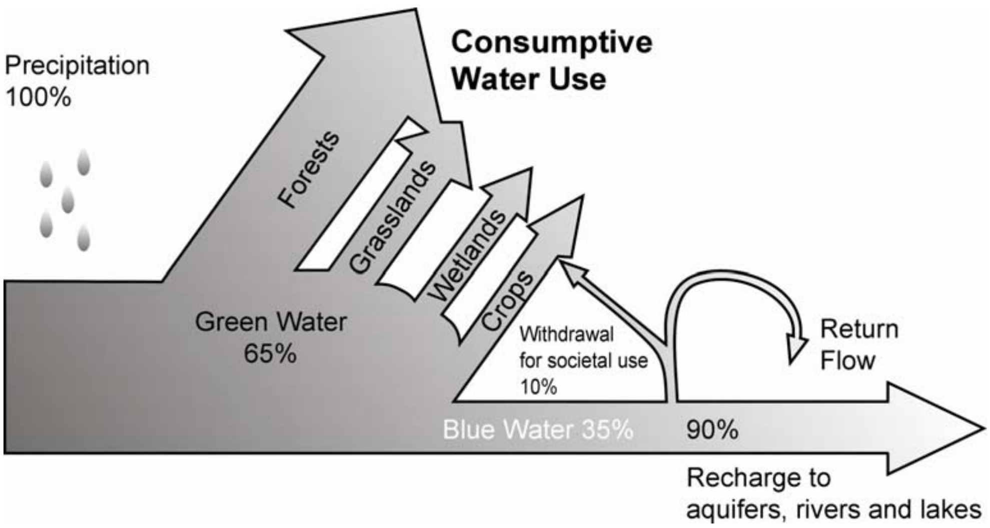

Fig. 2.9 *Global water flows as green water and blue water (after Stockholm International Water Institute et al., 2005a).*

the local people within basins, water users and other stakeholders to become more involved in basin/regional water resources management.

2.9.3 Hydrology for better water resources management

Hydrology is the basis of water resources management Hydrology in its broad sense is the science that relates to water (Chow, 1964). The *Ad Hoc* Panel on Hydrology of the US Federal Council for Science and Technology (1962) defined hydrology as: "*… the science that treats of the waters of the earth, their occurrence, circulation, and distribution, their chemical and physical properties, and their reaction with their environment, including their relation to living things. The domain of hydrology embraces the full life of water on the earth*".

From this definition of hydrology, it is clear that hydrology is an essential component of water resources management. Indeed, historically, hydrology and water resources management have been very closely related (Szolgay & Gottschalk, 1987). For example, a common problem with the development of water resources facilities, such as storage, conveyance, treatment and flood protection systems, is that river flow is not uniformly distributed in space and time. Hydrology is the discipline that has the most knowledge and expertise in this topic and hence input from hydrologists is critical for the design of effective water resources facilities.

Problems cannot be solved without hydrological sciences It is true that water resources management involves many disciplines, but hydrology is always at the core. Many water resources management problems CANNOT be solved without hydrology. A few examples are listed below:

– Estimates of the amount of available and renewable water resources in a given region or basin can only be provided by hydrology and hydrologists.
– Hydraulic engineering planning and design for water resources facilities must have a hydrological base.
– Climate change and land use/land cover changes will definitely affect water availability either at global or regional scales with great impacts on water resources management. Hydrological models are required to estimate the timing and magnitude of these impacts.
– Hydrological science is the basis for water quality control, which is one of the most challenging problems facing water resources management today.

The development of hydrology for better water resources management Water resources management is of increasing concern because of the demands placed on limited water resources by expanding populations and economic development. This will require hydrological science to provide more accurate and reliable information to make better water resource management decisions. In order to meet the requirements of water resources management, hydrological science should develop in the future to:

– deepen understanding of the entire hydrological cycle and its elements, as hydrological process understanding is the foundation of hydrology;
– improve the accuracy of hydrological predictions and develop advanced hydrological models to supply better information and tools for water resources management;

- enrich methodologies in various aspects of water resources management. For example, to estimate hydrological and water resources data in regions with no or limited observations that normally have lesser developed economies and require more support.
- cope with global environmental change (e.g. climate change, land use/land cover change), as well as human activities (e.g. economic development, population increase, life-style changes).

2.10 CONCLUSIONS

Hydrology will play a key role in the resolution of world water problems in the future so it is relevant to speculate on the nature of global hydrology in 2020. It is only 15 years ahead so a few trends can be readily identified from current programmes.

The spatial resolution of global simulations will be much higher in 2020. Current global simulations have grids of the order of one degree (approximately 100 km) or up to 0.25 degrees; however, a land information system is already under development that will have a spatial resolution of 1 km^2. It is not simply a simulation model but an operational hydrological model that will provide estimates of surface hydrological quantities, such as soil moisture, snow depth and melt, runoff, evaporation, transpiration, and even intercepted water storage on a daily timestep. Model parameter data, such as vegetation type, leaf area index, soil type, and forcing data such as precipitation, downward radiation, and surface meteorology, will be estimated from combinations of surface (*in situ*) observations and remote sensing. In addition four dimensional data assimilation (4DDA) will be used for estimating forcing data. The spatial resolution of such a land information system will become as high as 100 m globally, corresponding to the horizontal resolution of most regional hydrological models or higher. If such a system becomes operational on a daily timestep then it could form an early warning system for hydrological disasters, such as floods and droughts, for anywhere in the world.

Global monitoring of the hydrological cycle is also very important for supporting a detailed land information system. Initiatives such as the Global Earth Observation System of Systems (GEOSS), which was approved by 61 countries in February 2005 and will be implemented over the next 10 years, will increase the amount and accuracy of global hydrological data. Guaranteeing access to such information will also be vital, and hydroinformatics will help to develop user-friendly interfaces for stakeholders in water-related issues and the public interested in water cycles. In addition, the collection and synthesis of information on water-related disasters in a shared global database will contribute to improving understanding and mitigation of such extreme and rare events. Ideally, a land information system will be used as a tool to assess the possible impact of human interventions on global or local water cycles. To support such applications, more systematic collection will also be required of social and cultural information relating to water resources. Simulations will not be necessary for the whole world, but it is important that the land information system can be applied to any part of the world. In this sense, a global hydrological perspective will contribute to local water issues.

Some of the data presented in this chapter demonstrate the current water crisis in the world which will become even more acute in coming decades. The developing countries with high population growth and low incomes face the most severe water problems. These are exacerbated because most developing countries are located in zones where, even under natural conditions, renewable water resources are not substantial and are variable in time and vulnerable to even small anthropogenic changes. However, identifying and warning anticipated water-scarce regions in the future are not the final goals of world water resources assessment research. Instead, it is expected that the results from current assessments will be the foundation for proposing alternatives that change the current direction so that situations do not worsen. Virtual water trade is a neutral concept and does not view the globalization of food trade as good or bad, but it provides a more realistic picture of water scarcity considering both natural and social (economic) conditions. Furthermore, it can be a measure that leads to a solution of water shortage for food production in developing countries anticipated during this 21st century; absolute deficit of food production in developing countries can be compensated by food production in relatively water rich countries if an appropriate framework can be prepared to support such virtual water trades.

To solve water supply problems in areas of water shortage requires, on the one hand, extensive freshwater savings due to the introduction of more effective updated technologies, and, on the other hand, the provision of additional water sources. Priority should be given to those projects which will be most effective at minimizing cost, taking into account the physiographic features, technical facilities, available funds, environmental conditions and national interests of the country or region. Provision of additional water resources (including through water transfer) is the most important component of resolving water supply problems in regions with low specific water availability and rapid population growth because stabilization of the population number is difficult due to ethical, national and political considerations. Huge investments are required for the intensive introduction of updated water-saving and water-protecting technologies for freshwater use. Most expert assessments show that such investments are too excessive for the budgets of developing countries, even if these investments are extended over 20 or 30 years.

Nevertheless, water problems may be solved during the first half of the 21st century within the whole global community of developed and developing countries if the joint will and desire of humankind are aimed at sustainable economic development and the maintenance of sufficient quantity and good quality of renewable freshwater resources all over the world. A cardinal change in the attitude of people to freshwater is the most important prerequisite for joint efforts in the solution of water problems in the world. Freshwater should be recognized everywhere, at each level, first, as the most valuable natural resource without which the prosperity of humankind and global economic development are impossible; and second, as the most important vital component of the environment. It is necessary to develop effective international agreements, strict legislation and governmental decisions on the protection of water bodies, effective water use, provision of a human right to water, and water pricing, and to place greater emphasis on coordinated public and private initiatives to find solutions to water problems. It is essential to develop a strategy for water resources management as a multipurpose and long-term programme for human activity in each region to achieve a sustainable water supply.