

WORLD WATER RESOURCES

A NEW APPRAISAL AND ASSESSMENT FOR THE 21ST CENTURY

A summary of the monograph
World Water Resources

prepared in the framework of the
International Hydrological
Programme

by

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Preface

In the framework of UNESCO's International Hydrological Programme (IHP), a monograph on world water resources has been prepared by Professor I. Shiklomanov and his team at the State Hydrological Institute, Saint Petersburg, Russian Federation. It is a result of a decade of international co-operative research and provides an updated assessment of the freshwater resources of the world at the beginning of the 21st Century and also addresses the problems of availability, protection and management of water resources.

This brochure is a summarized version of the monograph and is designed to help decision-makers, administrators and the general public to fully understand the challenges in the domain of water which we are facing today and which need to be met tomorrow. It presents, in summarized form, the distribution of world water resources, their main basic components, their present water supply, agricultural and industrial use for a forecast for water use according to increasing demand, the impact of human activity on the availability of water together with recommendations for the future.

The brochure also clearly shows that much is still to be achieved and that many aspects need to be improved, in particular, global hydrological networks and the collection and processing of data to ensure greater accuracy and reliability in water resources assessment. Worldwide efforts need to be made. There is a pressing need for even closer co-operation amongst scientists, international and non-governmental organizations dealing with hydrology and water resources so that water resources assessment capabilities can be improved from national through regional to global levels.

We hope that the information the brochure contains will prove useful for understanding the problems raised by an ever-increasing demand for water, especially in areas where the freshwater supply is limited, such as arid and semi-arid regions. The monograph will be published in UNESCO's International Hydrology Series.

A. Szöllösi-Nagy
Secretary
International Hydrological Programme

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Introduction

...Water is the most widely distributed substance on our planet...

Water resources occupy a special place among other natural resources. Water is the most widely distributed substance on our planet: albeit in different amounts, it is available everywhere and plays a vital role in both the environment and human life.

Of most importance is fresh water. Human life itself is impossible without it because it can be substituted by nothing else. Human beings have always consumed fresh water and used the various natural surface water bodies for a whole range of purposes. For many hundreds of years man's impact on water resources was insignificant and entirely of a local character. The magnificent properties of natural waters - their renovation during the water cycle and their ability for self-purification - allowed a state of relative purity, quantity and quality of fresh waters to be retained for a long time. This gave birth to an illusion of immutability and inexhaustibility of water resources, considered as a free gift of the natural environment. Under these preconceptions a tradition has arisen of a careless attitude in the use of water resources, along with a concept that only minimum expense is required for either the purification of waste water or for the protection of natural water bodies.



The situation has changed drastically during recent decades. In many parts of the world the unfavourable results of man's long-term - often unreasonable - activities, have now been discovered. This concerns both the direct use of water resources and also the surface transformations that have taken place in many river catchments.

To a large extent this has been due to a drastic increase in global water withdrawal since the 1950s. In turn, this increase was caused by the scientific and technological revolution which permitted the intense development in production capabilities in all spheres of the world economy. Compared with previous decades, annual water withdrawal during 1951-60 increased fourfold. This occurred because of the dramatic expansion in irrigated areas, the growth in industrial and heat and power engineering water consumption, and the intensive construction of reservoirs in all continents.

All over the world during the last 25-30 years there has been a massive anthropogenic change in the hydrological cycle of rivers and lakes, affecting their water quality, their potential as water resources and the global water budget. The extent of water resources, their spatial and temporal distribution, are determined not only by natural climate variations as previously, but now also by man's economic activities. In many parts of the world water resources have become so depleted and much contaminated that they are already unable to meet the ever-increasing demands made on them. This has become the main factor impeding economic development and population growth.

Severe freshwater problems arise in arid regions characterised by having limited water resources, a high degree of use and very fast demographic growth. In 1977 the United Nations held the first World Conference on Water Resources in Argentina. This conference discussed the unfavourable situation pertaining

to fresh water in the one-third of the world located in zones with insufficient moisture. It was also noted that many of the same problems currently to be found in these areas would arise in most other countries by the end of the century.

The 1977 Conference contributed greatly to the strengthening and co-ordination of international co-operation in studying and assessing water resources. It also stimulated the development of national investigations and attracted the attention of the general public, governments, planning agencies and decision-makers to many problems of management and also future development in the hydrological sciences.



Water resource problems at regional and global scales fall within the sphere of activities of many international governmental and non-governmental organisations such as UNESCO, WMO, UNEP, FAO, IAHS, IWAR and others, all of whom have sponsored numerous scientific conferences and symposia to focus on these problems. An enormous quantity of studies have been published in many different countries, with perhaps the most complete and detailed estimates of the water balance and water resources for all the continents and the Earth's natural geomorphologic zones published in 1974. Based on close international co-operation, these figures were obtained by Russian scientists under the guidance of the State Hydrological Institute and cited in the monograph *World Water Balance and Water Resources of the Earth*, Baumgartner and Reichel (Germany) also presented similar estimates in 1975 in the monograph *World Water Balance*.

The data in both these monographs have been widely used by scientists ever since as the most comprehensive and reliable data sources, as no subsequent publication dealing with global water data has produced any new information, even for those countries with ample scientific facilities. Further, the reliability of data is not considered to be very high because it comes from different sources, including obsolete methods for obtaining readings, sometimes even relating to different years or other long-term periods. It was in this context, therefore, that UNESCO established a new project within the International Hydrological Programme to standardise the world's data on water resources and their uses and to prepare a monograph *World Water Resources by the beginning of the 21st century*. The State Hydrological Institute at St Petersburg, Russia, was charged with carrying out the project during 1991-96.

This executive summary introduces the reader to the basic results and inferences made during the project and preparation of the monograph.

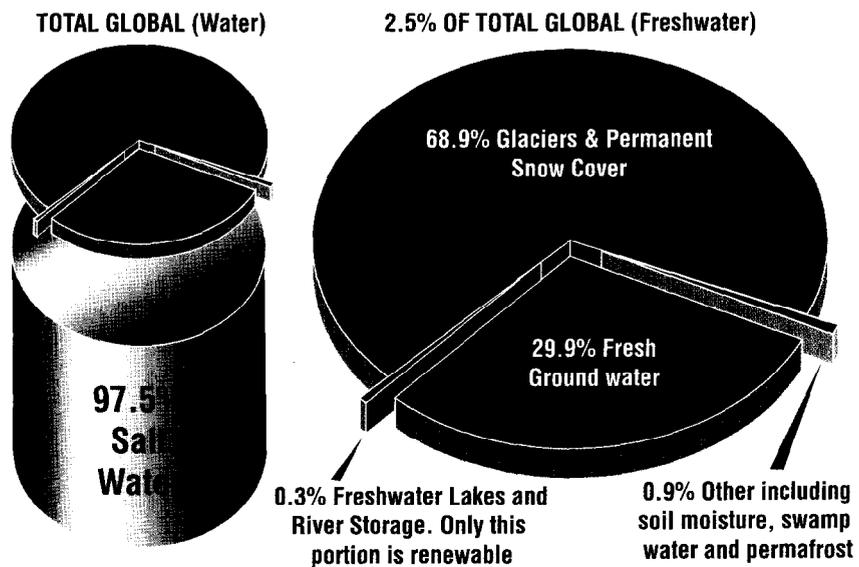
Definition of freshwater resources

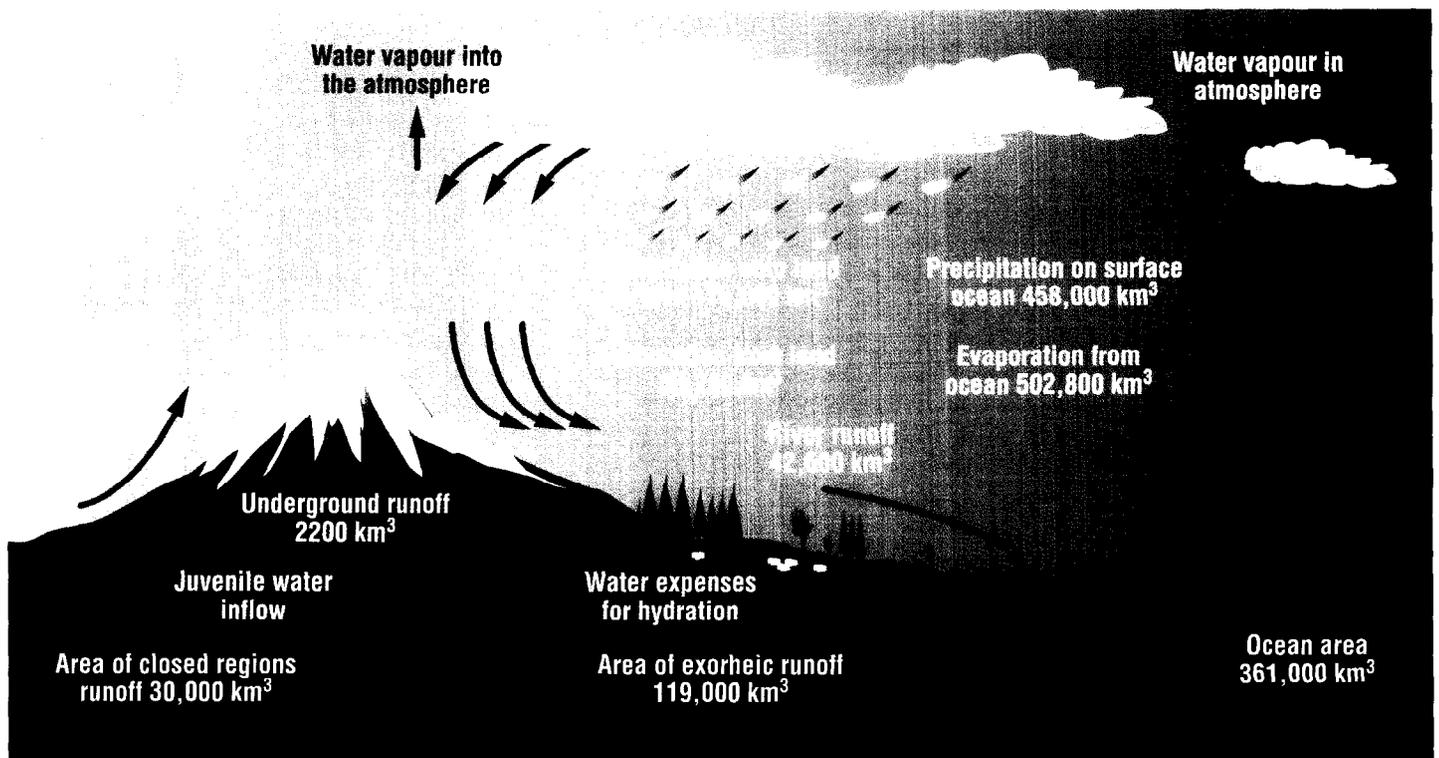
Water is the most widespread substance to be found in the natural environment. Water exists in three states: liquid, solid, and invisible vapour. It forms the oceans, seas, lakes, rivers and the underground waters found in the top layers of the Earth's crust and soil cover. In a solid state, it exists as ice and snow cover in polar and alpine regions. A certain amount of water is contained in the air as water vapour, water droplets and ice crystals, as well as in the biosphere. Huge amounts of water are bound up in the composition of the different minerals of the Earth's crust and core.

To assess the total water storage on the Earth reliably is a complicated problem because water is so very dynamic. It is in permanent motion, constantly changing from liquid to solid or gaseous phase, and back again. It is usual to estimate the quantity of water found in the so-called hydrosphere. This is all the free water existing in liquid, solid or gaseous state in the atmosphere, on the Earth's surface and in the crust down to a depth of 2000 metres. Current estimates are that the Earth's hydrosphere contains a huge amount of water -

about 1386 million cubic kilometres. However, 97.5% of this amount are saline waters and only 2.5% is fresh water. The greater portion of this fresh water (68.7%) is in the form of ice and permanent snow cover in the Antarctic, the Arctic, and in the mountainous regions. Next, 29.9% exists as fresh groundwaters. Only 0.26% of the total amount of fresh waters on the Earth are concentrated in lakes, reservoirs and river systems where they are most easily accessible for our economic needs and absolutely vital for water ecosystems.

These are the values for natural, static, water storage in the hydrosphere. It is the amount of water contained simultaneously, on average, over a long period of time - in water bodies, aquifers, and the atmosphere. For shorter time intervals such as a single year, a couple of seasons, or a few months, the volume of water stored in the hydrosphere will vary as water exchanges take place between the oceans, land and the atmosphere. This exchange is usually called the turnover of water on the Earth, or the global hydrological cycle, as shown in the diagram below.





Solar heat evaporates water into the air from the Earth's surface. Land, lakes, rivers and oceans send up a steady stream of water vapour; this spreads over the surface of the planet before falling down again as precipitation. Precipitation falling on land is the main source of the formation of the waters found on land: rivers, lakes, groundwater, glaciers. A portion of atmospheric precipitation evaporates, some of it penetrates and charges groundwater, while the rest - as river flow - returns to the oceans where it evaporates: this process repeats again and again.

A considerable portion of river flow does not reach the ocean, having evaporated in the endorheic regions, those areas with no natural surface runoff channels. On the other hand, some groundwater bypasses river systems altogether and goes directly to the ocean or

evaporates. Quantitative indices of these different components of the global hydrological cycle are shown in the diagram. Every year the turnover of water on Earth involves 577,000 km³ of water. This is water that evaporates from the oceanic surface (502,800 km³) and from land (74,200 km³). The same amount of water falls as atmospheric precipitation, 458,000 km³ on the ocean and 119,000 km³ on land. The difference between precipitation and evaporation from the land surface (119,000 - 74,200 = 44,800 km³/year) represents the total runoff of the Earth's rivers (42,700 km³/year) and direct groundwater runoff to the ocean (2100 km³/year). These are the principal sources of fresh water to support life necessities and man's economic activities.

...water is in permanent motion, constantly changing from liquid to solid or gaseous phase, and back again...

River water is of great importance in the global hydrological cycle and for the supply of water to humankind. This is because the behaviour of individual components in the turnover of water on the Earth depends both on the size of the storage and the dynamics of water movement. The different forms of water in the hydrosphere are fully replenished during the hydrological cycle but at very different rates. For instance, the period for complete recharge of oceanic waters takes about 2500 years, for permafrost and ice some 10,000 years and for deep groundwater and mountainous glaciers some 1500 years. Water storage in lakes is fully replenished over about 17 years and in rivers about 16 days.

Based on water exchange characteristics, two concepts are often used in hydrology and water management to assess the water resources in a region: the static storage component and the renewable waters. The 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. Intensive use of this component unavoidably results in depleting the storage and has unfavourable consequences. It also disturbs the natural equilibrium established over centuries, whose restoration would require tens or hundreds of years.

Renewable water resources include waters replenished yearly in the process of the water turnover of the Earth. These are mainly runoff from rivers, estimated as the volume per unit of time (m^3/s , km^3/year , etc.) and formed either within a specific region or from external sources, including groundwater inflow to a river network. This kind of water resource also includes the yearly renewable upper aquifer groundwater not drained by the river systems. However, on the global scale, these volumes are not large compared with the volume of river runoff and are of importance only for individual specific regions.

In the process of turnover, river runoff is not only recharged quantitatively, its quality is also restored. If only man could suddenly stop contaminating rivers, then with time water could return to its natural purity.

Thus, river runoff, representing renewable water resources, is the most important component of the hydrological cycle. It exerts a pronounced effect on the ecology of the earth's surface and on human economic development. It is river runoff that is most widely distributed over the land surface and provides the major volume of water consumption in the world. In practice, it is the value of river runoff that is used to estimate water availability and/or deficit in water resources for this or that region. Therefore, the following sections of this summary deal mainly with the assessment of river runoff, its spatial-temporal dynamics on the global scale, and an analysis of its use for different economic needs, now and in the future.

Distributed variability of Earth's water resources

The basic measurements: assessment methodologies

The quantitative characteristics of renewable water resources of a region or river basin can be determined by two approaches: by using meteorological data or by using river runoff observations.

The first approach is widely applied where there are insufficient hydrological observations but where the meteorological data is both significantly detailed and comprehensive. In practice, it is usually achieved by using the simplest equation for the long-term water balance of a territory. According to this equation, the size or extent of renewable water resources, averaged over a long period of time, is determined by the difference between precipitation and evaporation from land. Precipitation is calculated from observational data and evaporation by various estimation formulae. This estimation technique is quite simple and has been widely used in many countries since the beginning of this century when the hydrological network was insufficiently developed and meteorological data were much more widely available. The technique is still applied quite frequently; for instance, an estimation of water resources for the Latin-American countries was made in this way.

Estimating renewable water resources by meteorological data, though very simple, has a number of serious disadvantages. It cannot be

recommended for use in detailed calculations, especially in countries and regions with limited water resources. First, because of low accuracy, this technique is not applicable to arid and semi-arid regions where river runoff is very small since absolute values will be close to any errors in the determination of evaporation and precipitation. Second, it is impossible to estimate water resources reliably by this method for individual years or, moreover, for a specific season or month. Third, this technique is inapplicable for water resources estimation in countries and regions located in international river basin because a larger volume of river runoff comes from outside than is generated within the territory in question.

In this connection, the second approach has been applied to estimate global water resources for continents, regions and even countries located within various different physiographic conditions. This is based on observations from the world's hydrological network, and the meteorological information serves a subsidiary role. The approach was successfully applied as early as the 1960-70s in the preparation of the monograph *World Water Balance and Water Resources of the Earth* referred to earlier. By now, an even longer series of hydrological observations has been collected and it was possible to obtain data, previously inaccessible, for many regions in Africa, Asia and Latin America poorly covered with hydrological information. There is, therefore, considerably more justification to apply this latter approach.

The availability of a long-term observational series was one of the main conditions for choosing hydrological sites to meet a fundamental criterion that water resources estimation for all parts of the world should be based on the same long-term period. Unfortunately, a considerable number of the sites selected, especially those located in the developing countries in Africa, Asia and Latin America, had only very short records (5 to 10 years). Indeed, for most sites we succeeded in



obtaining observations only up to 1980-88. The single design period of 1921 to 1985 was chosen, although for many countries in Europe and North America there are data available for 1990-94. The acceptance of this fairly robust 66-year design period allowed comparable mean values of water resources to be obtained for all regions of the world. Also, it was possible to estimate reliably their extreme values and long-term variability.

Many efforts were made to update the series and to restore the gaps in observations so as to obtain continuous data for the long-term period selected. This has been achieved using well-known correlation methods and, in many cases so as to obtain more reliable results, meteorological data have also been used: making the most of the global database of meteorological information at our disposal, we had monthly precipitation and air temperatures for the entire observation period from more than 7000 meteorological stations.

The World Meteorological Organization has at present information on 64,000 stations with measured river runoff. These are very unevenly spread throughout the world. The duration of observations varies from only a few months to more than 180 years. To a greater or lesser extent, we have had at our disposal data on river runoff from about 40,000 stations although there is a great difference in the quality of information from different countries, including some which is only fragmentary. We have also had access to the observational data that served as the basis for constructing national or regional charts of mean annual river runoff. Using all this information to estimate the dynamics of water resources on a global scale would be impossible, so a selection was made of hydrological sites based on the following conditions:

In spite of the fairly dense hydrological network in the world, a considerable part of the land surface, some 15-20%, is not covered by data from regular observations. These are the usually sparsely populated northern, desert and tropical regions, and to calculate runoff from these territories, hydrological models and methods for mapping annual runoff have been used.

Special methods are required to estimate the water resources of individual countries and those natural-economic regions whose boundaries do not coincide with river watersheds. In this case, hydrological models specially developed at the Russian State Hydrological Institute have been used to generate reliable estimates of the basic characteristics of renewable water resources from specific regions.

- the availability of the longest series of continuous observations;
- the location of sites on large and medium rivers, preferably evenly distributed throughout a territory;
- observations should reflect the natural (or close to the natural) river runoff regime.

Thus, monthly and annual observations from about 2500 hydrological sites have been used directly in the estimation of renewable water resources on a global scale, distributed as widely as possible across all continents. This amounts to about 800 sites 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.

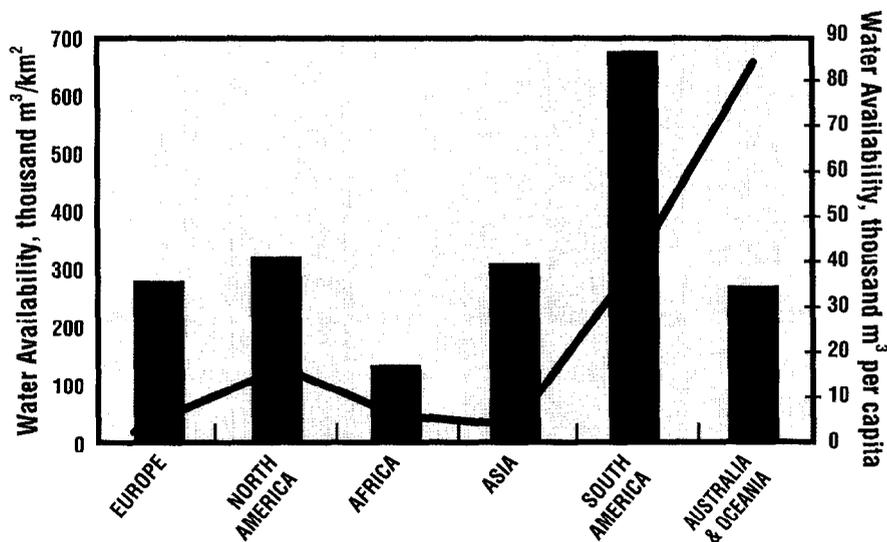
Continental, regional and country distribution

The mean value of renewable global water resources is estimated at 42,700 km³ per year, and they are extremely variable in space and time. In absolute values, the largest volume of water resources are those of Asia and South America (13,500 and 12,000 km³ per year, respectively). The smallest are typically those for Europe and Australia with Oceania (2900 and 2400 km³ year). For individual years, the extent of water resources can vary \pm 15-25% of their average values. Indeed, absolute values do not fully reflect water availability within the continents as they differ so much in area and population numbers. Much more informative is specific water availability, as shown shown in the diagram.

The rapid population growth between 1970 to 1994 has resulted in the potential water availability for the Earth's population decreasing from 12.9 down to 7.6 thousand cubic metres per year per person. The greatest

reduction in population water supply took place in Africa (by 2.8 times), in Asia (by two times), and in south America (by 1.7 times). The water supply for the population of Europe decreased by only 16% for that period. (Note that if the growth in water use is taken into account, actual water supply decreased considerably more than these amounts for many countries in Africa, Asia and south America; this aspect is discussed later.)

Studies have shown that variations in the total river runoff on the continents for Earth as a whole are of a cyclic nature. Cycles of wet and dry years alternate, and deviations from average values differ considerably in both duration and magnitude. For instance, low water content periods, e.g. 1940-44, 1965-68, and 1977-79, are clearly seen in the variations in the total runoff of the world's rivers when values fell 1600-2900 km³ below average. Conversely, the years of 1926-27, 1949-52 and 1973-75 all had appreciably increased river runoff.

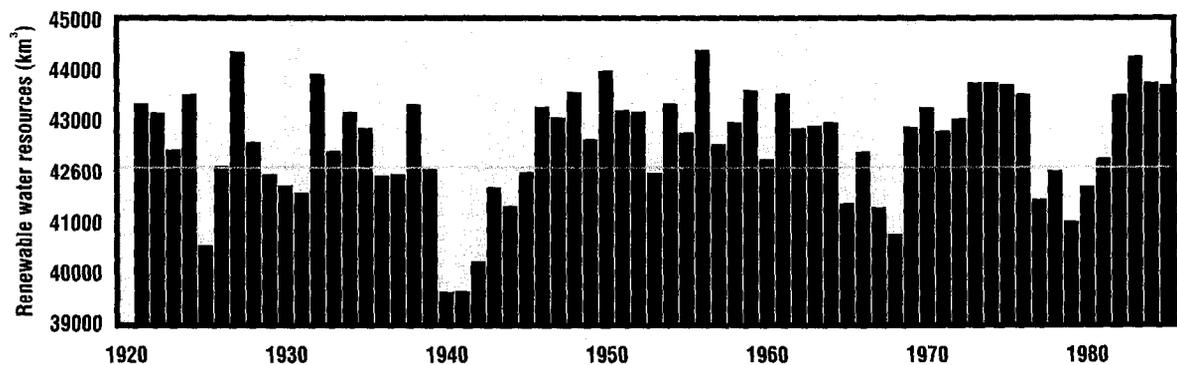


Alongside such clearly defined cyclic variations in the total runoff from the world's rivers, it is also quite apparent that there is no discernible trend within the entire 65-year period. This pertains to all continents, particularly so if no attention is paid to the data for the two recent decades for Africa and South America where there does seem to be an increase in river runoff in South America and a decrease in Africa. If there is in fact no noticeable increase in global river runoff over such a long-term period, this must raise doubts about the widely-held hypothesis of an elevation in the World Ocean since the beginning of the present century due to an intensive melting of continental mountain glaciers.

River runoff is very unevenly distributed throughout the year in almost all regions of the world. About 60-70% of runoff is generated during flood periods and therefore values for renewable water resources vary noticeably during a year. Current estimates are that the

major part of European runoff takes place during April to July (46%), in June to September in Asia (54%), during September to December (44%) in Africa, 45% during April to July in South America and 40% during January and April in Australia/Oceania. On average, the wet season for the entire land surface lasts from May to August, during which time total global runoff amounts to some 45% of the annual total.

Unevenness in the distribution of river runoff during a year leads to the necessity for regulation by creating reservoirs of different types. Of most importance for water supply is what we call base-flow runoff, a stable volume, varying little both during a year and from year to year, whose use is possible without artificial regulation. Its value is approximately 37% of the total volume of global river runoff, or about 16,000 km³ per year.



Temporal / spatial variations in renewable water resources

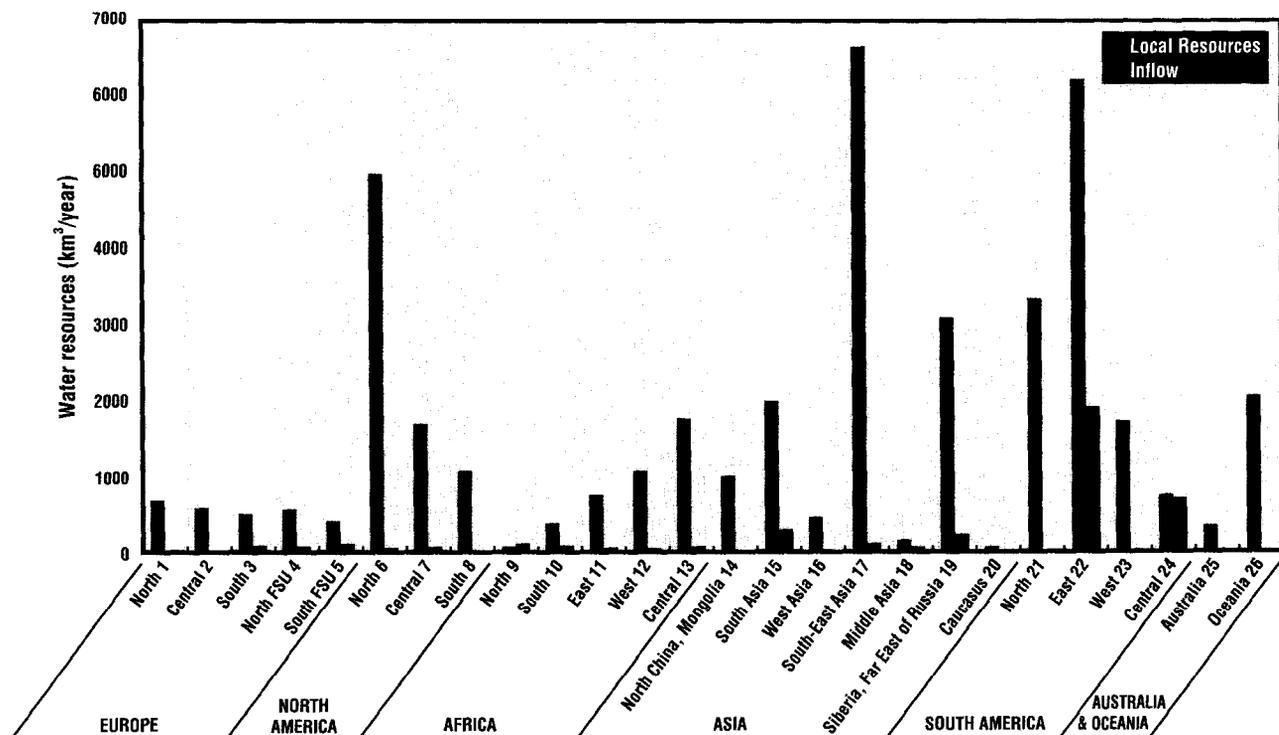
Let us now analyse the temporal-spatial variations in renewable water resources in more detail. For this purpose, large 'natural-economic' regions with homogeneous physiographic characteristics and a similar economic development level were selected, i.e. some 26 specific regions in total, from three to eight within each continent.

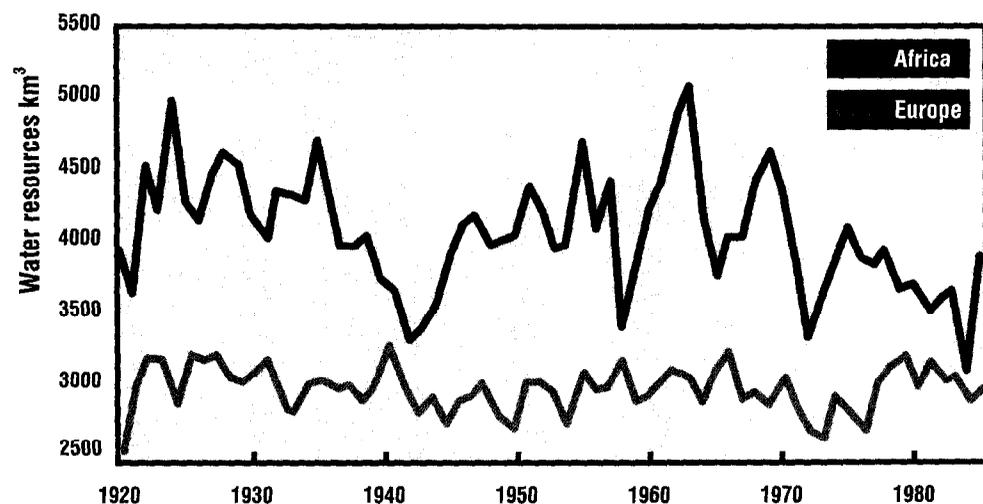
In the majority of cases, regional boundaries followed administrative borders and thus some regions include the entire territories of individual countries. This was done because of the need to analyse the extent of water resources alongside population dynamics and water use, the data for which are only published by individual countries. Exceptions to this were Russia, China and the USA, where some individual parts were grouped in different natural-economic regions. The areas of

individual regions vary widely, from 12-13 million km² for Siberia and the Russian Far East, Canada and Alaska, to 0.19 million km² for Transcaucasia: most regions have areas of 1 to 8 million km².

The figure below presents the mean values for renewable water resources. These were obtained for every region for 1921-1985, based on the local water resources formed within the territory of the region, plus the freshwater inflow from neighbouring territories. As can be seen in the figure below, in most instances the bulk of water resources are formed within a region, with insignificant inflow from outside; the exceptions are regions 3, 5, 10, 18 and 22 where the value of the inflow reaches 20-25% of the local water resources. In regions 9 and 24 (North Africa and central South America) the inflow has a comparable value to that of local water resources or even exceeds them several times.

...in some regions river runoff amounts to only 2 - 20% of annual runoff during the low flow season; it can be as little as 0.8% in West Africa...





Year-to-year variability within the regions can be quite significant and considerably exceed averaged data for the continents. This is especially so in the arid and semi-arid regions where the actual values are small. Here, values for individual years can be 1.5 to 2 times less than the averages over a long period, whereas for wet regions this difference is within 15 to 25%. The figure (top right) shows some long-term variations in renewable water resources for Africa and Europe. It demonstrates a cyclic nature and in practically all regions the dry periods can last for three to six years, during which time many regions experience severe water supply problems.

Note the decrease in water resources that has occurred since the 1970s in a number of regions of Africa. For the Sahel, this decrease has been particularly hazardous since water resources there have reduced almost by half during the last 15 years.

The possibilities of using water resources for economic needs are determined not only by their year-to-year but also seasonal and

monthly variability. Many regions are characterised by an extremely uneven river runoff distribution, with 60-80% of annual runoff occurring during the flood season of some three to four months. For example, 64% of annual runoff occurs during the three flood months in the north and south of the European part of the former Soviet Union.

An estimate of renewable water resources has also been made for some 60 separate countries. Those selected include developed and developing countries as well as those with a transitional economy, and the largest and the smallest in both area and population.

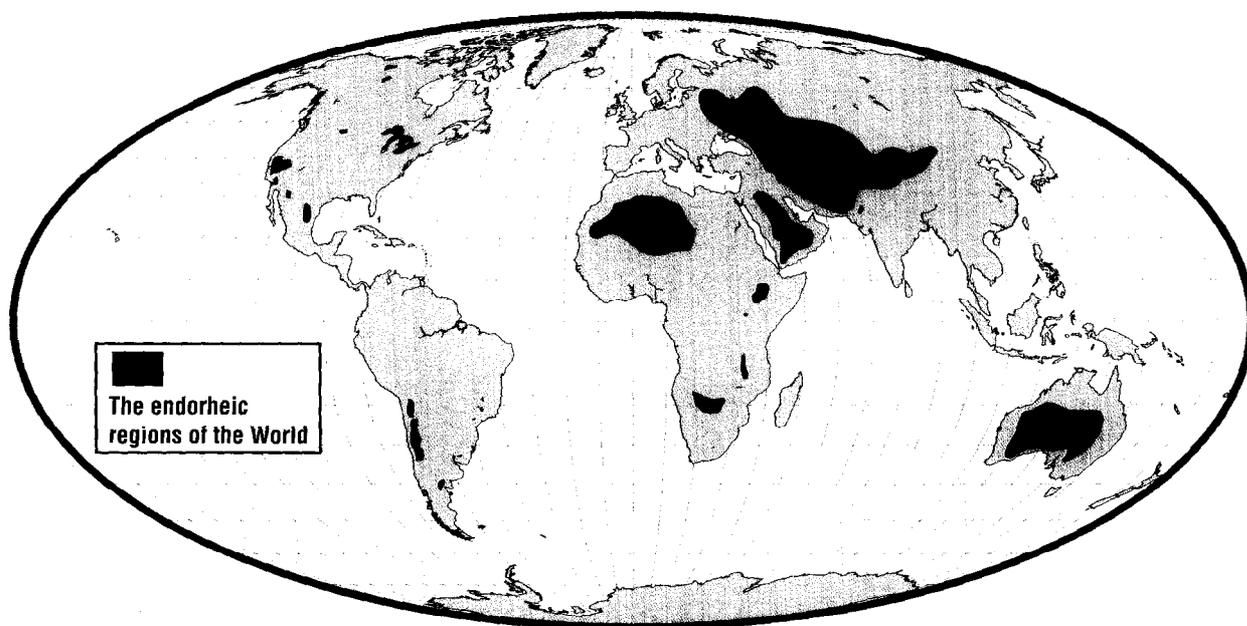
The greatest renewable water resources are concentrated in six principal countries of the world: Brazil, Russia, Canada, United States of America, China, and India, which have more than 40% of total annual river runoff formed within their territories. Runoff distribution during a year is evened out to a considerable extent in these countries because of their vast land mass and diverse climatic conditions.

River basins and runoff to the oceans

The greatest river in the world, the Amazon, produces 16% of annual global river runoff; 27% of the world's water resources are formed by the five largest river systems of the Amazon, the Ganges with the Brahmaputra, the Congo, the Yangtze, and the Orinoco. The rivers shown in the figure are located throughout all the Earth's continents with the exception of Australia. The total for all these rivers comprise 52% of world water resources.

By generalising river runoff data from the global hydrological network it was possible to assess the freshwater inflow to the World Ocean. This inflow is very important for studying its freshwater balance and dynamic processes. However, freshwater inflow to the World Ocean cannot be identified simply on the basis of the value of global river runoff for two reasons:

- First, river watersheds mostly belong to the so-called endorheic (drainless) runoff regions that are not connected to the World Ocean. The distribution of these regions is shown overleaf on a schematic world map. The total area of the endorheic regions is about 30 million km², or some 20% of the total land area. However, only 2.3% (about 1000 km³/year) of annual global river runoff is formed in these regions simply because most of these drainless regions are occupied by deserts and semi-deserts with very low precipitation.
- Second, in the regions of the exorheic drainage which are directly connected to the World Ocean, the values for water resources of river basins do not always coincide with river mouth runoff. This pertains particularly to those regions with a hot climate. There, the basin's water resources are formed in mountainous areas with large precipitation; moving towards the river mouth, much





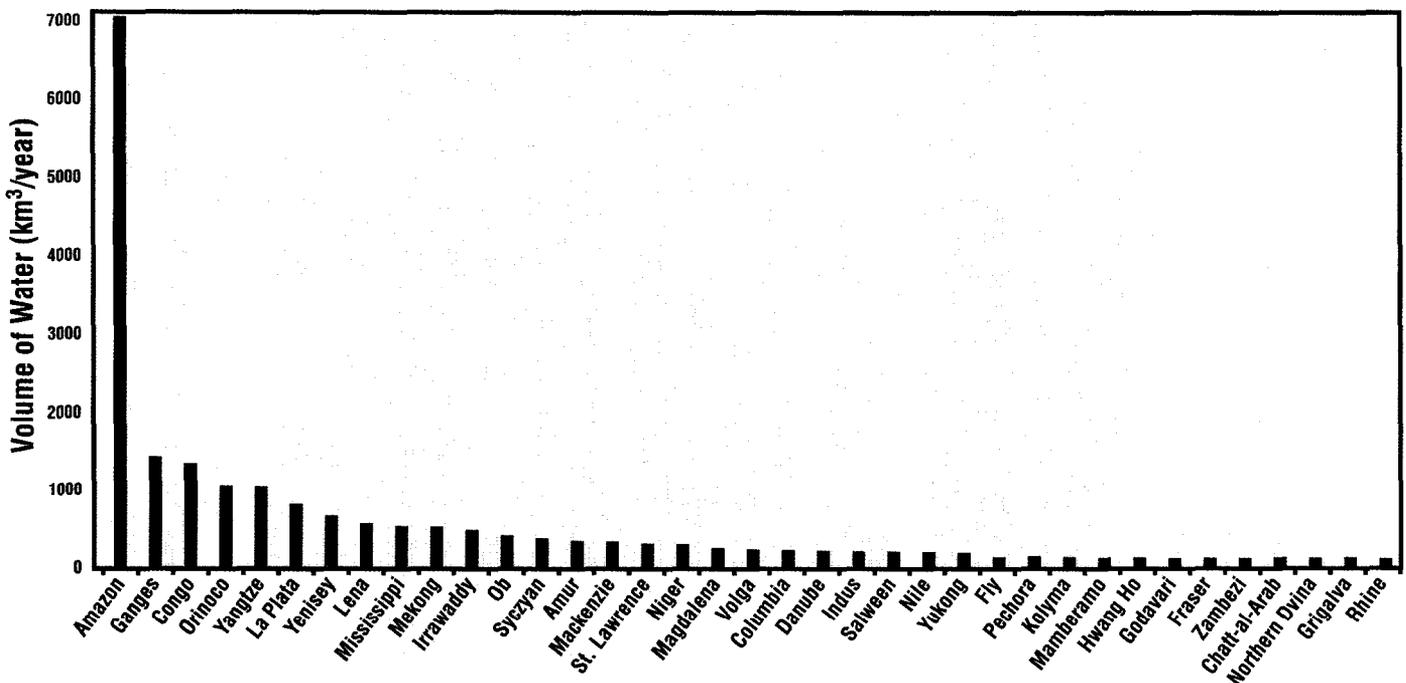
runoff is lost as evaporation in the flood plain and lowland parts of the basin. The Ganges and Indus in Asia, the Niger and Zambezi in Africa, the Mississippi and Colorado in North America, are all examples of such river basins. Taking all the exorheic regions as a whole, about 1100 km³ of runoff per year are lost as evaporation and does not reach the river mouth.

amount of river water - some 43000 km³ per year - flows into the Arctic Ocean but river waters are nevertheless of the utmost importance for the regime of this ocean. There is a very simple explanation for this: the Arctic Ocean contains 1.2% of the total water storage in the World Ocean while at the same time it accepts 11% of global river runoff.

Thus, the total river water inflow to the World Ocean will be somewhat less than the value of renewable water resources of all the Earth's continents. Approximately half the total river water inflow to the World Ocean enters the Atlantic Ocean where four of the six largest rivers of the world go, the Amazon, the Congo, the Orinoco, and the Parana. The smallest

To simulate the dynamic processes in the oceans, it is very important to take into account not only the volume of river water inflow but also its distribution since river runoff enters the World Ocean very unevenly. On average, about 40% of total river runoff enters the ocean in the equatorial region between 10°N and 10°S.

The world's major rivers, i.e. those whose average long-term runoff volume exceeds 100km³



River runoff and groundwater

The extent of renewable water resources is estimated from total river runoff. River runoff includes all the water coming in directly to the hydrological network during rainfall or snowmelt, plus groundwater from the upper aquifers feeding rivers more or less evenly throughout a year. A part of the groundwater which may also be referred to as renewable water resources does not enter rivers but goes directly to seas or oceans or is expended for evaporation. In this case estimation of renewable water resources using only river runoff data produces underestimated results.

Reliable information on the renewable groundwater volumes which do not enter the river system is therefore of great practical importance. The regions where they are of most importance are those with a weakly developed hydrological network, particularly plains with arid and semi-arid climates. There, rivers are often ephemeral and runoff occurs only after rain periods; in such circumstances groundwater resources may play an important

role in contributing to the total volume of renewable water resources.

To estimate this groundwater reliably for all regions of the world is a very complicated problem because of the lack of essential data. Nevertheless, this estimation was made for a number of regions and countries and allows certain conclusions to be drawn for different physiographic conditions on a global scale.

In particular, the most detailed estimation of renewable water resources, including river runoff and unrelated groundwater, was made in 1995 by the FAO. It is given for all countries of Africa, where arid and semi-arid regions occupy more than half of the continent. From the FAO data, the total volume of renewable groundwater resources, un-related to river runoff, is 188 km³ per year for the continent as a whole, or perhaps up to 5% of total river runoff volume. These values are very important in individual countries such as Egypt, Libya, Tunisia, and Morocco located in arid regions and should certainly be taken into account.



Water use in the world: present situation/future needs

To reliably assess in detail future water resources and present water availability, it is insufficient to rely simply on volume data and natural variations in river runoff. It is also necessary to take into account changes due to human activities. During recent decades natural variations in river runoff and quantitative and qualitative characteristics of renewable water resources have been much affected by a whole complexity of anthropogenic impacts. They include those related directly to water intake from river systems for irrigation, industrial and domestic water use. They also include reservoir runoff control, river basin landuse change such as afforestation and deforestation, field management, urbanisation, and drainage. All these factors differently affect the total volumes of water resources, river runoff regime and water quality.

To estimate the true role of all anthropogenic factors is likely to be problematic. However, we should not overlook those factors transforming the surface of river catchments. Such factors may exert major effects on the runoff of small and middle-sized rivers, and on monthly and extreme river runoff characteristics rather than annual values, as well as on water quality. Under certain physiographic conditions these kinds of human activities can even promote an increase in renewable water resources simply by decreasing the total evaporation loss from basins.

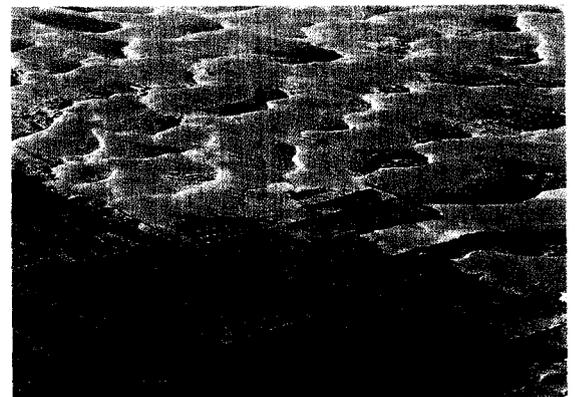
However, estimation of global anthropogenic effects on water resources is based, primarily, on a consideration of the role of those factors related to direct water intake from water bodies and reservoir runoff control. These factors, causing unilateral decrease in surface and groundwater runoff, are widely distributed, most intensively developed and able to exert a pronounced effect on water resources in large regions.

Speaking of man's impact on water resources, it is impossible to avoid touching upon an acute modern problem, the problem of global

warming due to increasing carbon dioxide concentration in the atmosphere and strengthening of the 'greenhouse' effect. An expected rise in air temperature and change in precipitation could not help but affect the values of renewable water resources and the character of their economic use. However, an insignificant anthropogenic global climate change recorded for recent decades is more or less reflected in observation-based estimates of water resources and water consumption variations.

As to calculations for the future, it has to be said that the global warming forecasts for most regions so far available are very contradictory, particularly with regard to expected changes in precipitation. They are, therefore, unusable for obtaining anywhere near certain estimates of water resources and water consumption. In addition, according to the recent assessments for the future, the most serious anthropogenic changes in global climate are not to be expected until after 2030-40.

Thus, a quantitative estimation of global water resources for past years and for the decades to come was based on water use for public and domestic needs, industrial production, and agriculture (irrigation). Water losses occurring during reservoir construction were also taken into account. All the estimations for the future have been made ignoring potential anthropogenic global climate change, i.e. they are for a stationary climatic situation.



Municipal water use

Municipal water use is directly related to the quantity of water withdrawn by populations in cities, towns, housing estates, domestic and public service enterprises. The public supply also includes water for industry that provides directly for the needs of urban populations and this demand also consumes high quality water from the city water supply system. In many cities, a considerable quantity of water is used in market gardening and for watering vegetable gardens and domestic garden plots.

The volume of public water use depends on the size of an urban population and the services and utilities provided, such as the extent of pipe networks for supply and sewerage, or centralised hot-water supply where available. Also, much depends on climate conditions. In many large cities, present water withdrawal amounts to 300-600 litres per day per person.

By the end of this century, the specific per capita urban water withdrawal is expected to increase to 500-1000 litres per day in the industrially developed countries of Europe and North America. On the other hand, in developing, more agricultural countries found in Asia, Africa and Latin America, public water withdrawal is a mere 50-100 l/day. In certain individual regions with insufficient water resources, it is no more than 10-40 l/day of fresh water per person.

A greater part of the water that has been withdrawn from the urban water supply system is returned to the hydrological system after use (purified or not) as waste water, if urban sewerage networks operate effectively. The major sources of actual consumption consist of water lost through evaporation from leaking supply and sewerage pipes, from watering plants and recreational areas, washing streets, and garden plots. Thus, to a large extent, the extent of the loss also depends on climatic conditions. In hot, dry regions losses are certainly larger than those where it is

cold and humid: water consumption for personal needs is insignificant as compared with water losses through evaporation.

Relative values for consumption are usually expressed as a percentage of water intake and depend to a considerable extent on the volume of water withdrawn for public supply. Thus, in modern cities equipped with centralised supply and efficient sewerage systems, the specific water withdrawal can be 400-600 l/day, and consumption is usually not above 5-10% of total water intake. Small cities with a large stock of individual buildings not fully provided with a centralised system, may have a specific water withdrawal of 100-150 l/day. Consumption increases significantly in this context and can reach 40-60%, with the lesser values occurring in northernmost and the larger values in the dry, southernmost regions.

The modern trend in the development of public water supply all over the world is the construction in both large and small cities of effective centralised water supply and sewerage systems, connecting together an even greater number of buildings and populated areas. In the future, however, the specific per capita water withdrawal is expected to increase, while water consumption *per se*, expressed as a percentage of water intake, will decrease considerably.

...water withdrawal is up to 10 times greater in Europe and North America than in some parts of Africa and Asia...





Water in industry

Water in industry is used for cooling, transportation and washing, as a solvent, and also sometimes entering the composition of the finished product. Thermal and atomic power generation lead the list of major users. It requires a great amount of water to cool assemblies. The volumes of industrial water withdrawal are quite different within individual branches of industry and also within different kinds of production, depending on the technology of the manufacturing process. Again, it depends on climatic conditions since, as a rule, industrial water withdrawal seems to be considerably less in northern than in southern regions where higher air temperatures prevail.

In addition to thermal power, the other principal industrial water users are chemical and petroleum plants, ferrous and non-ferrous metallurgy, the wood pulp and paper industry, and machinery manufacture. The major characteristics of industrial water use - the volume of fresh water withdrawal, water consumption, water diversion - depend to a very large extent on the water supply system in use.

The extent of industrial water consumption is usually an insignificant fraction of actual intake. In thermal power generation it may be only about 0.5 to 3% but up to 30-40% for some specific industrial processes.

The development of industrial water withdrawal is one of the main causes of water pollution in the world. This is explained by the rapid industrial growth in different countries and exacerbated by the fact that much of the intake is discharged as waste water to natural water courses, for the most part untreated or only partially purified. To struggle with such pollution problems, many countries have undertaken energetic measures to decrease industrial water withdrawals and discharges. Since the 1970-80s, a tendency towards stabilisation and even a decrease in industrial water demand has been observed. It is expected that the future will see a trend in most countries towards more use of circulating water supply systems and many industries will move towards more water-free, or dry, technologies.





Water for agriculture

Land irrigation has been practised for millennia through the necessity to maximise food supply for humanity but the dramatic expansion in irrigated land has mainly taken place during the 20th century, with irrigation becoming the principal water use in many countries. Indeed, agriculture is now reckoned to be the largest consumer of water, accounting for some 80% of total water use. Before the late 1970s, intensive irrigation development could be found in all the continents, forcing the growth in irrigated areas and guaranteeing an increase in crop production. In the 1980s, however, the rate of global increase in irrigated areas dropped considerably in both developed and developing countries.

The causes are primarily the very high cost of irrigation networks followed by soil salinisation due to the lack of proper drainage, the depletion of irrigation water-supplying sources, and the problems of environmental protection. In a number of developed

countries, the extent of irrigated land has now stabilised or even diminished.

At present, about 15% of all cultivated lands are being irrigated. Food production from irrigated areas, however, amounts to almost half the total crop production in terms of value. In the modern world, population growth proceeds at a great rate and at the same time there is an acute food deficit being experienced by almost two-thirds of the world's population. Irrigation therefore plays a large role in increasing arable production and cattle-breeding efficiency, with irrigated farming expected to continue to develop intensively in the future, mainly in those countries with extremely rapid population growth and sufficient land and water resources.

The values for specific water withdrawal usually vary. In the future they will change considerably depending on advanced irrigation systems, improved watering requirements, regimes, and techniques, all of which factors should be taken into account in projections for



Information on the volume of water intake and extent of irrigated areas available for different countries allows calculation of specific water withdrawal for irrigation under different physiographic conditions.

Naturally, the smallest values for specific water withdrawal are observed in the north; for instance, in northern Europe they are between 300-5000 m³/ha while in southern and eastern European countries they amount to 7000-11000 m³/ha. The returnable waters are equal to approximately 20-30% of water intake. In

the USA, specific water withdrawal for irrigation is estimated by different authors to be between 8000-10,000 m³/ha and returnable waters at some 40-50% of water intake. In the countries of Asia, Africa, Central and South America, where there is a great variety of climatic conditions, crop composition and watering techniques, the values for specific water withdrawal range from 5000-6000m³/h to 15,000 to 17,000 m³/ha and in individual regions of Africa, 20,000-25,000 m³/ha.



future irrigation water demand. Considerable water economy could be affected through the use of the best and up-to-date engineering methods and watering techniques such as sprinklers, drip irrigation, etc. which help to increase crop productivity and decrease the volume of irrigation water required.

In addition to irrigation, there may also be the problem of supplying rural populations and livestock with high quality fresh water in many developing countries located in arid regions. However, costs for drinking water are insignificant compared with those of irrigation.

Surface water reservoirs

The construction of large surface reservoirs can lead to major transformations in the temporal-spatial distribution of river runoff and an increase in water resources during the low flow limiting periods and dry years. As a result of flooding vast areas, reservoirs make a considerable contribution to evaporation from water surfaces in water-scarce regions. This leads to a decrease in total water resources and thus reservoirs are one of the greatest freshwater users. This important role of reservoirs ought always to be taken into account in estimations of total water consumption although many authors do not do so.

Although reservoirs have also been constructed for millennia, as objects of global scale they appeared only in the second half of the 20th century. All the largest reservoirs with a total volume of more than 50 km³ have been built in the last 40 years. At the present time, the total volume of the world's reservoirs is about 6000 km³ and their total surface area is up to 500,000 km².

Reservoir construction was most intensive during the period 1950-70 in many well-developed regions where river runoff was almost fully regulated. Subsequently, the rates of reservoir construction have decreased considerably although they are still high in those countries with rich natural resources of river runoff'. This is caused partly by the increasing role for hydropower engineering where there are liquid and solid fuel deficits. In addition, reservoirs provide the greater part of the water consumed by industry, power stations, and agriculture. They are the basis for large-scale water management systems regulating river runoff as well as protecting populated areas from floods and inundations. However, in the future it is likely that reservoirs will largely be constructed in mountainous, piedmont or in weakly developed regions only so that there is no longer any flooding of vast areas of fertile lands more suitable for agriculture use than water harvesting.



Forecasting global water use

There are several basic factors that determine the quantitative characteristics of water use in the world: the level of socio-economic development, population numbers, physiographic (including climatic) features, and the area of the territory served. Their combination determines the volume and structure of water use, its dynamics and development patterns for the future.

An analysis has been made of global water use. Total water withdrawal and consumption for urban population needs (domestic water consumption), industry (including power generation), irrigated farming and general agriculture were estimated for every region, country or river basin. An assessment was then made of water losses for additional evaporation from reservoir surfaces. All estimates were made for different design levels: for the earlier years 1900, 1940, 1950, 1960, 1970, 1980; for the current period 1990-1995; and for the future 2000, 2010 and 2025. This approach made it possible to follow the distribution of water use in the world by territory and through time within the current century and into the beginning of the next.

Primarily, water use was estimated for countries, with the values thus obtained then generalised for the larger natural-economic regions and whole continents. In total, to a greater or lesser extent, water use data and other determining factors were analysed for some 150 countries. Preference was given to national data for actual or calculated water use in individual countries or groups of countries. Where actual data were not available, estimates were derived using specially developed analysis and using as analogues information from countries which do have reliable data located in similar physiographic conditions and with the same level and features of economic development.

Potable use in cities and rural areas was estimated from data on population number (urban and rural) and per capita specific water withdrawal. The dynamics of population numbers for past years were taken from the statistical handbooks and for the future from the data given in the 1995 United Nations forecasts. Per capita specific water withdrawal and the fraction of total water consumption for every country were taken from the published national data or from the databases of the international organisations.

An assessment of water use for irrigation was carried out by analysing information for the previous 30-40 years such as population number, area of irrigated lands by years (FAO data, as ha per capita) and the values of Gross National Product (GNP) expressed in US dollars per capita. Values for specific water withdrawal and water consumption were taken from national estimates or by country analogues.

Calculations of water withdrawal for 2000, 2010 and 2025 were based mainly on forecasting the areas of irrigated lands. For this purpose, the analysis was primarily made by looking at the trends for previous years, coupled with the other determining factors outlined above. This analysis was carried out



separately for every country. Clear analogies were found in groups of countries with similar GNP-levels, showing that trends in irrigation depend on population number and GNP-values. The limiting factors are sufficient area of land suitable for irrigation and the value of the water resource accessible for use. To estimate the future irrigation water demands, consideration was given to the tendency for this to decrease because of improved technological procedures and engineering directed towards economising on the use of water.

Estimates of industrial water withdrawal were based on the dynamics of industrial production in different regions of the world, including those with different levels of economic development located in different physiographic conditions. Calculations for current and future periods were carried out separately for thermal power from other industries with considerably different trends, rates of development and water losses. In summary, total water consumption by thermal power engineering was assumed to be 1-4% and for other industries it was taken as 10-40% of water intake, depending on the development level, the availability of water supply systems and climatic conditions.

An assessment for the future up to 2025 was made for every country taking account of special UNIDO (1995) developments. These developments were based on the analysis of the current situation in the world and the forecast GNP values. As a result, increased industrial water withdrawal was predicted for 2025, compared with 1990, for all principal countries, with considerably different scenarios for global development and electric power generation. We based our figures on the most optimistic development scenario (Global Balance) for average growth in the level of electricity generation. In accordance with the UNIDO scenario, water demand is expected to

increase 1.4-2.9 times for developed countries and by 3-10 times for developing countries.

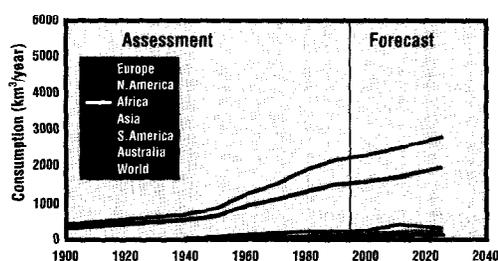
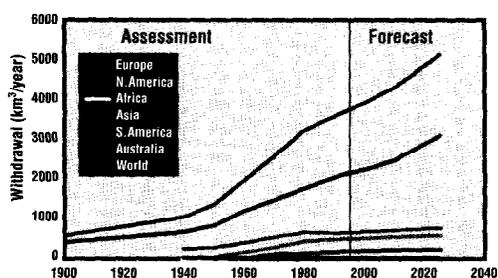
Additional water losses for evaporation from reservoirs were calculated for all the principal reservoirs of the world, i.e. those having a volume of more than 5 km³, by the difference between average evaporation from a water surface and the land. The initial data on reservoirs (area, volume, location, years of construction and other features) were taken from international monographs as well as from other publications on individual countries and regions. The evaporation norms for water and land surfaces were determined from the charts in the *Atlas of World Water Balance*.



Future water requirements

The figure below shows the dynamics of water use by continent for the current century and for the future up to 2025. Modern (1995) total global water withdrawal comprises some 3750 km³/year, with actual consumption at some 2270 km³/year (= 61% of withdrawal). In the future, total water withdrawal will grow by about 10-12% every ten years, and by 2025 it will reach approximately 5100 km³/year, a 1.38-fold increase. Water consumption will grow somewhat slower, with an increase of 1.26 times. At the present time, about 57% of total water withdrawal and 70% of global water consumption occurs in Asia where the major irrigated lands of the world are located. During the next few decades, the most intensive growth in water withdrawal is expected to occur in Africa and South America (by 1.5-1.6 times) and the smallest in Europe and North America (1.2 times).

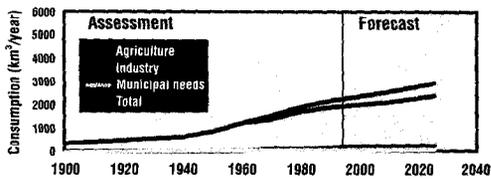
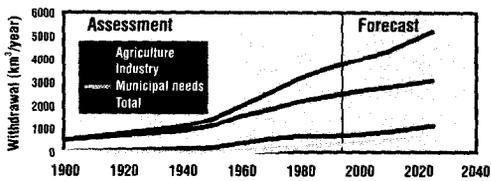
The next two figures (opposite) show the role individual water users play in the dynamics of global total water withdrawal and



consumption. At present, agriculture receives 67% of total water withdrawal and accounts for 86% of consumption. The global irrigated area was 254 million ha in 1995. By 2010 it is expected to grow to about 290 million ha and by 2025 up to 330 million ha. However, in future, the proportion of water used for agriculture is likely to decrease slightly, mainly at the expense of more intensive growth in other water demands such as industry and public water supply. In summary, agriculture is expected to increase demands by 1.3, industry by 1.5 and global public supply by 1.8 times. Additional evaporation from reservoirs contributes greatly to water losses; it is more than the total of industrial and potable supply put together.

Previously published forecasts on future water requirements predict considerably higher values for future demand, as indeed did the authors of this executive summary a decade or so ago. The main cause of these excessive forecasts is due to two factors: first, all 1960-80 forecasts predicted a drastic increase in irrigated lands based on the very high rates in irrigation development which were at that time ahead of population growth rates (see figure on opposite page) and, second, the forecasts took insufficient account of the stabilisation and even decrease in industrial water demand that occurred during the 1970-80s.

The role of individual users in the dynamics of water use for each continent shows that Europe and North America have a similar pattern for both current and future demand. Here, industry takes a considerable amount of the total water demand. In 1995, European industry used 44% of the total water withdrawal. This is expected to increase to about 50% by 2025. In North America, the current water demand by industry is 40% of total withdrawal but by 2025 it is expected to decrease to 37% because of the intense growth in irrigation in the countries of Central America which of course fall within the North American continent. As for water



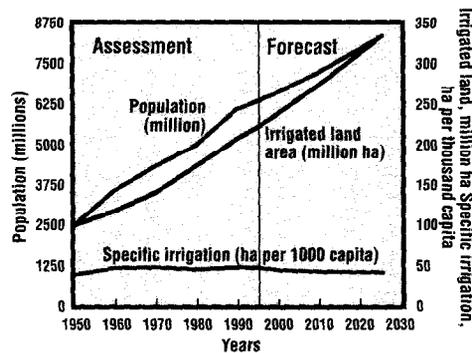
consumption, in both Europe and North America the lead is taken by agriculture which consumes more than 70% of total water consumption.

In Asia, Africa and South America, it is agriculture again which plays the leading role in the pattern of water use. In 1995 irrigation took 60-82% of total water withdrawal and accounted for 64-92% of total water consumption. These indices will also change slightly by 2025 although by that time industrial water consumption is expected to grow two or three times in these three continents. Nevertheless, the fraction of industry concerned in total water withdrawal is not expected to be above 20% in South America, 13% in Asia and 6% in Africa. The characteristic feature in the structure of water use in Africa is the dominance of evaporation from reservoirs. At present, and also in the future, it amounts to some 33-35% of the total water consumption in that continent.

The values for water withdrawal are very unevenly distributed throughout the continents and in no way match the values for water resources. For instance, in Europe 94% of water withdrawal falls within the southern and central parts of the continent; in North

America the USA takes 76% of water withdrawal; in Australia and Oceania 89% of water withdrawal is in Australia. On the Asian continent, the greatest volume of water withdrawal occurs in the southern regions - India, Pakistan, Bangladesh. In Africa, the greatest water withdrawal takes place in the northern part (53%) while in South America, water withdrawal is more or less evenly distributed throughout the continent.

The dynamics of growth in water use up to 2025 differ considerably by region. In developed countries and in those countries with limited water resources, water withdrawal is expected to rise by 15-35%. In developing country regions with sufficient water resources, the water withdrawal growth could be 200-300%.



...in many parts of the world supplies have decreased sharply and become catastrophically low in north Africa and on the Arabian Peninsula, very low in north China and south and west Asia...

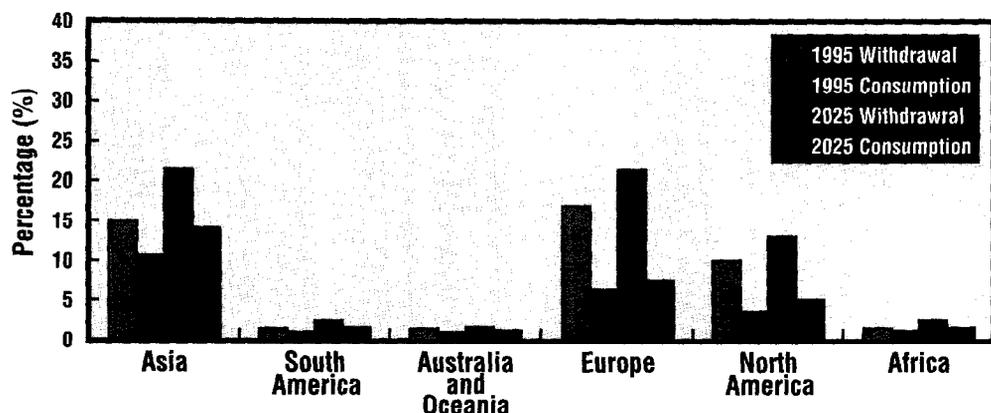
Resources in relation to demand

It is interesting to compare water use with the renewable water resources of surface waters, as shown in the figure. Current water withdrawal in the world as a whole is not great in total, amounting only to 8.4% of global water resources. By 2025 this figure is expected to increase to 12.2%. However, water resources are distributed very unevenly throughout the world, obvious even when comparing average water withdrawal and river runoff by continent. At the present time water withdrawal comprises 15-17% of total water resource in Europe and Asia and will reach 21-23% in the future, while at the same time only 1.2-1.3% of river runoff is used in South America and Oceania and even in the future it is unlikely that this value will increase above 1.6-2.1%.

The distribution of river runoff and water use is especially uneven in the natural-economic regions of the world. Within every continent except South America there are regions where water resources are used to a large extent alongside regions in the same continent with an insignificant water use (especially consumption)

as compared to water resources. For example, current water withdrawal is already as much as 24-30% of total resources in parts of southern and central Europe while at the same time in the northern part of the continent there are regions where these values are never more than 3%. In the northern part of North America water withdrawal is only about 1% of total water resources but for the territory falling within the USA, this value rises to 28%.

In the future, this unevenness in the distribution of water resources and water use will still be present and perhaps even increase as the demand in those regions where water use is already heavy will grow to reach critical levels. For the northern regions and in those areas with surplus supplies, water use (and especially consumption) will comprise, as now, only a very insignificant part of water resources. In other countries, especially those which use not only all their local supplies but also a greater part of the fresh water inflow coming from neighbouring territories, water resources are almost fully depleted. At present, about 75% of the Earth's population live in regions where the extent of water use is more than 20% of available resources.



Water availability and deficits

The distribution of water resources over the complete land mass of Earth is uneven and quite unrelated to population spread or economic development. These facts are very clearly revealed by analysing and comparing the specific water availability for a single period of time for different regions and countries. Specific water availability represents the value of actual per capita renewable water resources and, for every design level, is determined by dividing gross water resources by population number. Here, water resources are assumed to be river runoff originating within a given region plus half the river flow which comes from outside. Thus, what is meant by specific water availability is the residual (after use) per capita quantity of fresh water. Obviously, as population and water consumption grow, the volume of specific water availability decreases.

Specific water availability was obtained for all the natural-economic regions and selected countries for the 1950-2025 period. As expected, this analysis revealed much unevenness in their distribution over the Earth. For instance, the greatest water availability - 170-180 thousand m³ per capita for 1995 - is in the regions of Canada and Alaska and in Oceania while at the same time, in the densely populated areas of Asia, central and southern Europe, and Africa, current water availability falls within 1.2-5.0 thousand m³ per year.

In the north of Africa and on the Arabian peninsula, it is just 0.2-0.3 thousand m³ per year: note that water availability of less than 2 thousand m³ per year per capita is considered to be very low, and less than 1 thousand m³ per year catastrophic. With such low values of water availability, very serious problems arise in population life-support, industrial and agricultural development.

To discover more about the water resources deficit facing us in the future, it is very important to analyse the trends and rates of change in specific water availability in relation to socio-economic and physiographic conditions. And indeed, analysis of data from the natural-economic regions of the world shows that the rates of falling water availability depend on both socio-economic development of the countries within a region and on the climatic conditions.

Different approaches for assessing future water availability are required for the very rich and economically well developed countries of the Arabian peninsula. Here, the extent of available water increases constantly due to the intensive use of deep underground waters and desalination of salt and brackish water since there are sufficient funds available to use extremely expensive non-conventional sources of freshwater, inaccessible to the majority of other countries located in similar arid and semi-arid regions.

At the present time, 76% of the total population has a specific water availability of less than 5.0 thousand m³ per year per capita, with 35% having very low or catastrophically low water supplies. This situation will deteriorate further in the beginning of the next century: by 2025 most of the Earth's population will be living under the conditions of low or catastrophically low water supply.

...potential water availability for the Earth's population is decreasing from 12.9 to 7.6 thousand cubic metres per year per person...



Man's impact on climate and water

...the greatest complication in using GCMs to estimate regional climate is disagreement among the results produced for the same regions...

Throughout the entire existence of the science of hydrometeorology, methods for estimating water resources, water use, and water availability, and their temporal and spatial distribution, have all been based on the concept of climate stationarity. The implication has always been that climatic conditions and concomitant variations in water resources in the future would be analogous to those which have taken place during past observational periods.

In hydrology this concept has also been used all over the world not only to assess water resources and water use but also to calculate extreme river runoff characteristics necessary for construction design. Further, such a concept is integral in all the values for water resources and water availability given elsewhere in this document, including the projections for the future period 2010-2025.

Long-term experience in design and exploitation of different water management structures in the world has shown the correctness and reliability - in any case up to the present time - of using the premise of climate stationarity. However, the situation has changed dramatically in recent years with the question now raised of anthropogenic climate change due to atmospheric CO₂ increase arising from carbon fuel burning, industrial development, and deforestation.

Greenhouse effect and water availability

Carbon dioxide (and some other gases) present in the atmosphere even in very small amounts, is able to attenuate considerably the long-wave radiation coming from the sun, thus creating the so-called 'greenhouse' effect. This in turn promotes a rise in air temperature.

Authoritative assessments by climatologists are

Up to the present time the increase in carbon dioxide has led to about 0.5°C rise in air temperature, with an especially large rise beginning in the 1980s. And in the recent 10 to 15 years the air temperature has increased by 1-2°C in some regions on Earth, resulting in a noticeable change in renewable water resources and in particular their distribution during a year. Many authors associate these changes in climatic characteristics and river runoff regime directly with the processes of anthropogenic global warming.

that this effect may lead to drastic global climate change in the decades to come, such as has never been recorded throughout the history of mankind. In case it is true, this premise should be taken into consideration when estimating water availability for the distant future. And in which case, the questions arise: How valid is a concept of climate stationarity, especially when estimating water availability for 2010-2025? What errors may occur and in what regions if we ignore the possibility of global warming?

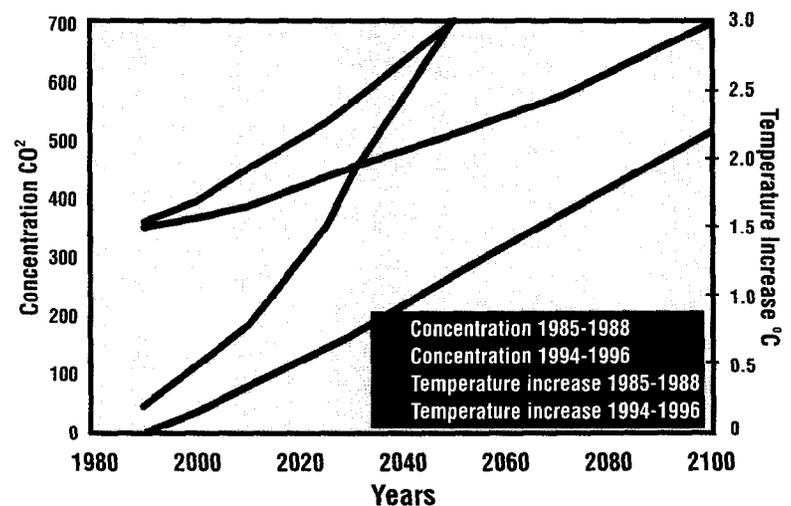
Individual measurements of atmospheric CO₂ were carried out in the previous century but they were very unrealistic. Modern, systematic measurements were started in 1958, at which time the carbon dioxide concentration was 315 conventional units (= 0.031% by volume of the total gas amount). By 1990 it had increased to 350 units, or by 11%. It has been reliably established that in 1880, the beginning of the era of intensive industrialisation, carbon dioxide concentration was 285 units. This means that for 110 years carbon dioxide concentration has grown by 22.8%, with 25% of this value occurring in the most recent 10 years, i.e. the increase is growing in intensity.

Carbon dioxide concentration will continue to grow in the future with an intensity determined by developments in power generation and industrial development. It will also depend on the measures undertaken in different countries to reduce the release into the atmosphere of carbon dioxide and other greenhouse gases. Nevertheless, according to available forecasts, the growth rates in the decades to come will still be high.

During the next century Earth's atmospheric carbon dioxide concentration is expected to double, i.e. to reach 700 conventional units. However, there are different points of view as to the question of when this point could occur exactly. Most forecasts made during 1984-88 anticipated that carbon dioxide concentrations of 700 units would be reached by 2050. A more detailed analysis has been accomplished recently by a group brought together under the auspices of the United Nations, the Intergovernmental Panel on climate Change (IPCC). This group considered different factors of the natural environment, new data on the future use of organic fuels and the measures to be undertaken to limit carbon dioxide emission to the atmosphere, with the result that lower concentrations are now predicted. The diagram on the right shows one of the variants of these new estimates which although anticipating the most intensive growth in concentration, predicts that they will double only by the end of the next century.

Carbon dioxide concentration increases result in a rising global air temperature, with the extent of the warming varying through a wide range of values depending of the premises accepted and a detailed consideration of the forcing factors. For example, the recent estimates consider that atmospheric aerosols noticeably attenuate solar energy income which thus contributes to air cooling.

The values given above for potential changes in global air temperature, however reliable they are, are insufficient even for the most



approximate estimates of future water resources. Such estimates can be obtained only on the basis of data on potential regional changes in climatic conditions, primarily precipitation and air temperature by season or month. Unfortunately, such assessments are extremely unreliable, even for the largest regions and river basins.

To forecast changes in regional climate with global warming, atmospheric general circulation models (GSMs) are widely used, as are palaeoclimatic reconstructions of the climate of past warm epochs. There is a wide variety of type of GCM developed in different countries of the world. They produce values for monthly variations in air temperature and precipitation for the entire land surface which would result from a doubling in carbon dioxide concentration: some of these models even postulate values for smaller concentrations. A general feature of all types of GCM used with palaeoclimatic analogues is that with a 2-3°C global warming in individual regions, especially those in high latitudes, air temperature is expected to rise by up 5-6°C, with much smaller values (0-1°C) likely in the subequatorial regions.

The greatest complication in using GCMs to estimate regional climate change is disagreement among the results produced for the same regions. Luckily, in the case of air temperature change, the different models all agree, at least qualitatively speaking. It is when assessing changes in precipitation for the same region, we find that the results are not only drastically different but even directly contradictory. This makes it impossible for the time being to plan any real action to solve water supply problems for the future.

Effect of climate change on water resources

The numerous estimates obtained for different countries for possible changes to the characteristics of river runoff, water resources and water requirements have to be considered as an analysis of the sensitivity of river catchments and water management systems to various potential changes in regional climate rather than as specific forecasts. Undoubtedly, this analysis is of scientific interest and can be very useful in practice to develop measures for increasing the efficiency of water management systems under the conditions arising from drastic climate change. Below are cited some of the principal conclusions drawn in different countries when studying the effects of climate change on water resources.

The studies point convincingly to the serious consequences for water resources, especially in arid regions, which are possible through changing regional climatic characteristics. For instance, with a 1-2°C increase in the annual air temperature and a 10% decrease in precipitation, a 40-70% reduction in annual runoff can be expected in regions with insufficient moisture. These results are obtained by many authors for individual catchments located in the arid zones of the northern hemisphere. The same is true for water resources of large economic regions; American scientists have calculated that with a 2°C climate warming and a 10% reduction in precipitation, a 1.5-2.0-fold decrease in water resources is possible for those regions of the country located in the arid climate zone.

These conclusions on the strong sensitivity of water resources to even comparatively small changes in climatic characteristics were also obtained for many other regions of the world. Under all physiographic conditions, the values for water resources turn out to be more sensitive to changes in precipitation than in air temperature. These results allow some very certain inferences to be made. In the case where the global warming is accompanied by a reduction in precipitation, water resources in the arid regions of the world will diminish drastically. Such regions occupy about 30% of Europe, 60% of Asia, the greater part of Africa and the south-west regions of North America, 30% of South America, and most of Australia. Under the present changing climate they have a freshwater deficit which is increasing annually.

Estimates for those regions with cold and temperate climates show that global climate change could affect seasonal and monthly river runoff to a considerably larger extent than the mean annual values. Particularly large changes in river runoff distribution during a year are to be expected in regions where the main bulk of water resources are generated during the spring high water period, such as the territories of the



greater part of the former Soviet Union, Europe, North America, and some mountainous regions. Calculations made for the three principal rivers of the European part of Russia and the Ukraine - the Volga, Dnieper and the Don - show that with a 2-2.5°C global warming, changes are expected to occur in their mean annual river runoff of between 12 and 20%. This would increase winter runoff two or three times and decrease spring high water runoff by 25 to 40%. Analogous inferences have been obtained by researchers from the Scandinavian countries of Finland, Norway and Sweden, as well as for some catchments in Poland, Belgium and the mountainous regions of the USA. This potential, very significant, change in seasonal river runoff is explained quite simply in physical terms: it occurs at the expense of a more intensive snow melt during the winter thaw which will take place through rising winter air temperatures.

A very important scientific and practical inference can be drawn from these studies. In regions where global warming enhanced runoff is mainly formed during the spring high water period, river runoff distribution during a year is going to be more sensitive to changes in air temperature than annual precipitation. A completely different situation occurs in the wet

tropical regions where river runoff regime and water resources depend entirely on changes in annual precipitation and its distribution during a year.

It is well known that the severity of water management problems is determined by the ratio of available water resources to demand. With a predicted future climate change, plans for further development in irrigated agriculture, reservoir construction, or for most water-consuming types of industry, will have to be revised. On the other hand, a problem may also arise with water supply to existing water users.

All such changes would, primarily, impact upon the hot arid regions. These regions already have difficulties with water supply and conflicts between different water users and consumers. However, as water use responds with some degree of inertia, smoothly varying through time, regional water availability would primarily be determined by the changing water regime within a territory. In all events, it is clear that global warming will contribute even more uncertainty in the problem of assessing future water consumption and availability since in some regions availability could improve considerably while in others problems will become even more acute.

One of the most important aspects of studying the hydrological consequences of global warming is estimating possible changes in the extreme characteristics of maximum and minimum river discharge. Through analysis of empirical data and through model calculations it can be shown, reasonably reliably, that global warming would lead to more changes in runoff extremes than in mean annual and

seasonal flows, especially for small and medium sized catchments. On the one hand, increased maximum floods can be expected and on the other, more frequent occurrence of severe drought. Both could result in very serious economic and ecological consequences, especially for urban areas and agricultural regions with unstable moisture regimes.

...the principal cause of these discrepancies is the different estimates for future potential changes in precipitation...

One thing is certain: the water management systems of river basins will be complex and will have to be extremely flexible, capable of efficient control over water resources under different climate situations. In this respect, the regions with a large capability in river runoff regulation, as in many parts of the USA and Canada, and in Europe, would have considerable advantages relative to solving water supply and flood regulation as compared with those regions with more natural river systems as, for example, in southern and south-eastern Asia and South America.

Approximate estimates have been obtained recently by the State Hydrological Institute for possible change in water resources due to global warming for the natural-economic

regions, the individual continents, and for the Earth as a whole. More recent estimates based on palaeoclimatic scenarios show an increased global river runoff of up to 16-18% to be expected with a 2-3°C global warming. In this case, such estimates appear to be very favourable for hot arid zones as well as for tropical regions.

However, these optimistic inferences are not confirmed if we combine GCM-scenarios with atmospheric carbon dioxide doubling. Under these scenarios, there is no noticeable increase in river runoff in either the arid regions or the tropical zones, for which GCMs show considerable growth in air temperature and a slight increase in precipitation.



Looking at the water resources assessments in more detail we find that the principal cause of these discrepancies is the different estimates for future potential changes in precipitation. This is the weakest part in all climatic scenarios. Indeed, it is changes in precipitation which have the most effect on assessments. The following general conclusions can be made concerning anthropogenic global climate change effects on water resources.

- Water bodies and water management systems are very sensitive to changes in climatic characteristics; the most noticeable changes are to be expected with a $>1^{\circ}\text{C}$ warming and $>10\%$ precipitation change.
- The currently available scenarios of potential anthropogenic changes in regional climate are extremely uncertain. There is disagreement among them all, primarily related to precipitation change as the principal factor determining water resources and water use. None of the currently available scenarios for future climate can produce a reliable basis for estimating global changes in water resources for the large natural-economic regions, any of the continents, or for Earth as a whole.
- When assessing water resources, water use and water availability on a global scale up to 2025, it seems perfectly sensible to neglect possible anthropogenic climate change. This view is based on the data used to compile the diagram on page 29 which shows recent estimates for air temperature rises of just 0.6°C ; it is supported by the great uncertainties encountered in regional precipitation and air temperature changes.



Safeguarding the future

...in the first half of the 21st century water will be the most important issue facing humankind...

As we saw diagrammatically on pages 24 & 25 with an extremely uneven natural distribution for water resources in both space and time, intensive human activities, and rapid population growth, there is even now a significant fresh water deficit in many areas, especially during dry years. Calculations show that in the decades to come most of the Earth's population will face a critical situation with regard to water supply. This water deficit will become a factor depressing the living standards of populations and retarding the economic and social development in most developing countries of the world. It is already clear that in the first half of the 21st century water issues will be the most important, even among other global problems facing humankind such as adequate food and power production.

The critical situation with water supply will require enormous financial and material expense to eliminate the deficit of pure freshwater found under different physiographic conditions. At the present time and for the foreseeable future, the most realistic and efficient measures will be:

- economy in the use of and protection of water resources by a drastic decrease in specific water consumption, especially in irrigated land use and industry;



- reduction or complete cessation of waste water discharge into hydrological systems;
- more use made of local waters through seasonal and long-term river runoff regulation;
- more use of salt and brackish waters;
- an active influence on precipitation-forming processes;
- use of secular storage in lakes, underground aquifers and glaciers;
- spatial and temporal redistribution of water resources.

All these measures require rather large material expense and have different limitations. Almost all of them exert a pronounced effect on the natural environment which means that they are far from being harmless in terms of ecological consequences. Such consequences could be very significant and difficult to predict, with the exception of waste-water treatment and decreasing specific water withdrawals which are always necessary, desirable and useful for preserving both water resources and the natural environment.

Among all the measures possible for eliminating water resource deficits and which is very promising for the future is runoff regulation and territorial redistribution which has of course been in existence for a long time. Measures for partial transfer of river runoff from one region to another are based objectively on the known facts on current formation, spatial distribution, and end-use, and with the following assumptions:

- First, total global runoff is sufficient to meet the demands for water for many decades ahead.
- Second, freshwater resources on Earth are distributed extremely unevenly: on every continent there are regions with excess and regions with deficit.

- Third, man's economic activities exacerbate the natural unevenness in the spatial distribution of water resources.

This last factor means that where resources are in excess, they are used less and river runoff is virtually unchanged. In the regions where water deficits are due to anthropogenic factors, the effects become more and more tangible with every year. In the future, as water requirements and technological and economic possibilities expand, the volume and scale of runoff transfer would seem likely to increase. As this occurs, the principal difficulties in developing large-scale measures for runoff diversion will be determined more by the necessity for detailed estimation of effects on the natural environment, reliable forecasts of possible ecological consequences (plus the development and realisation of effective measures for their elimination) rather than simply by financial and technological possibilities.



In the long term, with anthropogenic global climate change and redistribution of heat and moisture over the Earth's surface taking place, as some scientists believe, it could be necessary to return to large-scale projects for major river diversions such as the projects favoured in the 1960-70s. However, we now know more about potential complications. First, unfavourable climatic changes could embrace vast areas, including the basins where runoff withdrawals are planned and, second, the uncertainties surrounding the scale of possible regional climatic changes are probably too great to be able to realistically plan such large-scale measures, even for the far distant future.

Conclusions

...urgent measures need to be undertaken by authoritative international organisation to improve the state of global hydrological networks and the collection, processing and exchange of hydrological information...

Every time that new data on Earth's water resources and their use are presented, especially those for the future, the question arises of their reliability and accuracy. These factors depend on many things and differ considerably for individual countries, regions and even continents. Estimates for renewable water resources are based on observational data from hydrological networks. Therefore, their reliability is primarily determined by the conditions of these networks: the number of hydrological sites, the character of their spatial distribution, the duration and continuity of observations, measurement quality and processing.

Based on the World Meteorological Organization's analysis, more than half of the observational stations for water discharge on world rivers are located in Europe and North America. The countries in these continents have the longest observation series, with most sites (70%) equipped with automatic data loggers, allowing the most detailed and objective information to be obtained. This means that any discrepancies can almost always be attributed to different periods of averaging observed data.

Water resources estimates are most erroneous for a number of regions in northern, eastern and western Africa, southern and south-east

Asia, and the islands in the northern part of the North American continent with poor hydrological data.

In many developing countries, the hydrological network is weakly developed and the number of observation stations is being reduced, while the time between measurements, processing and data publication, and submission to regional and international centres, is being increased. There are many countries that have the technical skills and resources but are not interested in the operational exchange of hydrological information and its timely publication. Urgent measures are to be undertaken by authoritative international organisation to improve the state of global hydrological networks and the collection, processing and exchange of hydrological information.

The situation is not much better for assessments of freshwater use. Reliable, systematic information on water withdrawal and diversion are, as a rule, unavailable in most developing countries, with even published national data based only on very approximate estimates.

Some errors in water availability estimates arise because estimates are derived from runoff data only. In many countries a considerable amount of water withdrawal comes from groundwater; at the present time, some 600-700 km³ comes from underground sources according to Prof J Margat of France. A greater part of this water is used for irrigation and municipal needs. Indeed, for a number of countries with almost no river runoff such as those in the Arabian Peninsula, underground water is the main source of water supplies.

It may be a surprising observation, but we find that the general pattern of global water availability does not change much if the problem is considered either on a global scale or for individual regions. First, the extent of surface water used at the expense of



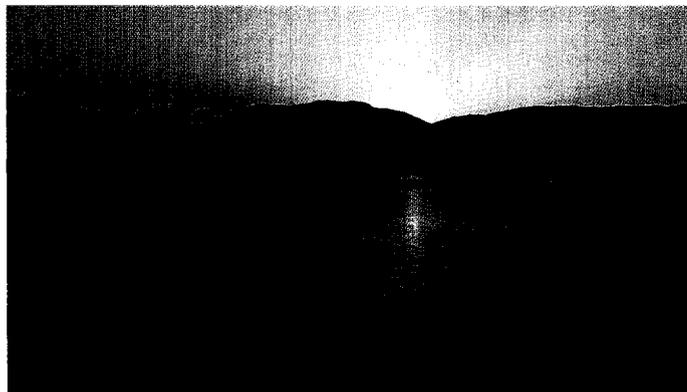
groundwater is as much as 15% of total global water withdrawal and approximately the same proportion of water consumption by continents and regions. Second, at least half the underground water used is hydraulically connected to river runoff, in which case groundwater extraction would affect directly the reduction in river runoff. Thus the proposed values for water consumption at the expense of groundwater can be halved. Nevertheless, ignoring groundwater in assessments of water availability dynamics for a number of regions seems to produce a more pessimistic picture than the reality.

All water resources estimates are optimistic because no account is taken of the qualitative depletion of water resources through the ever-increasing pollution of natural waters. This problem is very acute in the industrially developed and densely populated regions where no efficient waste water purification takes place. The major sources of intensive pollution of waterways and water bodies are contaminated industrial and municipal waste water as well as water returning from irrigated areas.

It is estimated that in 1995 the volume of waste water was 326 km³/year in Europe, 431 km³/year in North America, 590 km³/year in Asia and 55 km³/year in Africa. Many countries discharge most of their waste water containing harmful substances into the hydrological system with no preliminary purification. Prime water resources are thus polluted and their subsequent use becomes unsuitable, especially as potable supplies. Every cubic metre of contaminated waste water discharged into water bodies and water courses spoils up to 8 to 10 cubic metres of pure water. This means that most parts of the world are already facing the threat of catastrophic qualitative depletion of water resources.

The reliability of predictions for 2010-2025 requires special attention. Such estimates certainly take on board trends observed during

past decades but to a considerable extent they are based on long-term demographic and global economic development forecasts expressed in GNP values. Some additional errors can arise, especially for arid and semi-arid regions, because no account is made of the expected anthropogenic global climate change due to increasing atmospheric carbon dioxide and other greenhouse gases.



Forecasts of future populations, industry and thermal power generation growth are usually given for different socio-economic development variables. This information is used to predict water withdrawal and water availability. The values obtained for 2025 are $\pm 10-15\%$ for those regions with predominantly developed countries and $\pm 20-25\%$ for the regions with a predominance of developing countries.

More reliable and detailed water availability values for the future can be obtained but they will need to consider river runoff variability over a long period, to include data on groundwater resources plus the dynamics of resource quantity and quality under both a static climate and anthropogenic global climate change.

To solve this problem, it will be vital to achieve close co-operation between scientists from different countries and international organisations dealing with the problems of hydrology, climatology, and the complex use and protection of water resources.