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Threats To The World's Freshwater Resources

P. H. Gleick, A. Singh, and H. Shi

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FOR STUDIES IN DEVELOPMENT, ENVIRONMENT, AND SECURITY

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Cover Photo: Not more than 80 years ago the mighty Colorado River flowed unhindered from northern Colorado through Utah, the Grand Canyon, Arizona, and Mexico before pouring out into the Gulf of California. But as one can see in this image of the Colorado River Delta taken on September 8, 2000, by the Spaceborne Thermal Emission and Reflection Radiometer (ASTER), flying aboard the Terra spacecraft, irrigation and urban sprawl now prevent the river from reaching its final destination. Image courtesy NASA / GSFC / MITI / ERSDAC / JAROS, and U.S. / Japan ASTER Science Team.

About the Pacific Institute

The Pacific Institute for Studies in Development, Environment, and Security is an independent, non-profit organization created in 1987 to conduct research and policy analysis in the areas of environmental protection, sustainable development, and international security. Underlying all of the Institute's work is the recognition that the urgent problems of environmental degradation, regional and global poverty, and political tension and conflict are fundamentally interrelated, and that long-term solutions dictate an interdisciplinary approach. **The Institute's mission** is to conduct thorough, impartial research, and use the information to craft practical, sustainable solutions to real world problems of resource management.

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1 Introduction

The management and protection of regional, national, and international freshwater resources have reached a crucial period. In the last several decades, it has become obvious to many that traditional water policies are not up to the task of meeting the challenges of the 21st century. New threats to the world's freshwater resources face water managers and policymakers. These threats include increasing surface and groundwater contamination from pollutants, global climatic changes that are already beginning to affect water supply and demand, resurgent water-related diseases, and the destruction and degradation of freshwater ecosystems. Yet water institutions and policymakers have so far been largely unable to develop new tools and approaches for addressing these new risks. This science-based report offers early warning of several of these risks. While much has been written about them in the past, great uncertainties still remain, posing challenges to the scientific community, policymakers, and the public.

Several disturbing trends exemplify these new challenges: the continued inability to meet basic human needs for water; the increasing conflicts among urban, agricultural, and environmental water interests; growing numbers of endangered and threatened species; and new outbreaks of water-related diseases. The traditional response to past water problems has been to focus on large-scale solutions: to build major new facilities; to use engineering solutions to ecological problems; and to treat diseases as they appear, rather than focus on prevention. In many regions, these solutions must continue to help address water-related problems. But new approaches are needed as well. Efforts to explore non-structural alternatives to water supply should be widely encouraged, including efficiency improvements, wastewater reuse, and demand management. Focused activities to reduce threats of water-related diseases are necessary. Large-scale climatic changes should be factored into long-range water planning and management. New water institutions should be evaluated and tested. Unless new thinking is applied, international water policy makers will increasingly struggle to offer reasonable guidance for a highly complicated future.

NREL / www.nrel.gov

This report focuses on four upcoming challenges and threats: water and human health; the destruction of freshwater ecosystems; freshwater quality concerns; and long-term global climatic change and its impact on water resources. It also offers some policy options and institutions for the future.

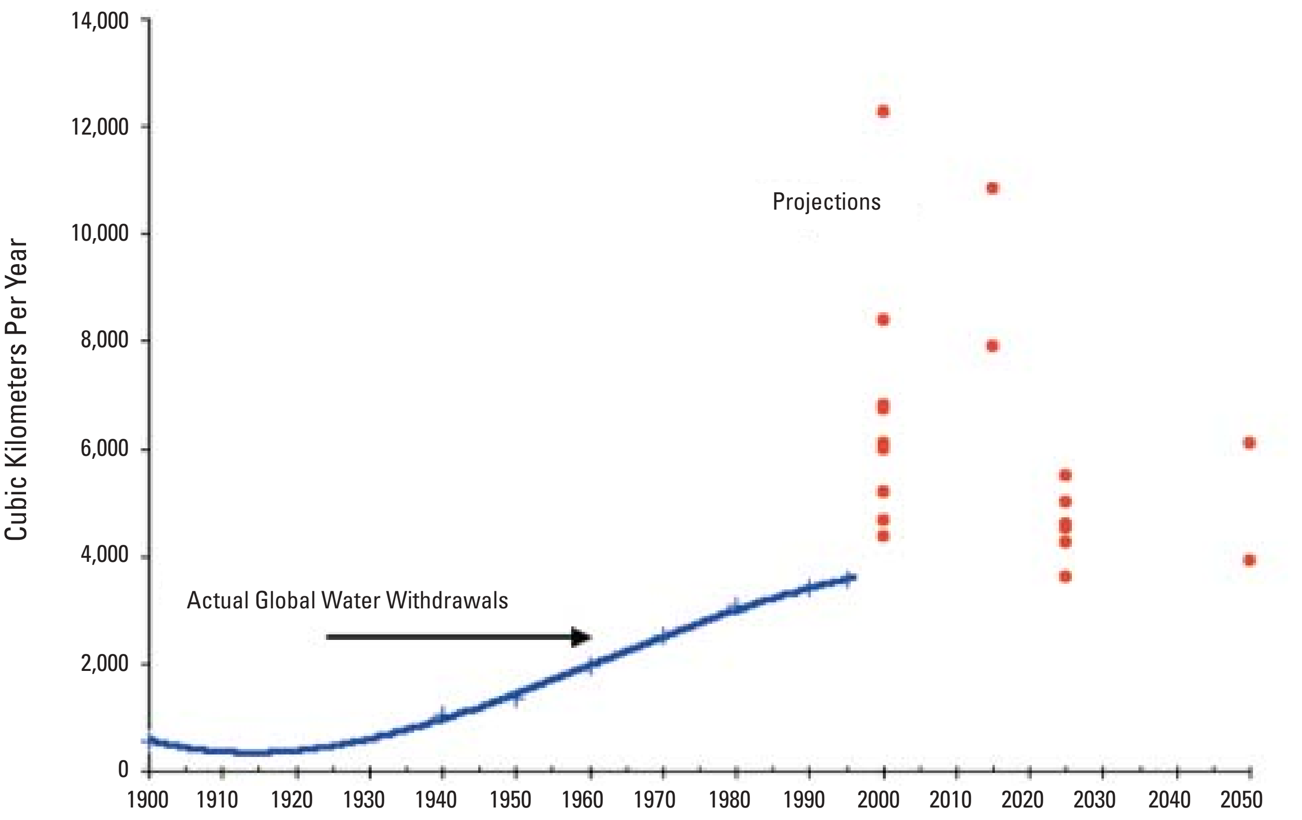
1.1 Twentieth Century Water Planning

During the 20th century, water-resources planning focused on making projections of variables such as future populations, per-capita water demand, agricultural production, levels of economic productivity, and so on. These projections were then used to forecast future water demands and to evaluate the kind of systems necessary to meet those demands reliably. This approach typically projects water demands independent of any analysis of specific human needs, water required for healthy ecosystems, or actual regional water availability. The next step in this traditional process consisted of identifying projects that could be built to bridge the apparent gaps between the projected demand and the estimated available supply.

The focus on supply-side solutions was based on the understanding that projected shortfalls could be met by building more physical infrastructure, usually reservoirs for water storage or new aqueducts and pipelines for interbasin transfers. Resource, environmental, or economic constraints were rarely considered. Although some water suppliers and planning agencies have begun to explore limited demand-side management options and improvements in water-use efficiency as a means of reducing the projected gaps, a reliance on traditional solutions continues to dominate water management actions.

Even ignoring the difficulty of projecting future populations and levels of economic activities, there are many limitations to this approach. Perhaps the greatest problem is that it routinely produces scenarios with irrational conclusions, such as water demands that exceed supply, and water withdrawals unconstrained by environmental or ecological limits. Equally important, however, public support for new projects is diminishing for economic, social, and environmental reasons. New proposals for concrete infrastructure are meeting

Figure 1: Projected And Actual Global Water Withdrawals



Source: Gleick (2000)

G. Bizzarri / www.fao.org

opposition in every region of the world, forcing policymakers to reconsider and rethink water planning.

The current lack of consensus on a guiding ethic for water policy has led to fragmented decision-making and incremental changes that satisfy no one. Some suggest that the problem is primarily technical and that we only need more efficient technology and better benefit-cost analyses to satisfy the needs of all interests involved. Others believe that only a reorganization and coordination of the water policy process will rationalize water decisions. This debate will continue to be an important part of the emerging challenges to 21st century water policymakers.

1.2 Future Water Use

A variety of projections of future water demand worldwide have been made over the past 50 years. With very few exceptions, these projections have overestimated, often substantially, actual rates of increase in water use. Figure 1 shows a number of such projections made for various years in the future. All of the projections shown for the year 2000 were made prior to 1990; some as early as the late 1960s and early 1970s. These show very significant increases in expected water use – some as much as a doubling or tripling of withdrawals. Yet current water use, also shown in the Figure, is only one-half or even one-third of what it was expected to be using traditional forecasting approaches. All of the projections shown for 2025 or later were made after 1997, showing the drop in estimated water needs in recent years. Most of the early projections traditionally assumed exponential increases in water demands. Even today, straight-line increases are often forecast for future use.

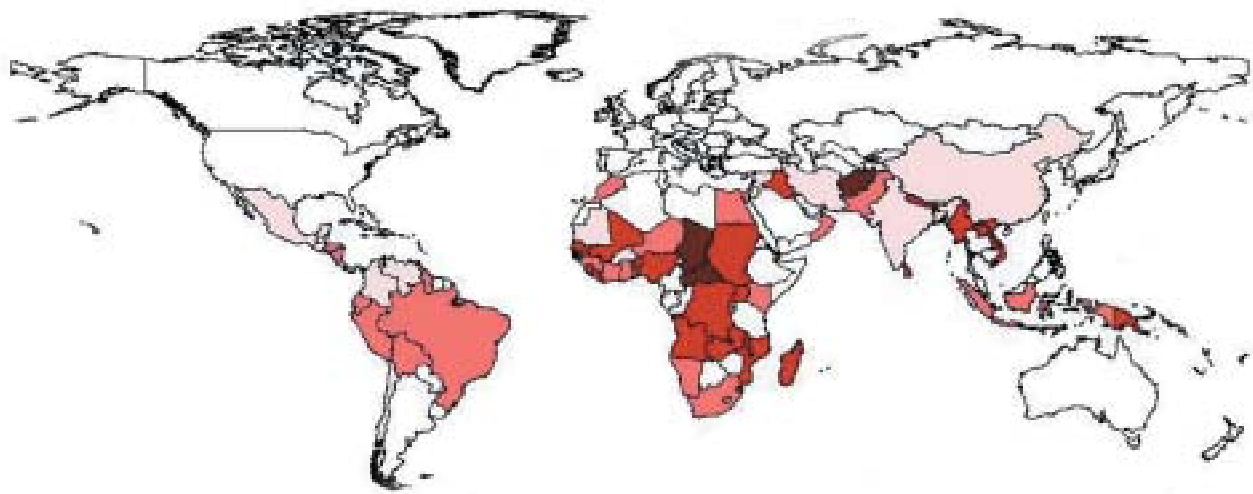
Although traditional water-supply planning remains the norm, new thinking about water-related goals, policies, and planning methods has evolved over the last three decades. These shifting perceptions are reflected in a number of international agreements and declarations, as well as in new strategies, initiatives, and policy documents set forth by a number of international agencies. Although they have not brought about the fundamental changes needed, these actions set the stage for a new approach. Any new water policy approach, however, will have to take into account a series of major water problems – existing and growing threats already facing water managers.

2 Water-Related Diseases:
Basic Water Needs

2.1 Access To Basic Water Needs And Implications For Human Health

Billions of people around the globe lack access to the most fundamental foundation of a decent civilized world: basic sanitation services and clean drinking water. The development of basic water services is a key element in advancing economic and social development and eliminating a host of debilitating and costly diseases. The seriousness of this problem has long been recognized. Over twenty years ago in 1977, at the Mar del Plata conference on water organized by the United Nations, a commitment was made to focus efforts on providing access to safe drinking water and sanitation services during the 1980s, the International Drinking Water Supply and Sanitation Decade (the "Decade"). The United Nations estimated that between 1980 and 1990 1,300 million people without access to an adequate water supply at the beginning of the decade received that access, while the population with sanitation increased by 750 million. By the end of the "Decade", however, there were still an estimated 1,200 million people without safe drinking water and 1,700 million without sanitation services.[1] Due to underreporting, poor data, and new definitions of "access," the actual number of people lacking these basic services was reassessed upwards in the mid-1990s by the United Nations. In a 1994 assessment, World Health Organization (WHO) estimated that the population

Map 1: Percent Of Population Without Access To Clean Drinking Water (Mid 1990s)

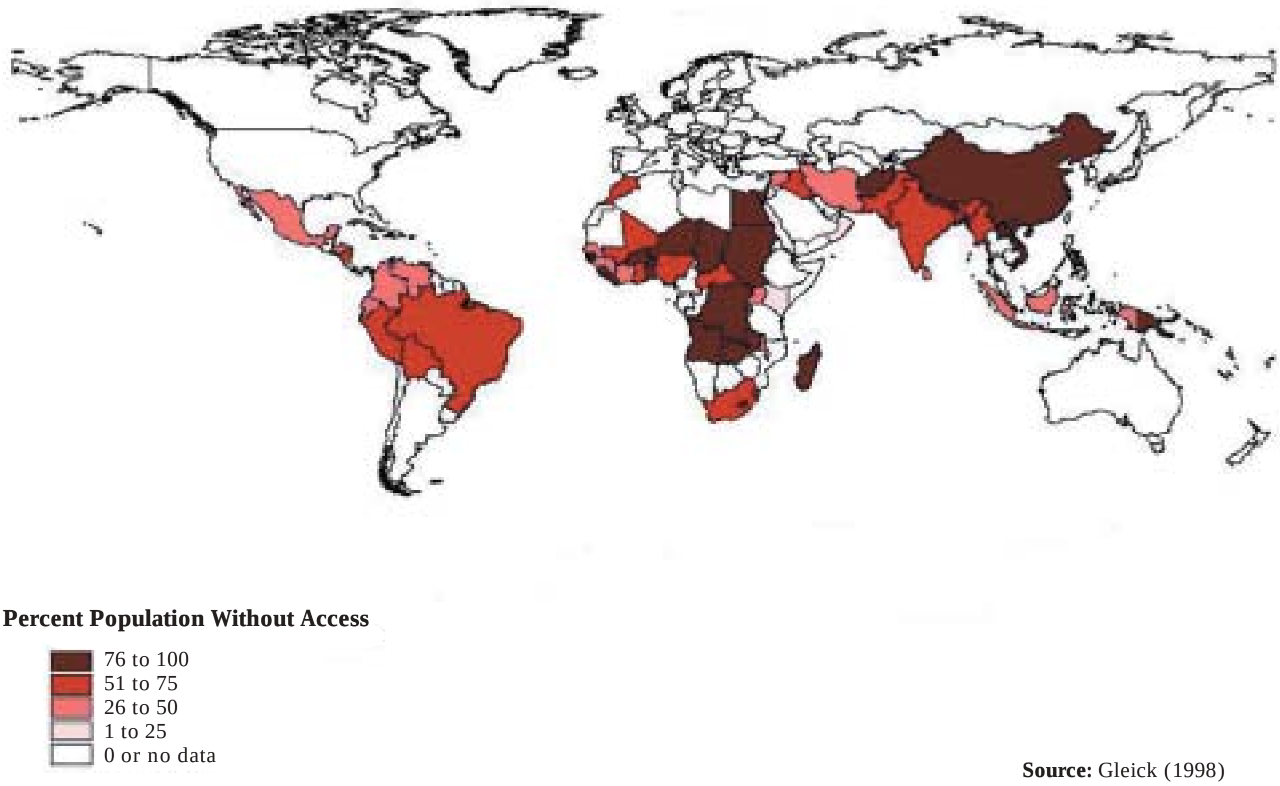


Percent Of Population Without Access To Clean Drinking Water (Mid 1990s)

- 76 to 100
- 51 to 75
- 26 to 50
- 1 to 25
- 0 or no data

Source: Gleick (1998)

Map 2: Percent Of Population Without Access To Adequate Sanitation Services (Mid 1990s)



Source: Gleick (1998)

without access to sanitation was closer to 2,600 million – nearly a billion more than their estimate just five years earlier.[2] The population without clean drinking water was estimated to be 1,300 million. Most recently, the World Health Organization estimated that at the end of the twentieth century, nearly 1,200 million people still lacked access to clean drinking water and twice that number, 2,400 million people, lacked access to adequate sanitation services.[3] While the precise numbers are uncertain due to data gaps and differences in definitions and reporting coverage, it is clear that billions of people still lack the most basic water requirements.

Map 1 shows those countries where access to clean drinking water remains limited. In most of Africa and many parts of Asia large numbers of people still drink unsafe water. Map 2 similarly shows the percent of populations without access to adequate sanitation services. Again, large parts of Africa and Asia, and parts of central and south America suffer from lack of these basic services.

The failure of the efforts of the past several decades to completely satisfy basic human needs for water and water services was the result of many factors, including rapid population growth, underinvestment, growing urbanization, and misdirected priorities. The extent of the problem means many governments, organizations, and agencies must be involved in planning and implementing programs. Unfortunately other social problems are often given higher priority and rapid population growth makes it difficult to catch up. One focus, however, must be the goal of providing for basic water needs.[4]

2.2 Meeting Basic Needs

More than 20 years have passed since the Mar del Plata conference, one of the earliest international efforts to address global water problems. At that meeting, the world water community raised the issue of meeting "basic needs" for water. This right was strongly reaffirmed during the 1992 Earth Summit in Rio de Janeiro and expanded to include ecological water needs. In 1997, the United Nations once again reaffirmed the importance of these concepts in the Comprehensive Assessment of the Freshwater Resources of the World, prepared for the UN General Assembly.

> "…all peoples, whatever their stage of development and their social and economic conditions, have the right to have access to drinking water in quantities and of a quality equal to their basic needs."[5]

> "In developing and using water resources, priority has to be given to the satisfaction of basic needs and the safeguarding of ecosystems."[6]

> "…it is essential for water planning to secure basic human and environmental needs for water [and]…Develop sustainable water strategies that address basic human needs, as well as the preservation of ecosystems."[7]

Implicit in the concept of basic human needs for water is the idea of minimum resource requirements for certain human and ecological needs, and the allocation of sufficient resources to meet those needs. Different sectors of society use water for different purposes: drinking, removing or diluting wastes, producing manufactured goods, growing food, producing and using energy, and so on. The water required for each of these activities varies with climatic conditions, lifestyle, culture, tradition, diet, technology, and wealth, as shown nearly 30 years ago in the groundbreaking work of White, Bradley, and White.[8]

Basic water requirements for humans should include the water necessary for human survival and for adequate sanitation. A further fundamental requirement not usually noted in the literature is that this water should be of sufficient quality to prevent water-related diseases. In regions where absolute water quantity is a major problem, waste-disposal options that require no water are available. In most cases, however, developing economic societies have tended to prefer alternatives that use at least some water, and some societies use enormous amounts of fresh water to dispose of wastes. The choice of sanitation technology will ultimately depend on the developmental goals of a country or region, the water available, the economic cost of the alternatives, and powerful regulatory, cultural, and social factors.

There have been various proposals for a basic water requirement, but most analysts agree that water for drinking and sanitation should be provided in the range of 20 to 30 liters per person per day; when cooking and cleaning are included 40 to 50 liters per person per day is a responsible minimum. Recent assessments have called for these quantities of water to be provided as a fundamental requirement.[9]

NASA / www.nasa.gov

Table 1: Morbidity And Mortality Associated With Water-Related Diseases, Late 1990s.

Disease	Morbidity (cases per year)	Mortality (deaths per year)	Relationship Of Disease To Water Supply And Sanitaton
Diarrhoeal Diseases	1,000,000,000	3,300,000	Strongly related to unsanitary excreta disposal, poor personal and domestic hygiene, unsafe drinking water
Infection With Intestinal Helminths	1,500,000,000 (1)	100,000	Strongly related to unsanitary excreta disposal, poor personal and domestic hygiene
Schistosomiasis	200,000,000 (1)	20,000	Strongly related to unsanitary excreta disposal and absence of nearby sources of safe water
Dracunculiasis	100,000	—	Strongly related to unsafe drinking water
Trachoma	150,000,000 (3)	—	Strongly related to lack of face washing, often due to absence of nearby sources of safe water
Malaria	400,000,000	1,500,000	Related to poor water management, water storage, operation of water points and drainage
Dengue Fever	1,750,000	20,000	Related to poor solid wastes management, water storage, operation of water points and drainage
Poliomyelitis	114,000	—	Related to unsanitary excreta disposal, poor personal and domestic hygiene, unsafe drinking water
Trypanosomiasis	275,000 (6)	130,000	Related to the absence of nearby sources of safe water
Bancroftian Filariasis	72,800,000 (1)	—	Related to poor water management, water storage, operation of water points and drainage
Onchocerciasis	17,700,000 (1,4)	40,000 (5)	Related to poor water management in large-scale projects

1 People currently infected.

2 Excluding Sudan.

3 Case of the active disease. Approximately 5,900,000 cases of blindness or severe complications of Trachoma occur annually.

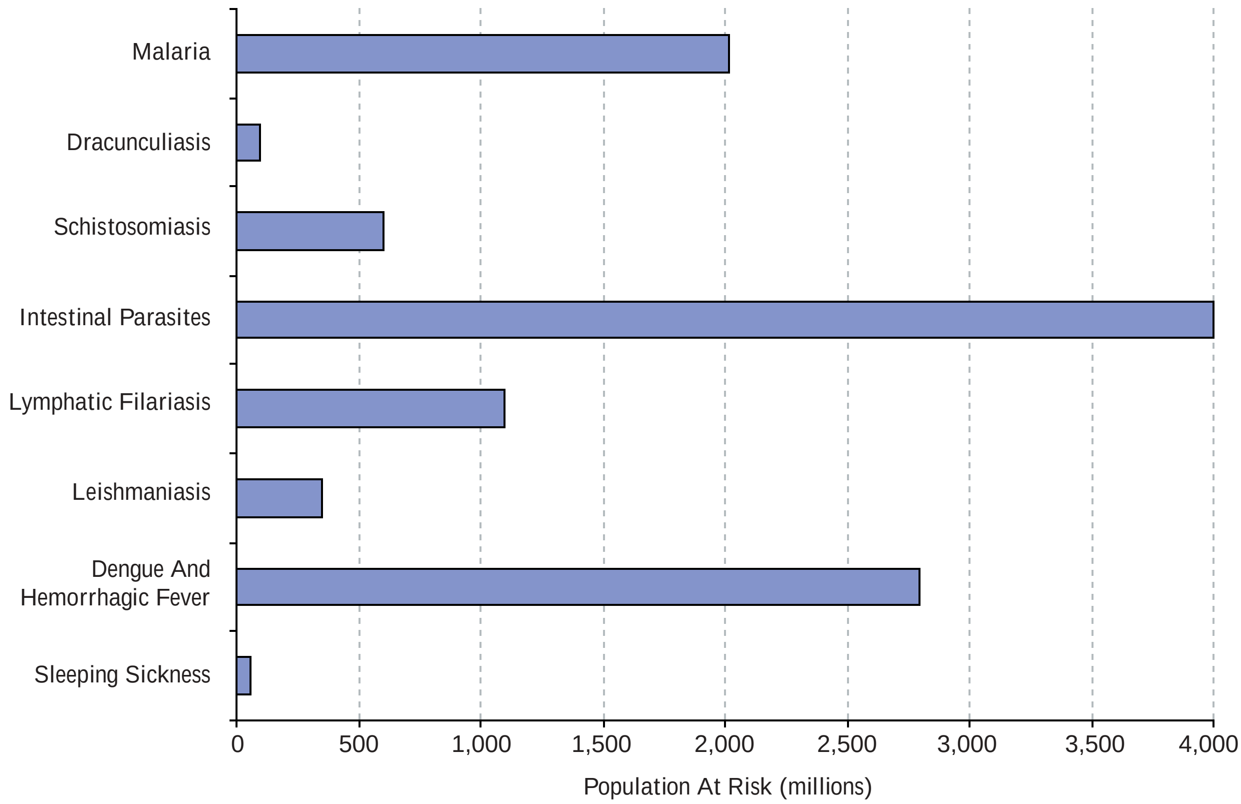
4 Includes an estimated 270,000 blind.

5 Mortality caused by blindness.

6 Estimated only. Includes officially reported cases numbering around 40,000 annually in the late 1990s.

Sources: WHO (1996)

Figure 2: Population At Risk Of Water-Related Diseases



Source: Gopalan, H.N.B. and S. Saksena (1999)

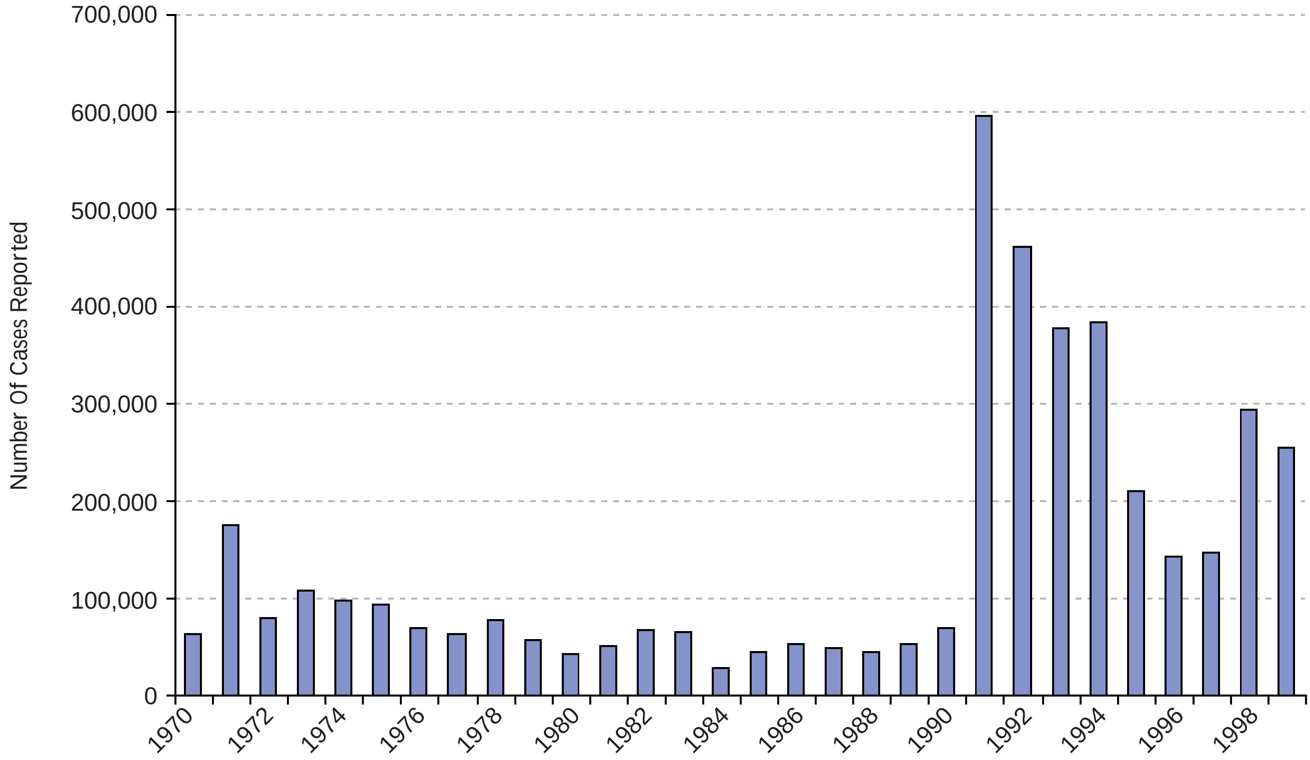
Whatever the appropriate quantity, the failure to provide basic sanitation services and clean water to so many people takes a serious toll on human health. In many developing countries, cholera, malaria, dysentery, and other water-related diseases are on the upswing. The next section discusses several emerging water-related health threats and identifies some trends worth further attention by the world health community.

2.3 Emerging Health Threats

Nearly 250 million cases of water-related diseases are reported every year, causing between 5 and 10 million deaths. Diarrhoeal diseases leave millions of children underweight, mentally and physically handicapped, and vulnerable to other diseases. Parasitic diseases are spread through ingestion or contact with contaminated water. Many infectious diseases are still carried by insect vectors, particularly mosquitoes, that breed in freshwater. Table 1 shows the approximate number of water-related illnesses and deaths reported in the late 1990s. Figure 2 shows current estimates of the populations at risk from water-related diseases. Although all water-related diseases are important, the following is a detailed review of only a few that are the most significant.

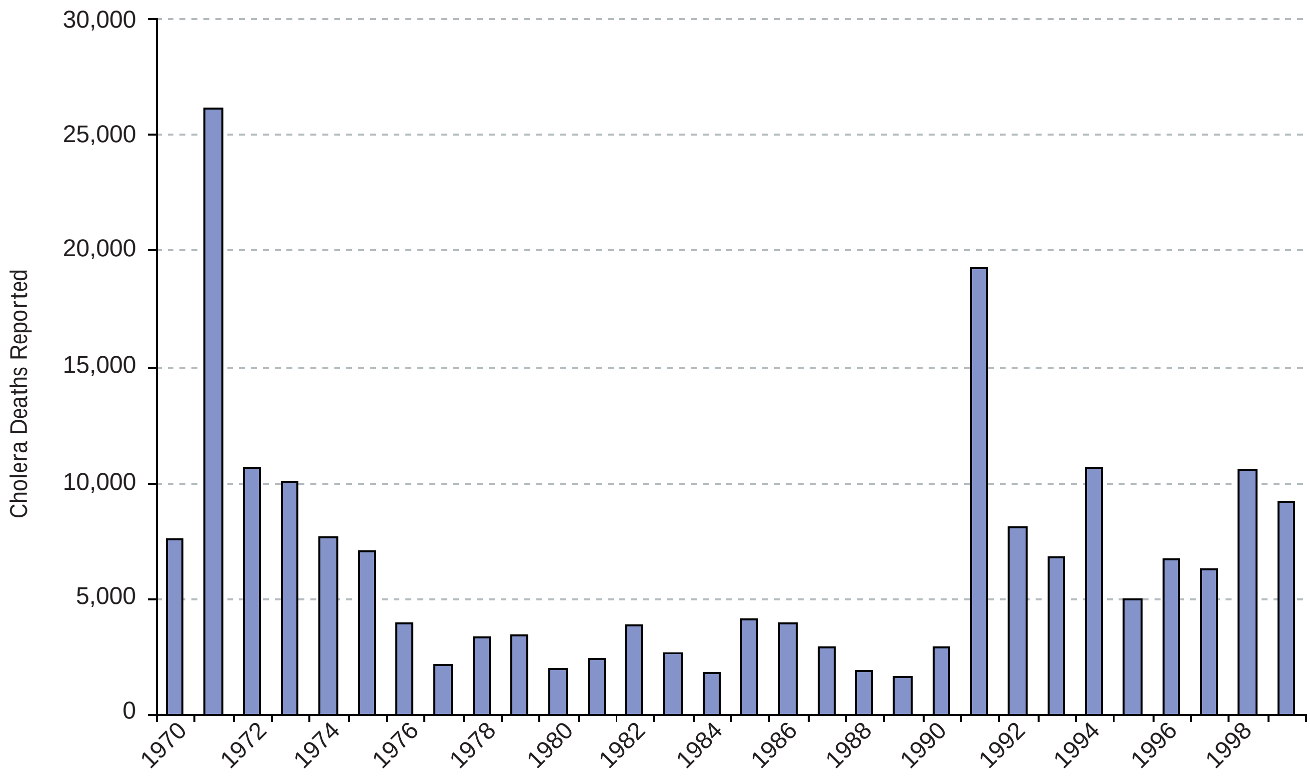
Cholera, which is spread by contaminated water and food, has expanded worldwide in the 1990s and is endemic in most of Africa. The disease struck Latin America in 1991 and has since spread throughout other regions.[10] The prevalence of dengue fever has grown dramatically in recent years, and has become endemic in more than 100 countries of Africa, the Americas, the Eastern Mediterranean, South East Asia and the Western Pacific. The UN estimates that 2.8 billion people are currently at risk of infection from dengue fever.[11] Malaria is a critical public health problem and is endemic in 101 countries and territories, affecting more than two billion people: worldwide prevalence of the disease is estimated to be in the order of 300 to 500 million clinical cases each year. Mortality due to malaria is estimated to be over 1 million deaths each year, with the vast majority of deaths occurring among young children in remote regions of Africa where access to health care and services remains limited.[12] These diseases bring both direct and indirect costs. The

Figure 3: Global Cholera Cases Reported, 1970 To Present



Source: WHO (2001)
WHO (1999)

Figure 4: Global Cholera Deaths Reported, 1970 To Present



Source: WHO (2001)
WHO (1999)

World Health Organization estimate of the costs of malaria in sub-Saharan Africa alone exceeds $2 billion (Source: http://www.who.int/inf-fs/en/fact094.html).

2.3.1 Cholera

Cholera is an acute, diarrhoeal illness caused by infection of the intestine with the bacterium *Vibrio cholerae*. Although cholera can be life threatening, it is easily prevented and treated. A person may get cholera by drinking water or eating food contaminated with the cholera bacterium, though a significant majority of cases is related to waterborne transmission. Only rarely is cholera transmitted by direct person-to-person contact. Sudden large outbreaks are usually caused by a contaminated water supply and inadequate treatment of sewage. The bacterium can survive in fresh water for long periods. In highly endemic areas it is mainly a disease of young children, although breastfeeding infants are rarely affected. Cholera bacteria may also live in the environment in brackish rivers and coastal waters where marine shellfish and plankton serve as the main reservoirs.

Cholera is epidemic in many developing countries because of the failure to provide adequate sanitation and clean drinking water. Cholera was prevalent in the United States and many other now industrialized countries in the 1800s but it was virtually eliminated by modern sewage and water-treatment systems. As a result, cholera has been very rare in industrialized nations for the last 100 years.

Within the past decade, however, there have been several disturbing trends in cholera distribution and intensity. In part this may be due to improvements in reporting, but there has also been an enormous expansion in geographical scope. Beginning in 1900, the total number of cases reported annually has rarely exceeded 100,000 (though systematic assessment began only around 1970). Even with the outbreak of the seventh pandemic in the 1960s, total reported cholera cases exceeded 100,000 only twice until 1991. In January 1991 cholera reached Peru and spread with explosive rapidity. Within a year cholera was epidemic in 11 countries in Latin America, which had been free of cholera for over 100 years.[13] By the end of 1991, nearly 600,000 cases had been reported worldwide, 390,000 of them in Latin America. Figure 3 shows total global cholera cases for 1970 to 1999. The spike in 1991 represents the massive outbreak in Latin America. Figure 4 shows total annual deaths from cholera from 1970.

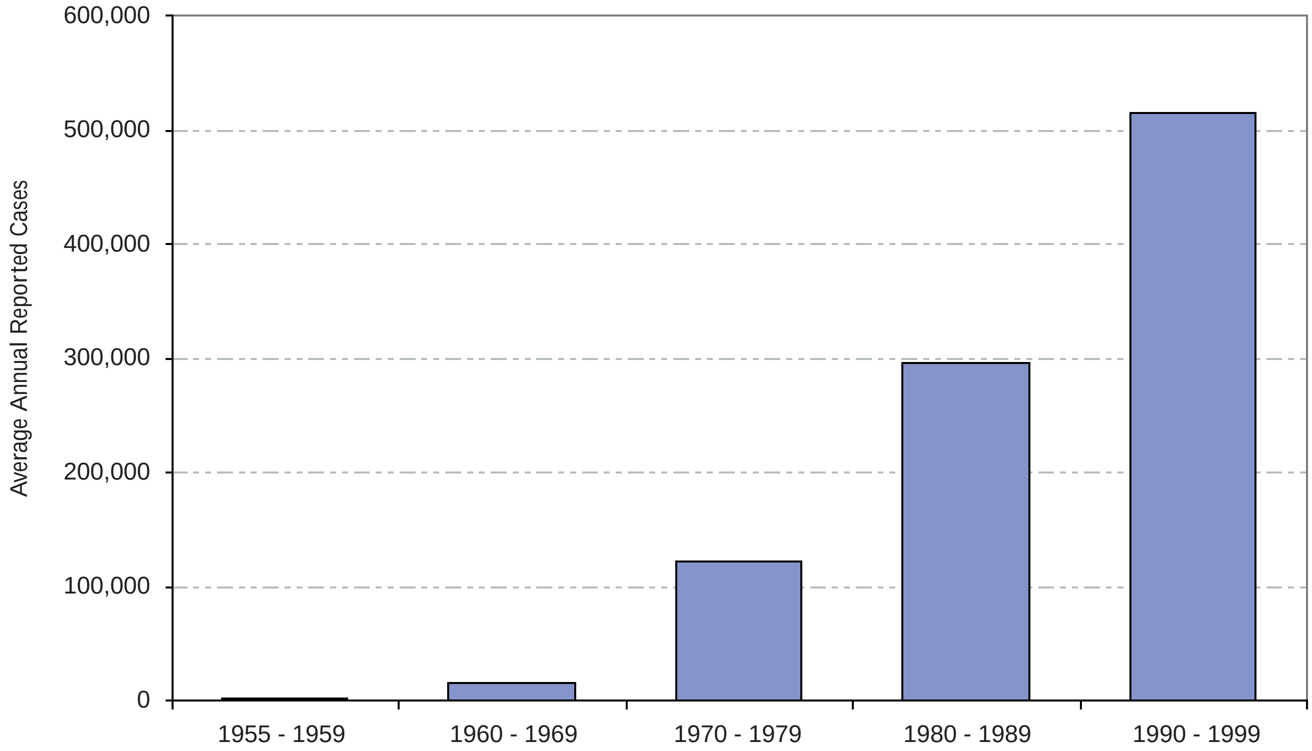
J. Holmes/www.fao.org

While the epidemic in Latin America received the most attention, two other events occurred in the early 1990s that warrant watching. In the midst of the Latin American outbreak, the total number of cases in Africa quadrupled, and a completely new form of bacteria capable of causing epidemic cholera appeared in Asia. Total cholera cases in Asia exceeded 100,000 in 1994, and by the mid-1990s the epidemic of cholera caused by this new form (*Vibrio. cholerae* O139) had affected at least 11 countries in the region.[14]

The resurgence of cholera in Latin America in the early 1990s is an indication that countries are falling behind in providing adequate sanitation and clean water, particularly in large urban areas. In detailed epidemiological assessments of the ongoing Latin America outbreak, waterborne transmission was identified in seven of eight and health scientists concluded that the first stage in prevention was to provide safe drinking water. They declared, "The longstanding deficits in basic urban infrastructure and the need for new efforts to correct them have never been more apparent."[15]

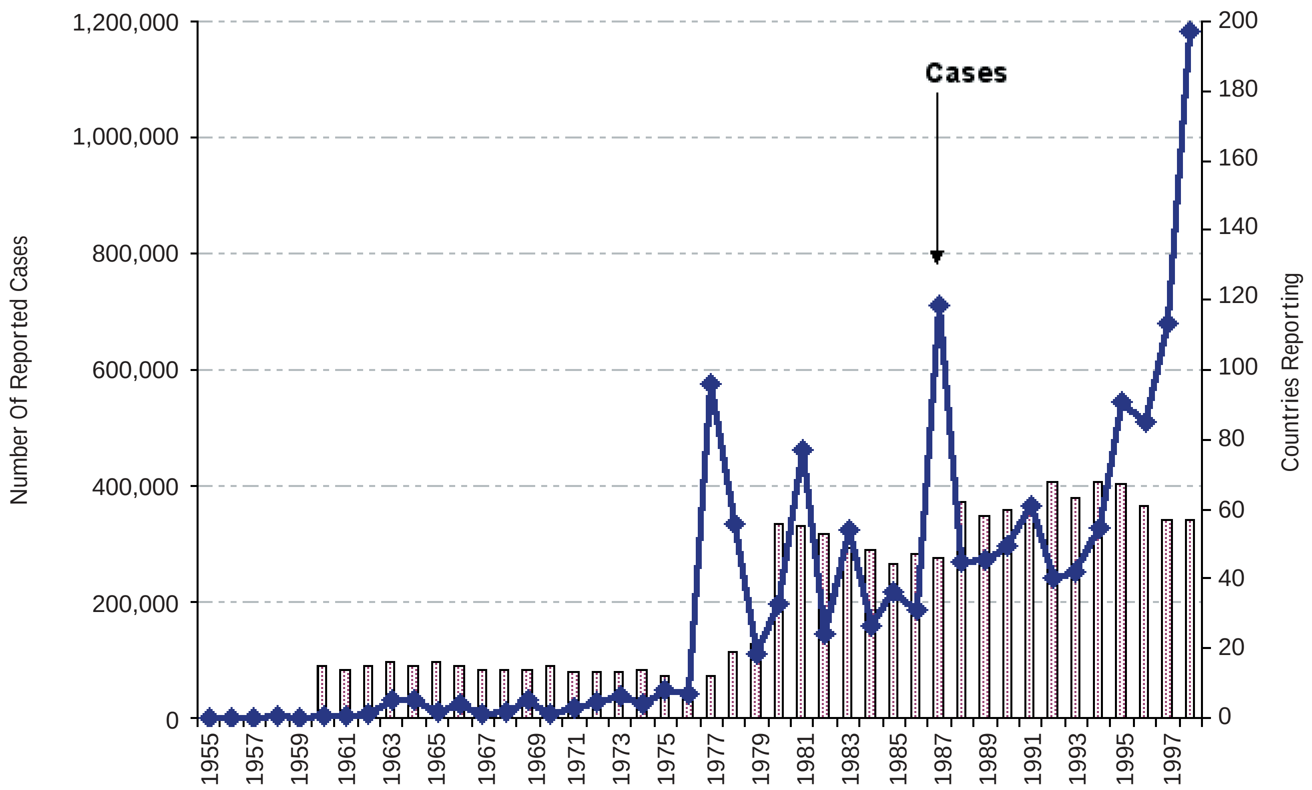
Improving cholera surveillance and developing a coordinated response for epidemic cholera are high public health priorities in Africa. The first priority is to prevent cholera-associated deaths by providing vigorous rehydration therapy to affected persons.[16]

Figure 5: Average Annual Cases Of Dengue Fever (reported to the World Health Organization)



Source: WHO (2001)

Figure 6: Total Reported Cases Of Dengue Fever (and number of countries reporting)



Source: WHO (2001)

Determination of the routes of cholera transmission is also important in developing effective prevention measures. Access to a functioning water tap is highly effective in preventing the disease.[17] Because waterborne transmission of cholera in Africa is associated with drinking untreated water from rivers and shallow wells, one strategy for preventing cholera is the provision of disinfected drinking water to persons residing in areas at risk. Boiling water is effective but consumes scarce fuel wood and is difficult to sustain. Chlorination is the most widely used method for purifying municipal water supplies. Providing safe, treated water supplies also may prevent other waterborne diseases (e.g., typhoid fever, hepatitis, and other diarrhoeal illnesses in children).[18]

Cholera is also a growing concern in many countries where the disease had formerly been eradicated. Although travelers returning from areas where epidemic cholera exists imported most cases of cholera in recent years in these countries, public health officials must become increasingly observant if non-imported cases are to be detected, caught, and treated promptly.

2.3.2 Dengue

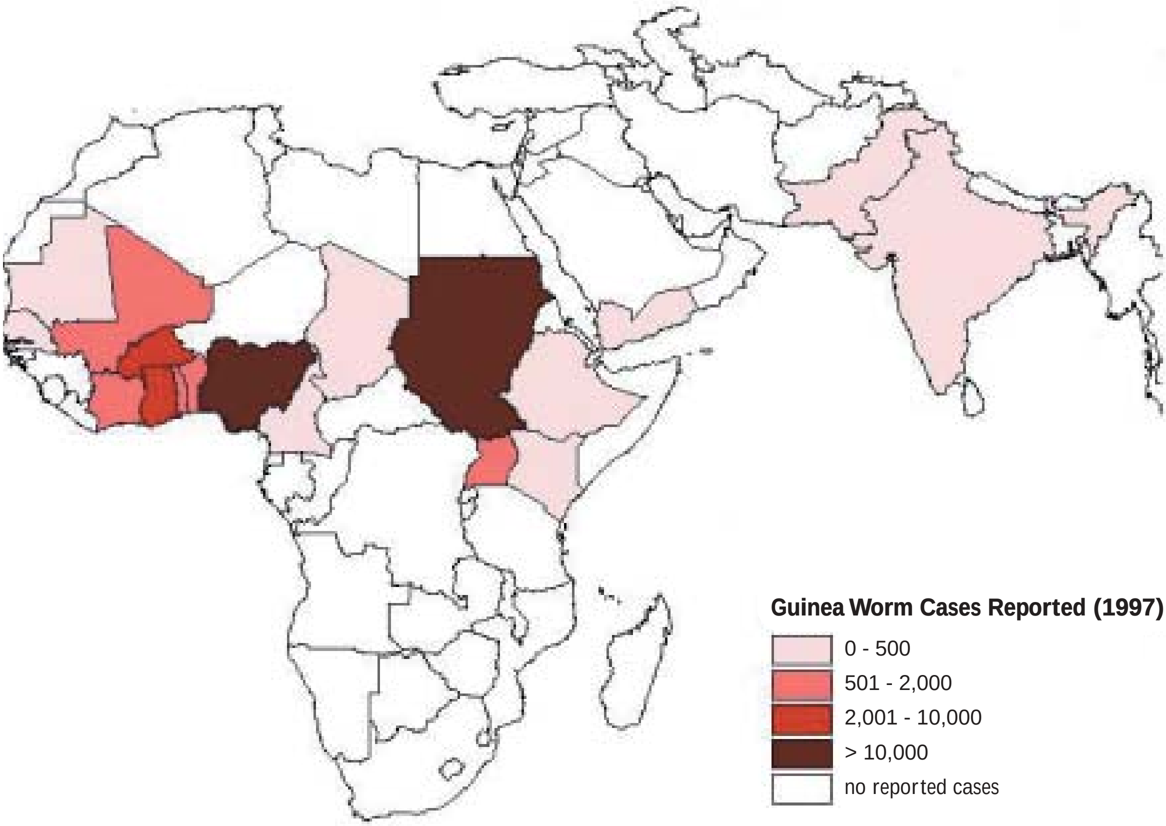
Another emerging water-related disease concern is the recent explosive growth of dengue fever in Latin America. Dengue is a mosquito-borne infection that in recent years has become a major international public health concern. Carried predominantly by *Aedes aegypti*, a common urban mosquito, dengue is appearing more commonly in urban and peri-urban populations, especially in areas favorable for mosquito breeding, such as where household water storage is common and where solid waste disposal services are inadequate. In recent years, *Aedes albopictus*, a secondary dengue vector, has become established in the United States and several Latin American, Caribbean, European, and African countries. Dengue haemorrhagic fever (DHF), a potentially lethal complication, was first recognized during the 1950s and is today a leading cause of childhood mortality in parts of Asia.

The World Health Organization estimates that 2,500 million people are at risk from dengue and that there may be 50 million cases of dengue infection worldwide every year (http://www.who.int/inf-fs/en/fact117.html). Without proper treatment, DHF case fatality rates can exceed 20%. With modern intensive care, the mortality rate can be reduced to less than 1%.

The global prevalence of dengue has grown dramatically in recent decades. This trend bears close monitoring. The disease is now endemic in more than 100 countries in Africa, the Americas, the Eastern Mediterranean, Southeast Asia, and the Western Pacific. Southeast Asia and the Western Pacific are most seriously affected. Figure 5 shows the huge increase in annual average number of cases reported during the past 50 years. Not only is the number of cases increasing as the disease spreads to new areas, but explosive outbreaks are occurring. Figure 6 shows the annual number of cases of dengue reported, together with the number of countries reporting. Before 1970 only nine countries had experienced DHF epidemics, a number which had increased more than four-fold by 1995 and continues to rise. While part of the increase represents better reported and monitoring, the dramatic increase in the late 1990s represents a

WHO/TDR/www.who.int

Map 3: Guinea Worm Cases Reported (1997)



Source: WHO (2000)

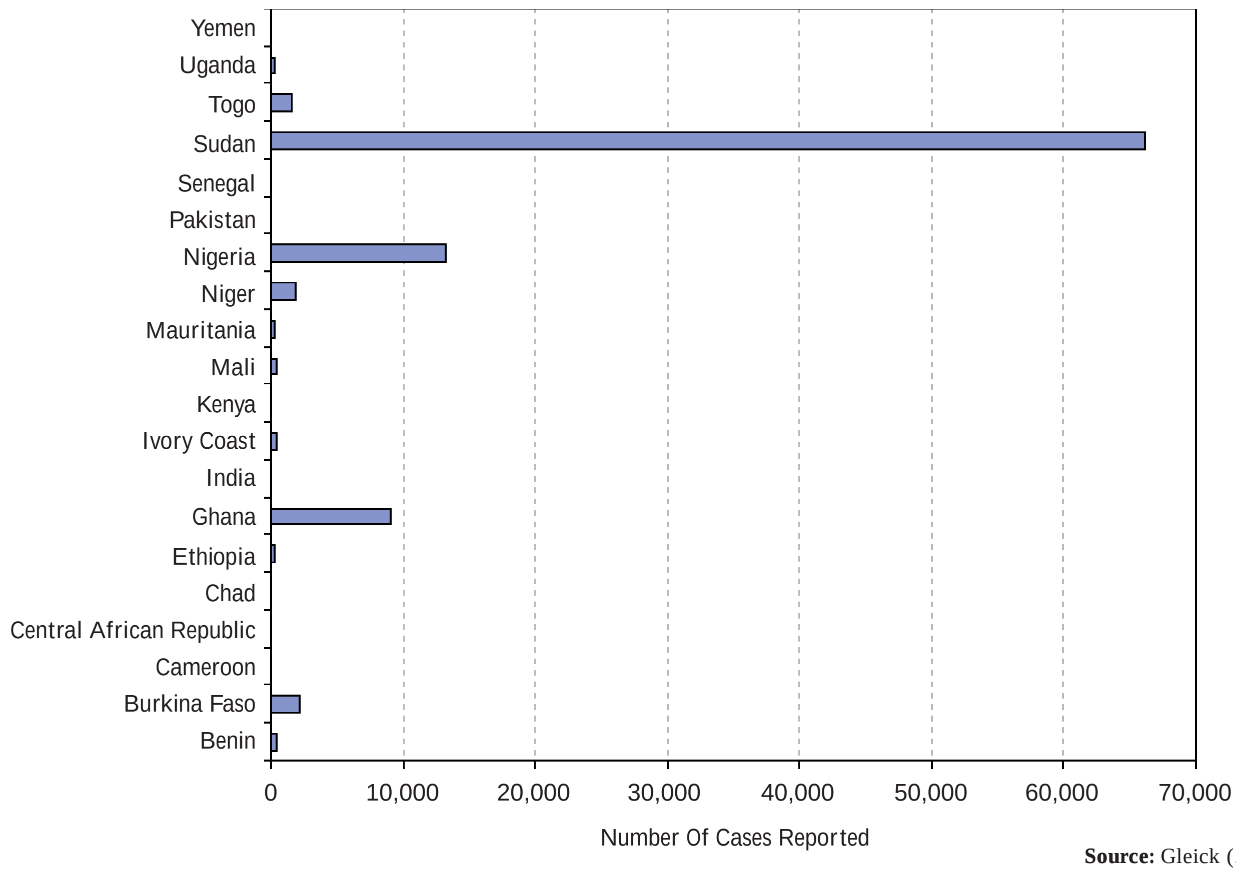
real rise in the prevalence of the disease. Over 740,000 cases of dengue fever were reported for 1998 by the Pan American Health Organization for countries of Latin America, more than twice the total for 1997. Some analysts have also raised the concern that such vectors could be encouraged by changes in climatic factors, discussed below.

2.4 Summary

Diseases associated with inadequate access to clean drinking water or inadequate sanitation services remain a scourge throughout the world, despite the fact that society has the means to reduce or eliminate them. Unless basic water needs are met, large-scale human misery and suffering will continue and grow in the future. These diseases cost society

C. Tipsuthom / www.fao.org

Figure 7: Distribution Of Dracunculiasis, By Country, 1997



Source: Gleick (2000)

billions of dollars a year in deaths, illnesses, and lost productivity, as well as huge uncounted costs in social and cultural disruptions. Far less money is needed to meet basic human needs for water, with a far better economic and social return to society.

Eliminating water-related diseases requires more than merely constructing infrastructure or providing clean water. It also requires maintaining and operating that infrastructure, teaching children about adequate hygiene habits, identifying other transmission routes such as unclean handling of food, and controlling disease vectors. But the continued failure to provide basic clean water and sanitation services for so many remains the major element of one of the most significant health disaster of the twentieth century.

Ironically, the world community of water experts knows what needs to be done and how to do it. A major effort is underway to eradicate one of the most dreaded water-related diseases: dracunculiasis or "guinea worm," the "fiery serpent" afflicting people in Africa and parts of Asia. Guinea worm cases have fallen from an estimated three million in the mid-1980s to 150,000 in 1996 and fewer than 80,000 in 1997 and 1998, though the number of cases reported in 1999 rose to over 96,000 (see Figure 7).[19] There are hopes that it can be eradicated entirely in the coming years if the right political, economic, and educational tools are applied.[20] At present, guinea worm is found in only a small number of countries in central Africa and effective eradication programs are in place in most of these areas (see Map 3).

3 Destruction And Degradation
Of Freshwater Ecosystems

The freshwater ecosystems most in danger are those in regions with high human populations and large freshwater withdrawals or large amounts of wastewater discharge. Freshwater ecosystem integrity is maintaining the ability of freshwater ecosytems to sustainably deliver the goods and services they provide. Human interventions in the hydrologic cycle are increasingly interrupting the delivery of these services.

There are direct connections between the human withdrawals of water and the quality and health of natural ecosystems. Throughout the world, human use of water contributes to water scarcity, competes with natural systems for water, and leads to the pollution of rivers, lakes, and aquifers. In the past century, over 50 percent of the world's wetlands have been lost. Of the more than 3,500 species currently threatened worldwide, one-quarter are fish and amphibians.[21] By the year 2025, some scenarios show water withdrawals increasing by 50 percent in developing countries and 18 percent in developed countries, putting even greater pressures on natural ecosystems.[22] Unless efforts are made to reserve water for natural ecosystems, the inevitable result of further human withdrawal of water on this scale will be degradation or complete loss of the terrestrial, freshwater, and coastal ecosystems that are vital for human well being.

Many factors contribute to this problem, including growth in human populations, infrastructure development, land-use policies, overexploitation of species and ecosystems, and chemical and biological pollutants. Table 2 summarizes many of these problems. The trends are not encouraging. In most developing countries, population will continue to grow at a rate of 2 to 3 percent. Large populations will live in urban areas located in coastal regions and near rivers, and growing consumption patterns will aggravate impacts on ecosystems. Maps 4, 5, and 6 show the current global population densities in major watersheds worldwide. Those watersheds with a high population density can expect to see

Map 4: Population Density In International Watersheds, Africa

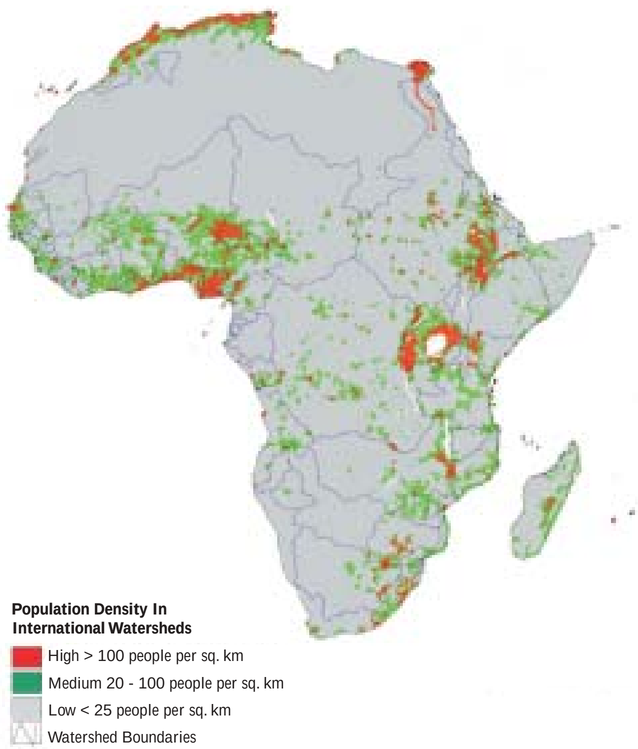
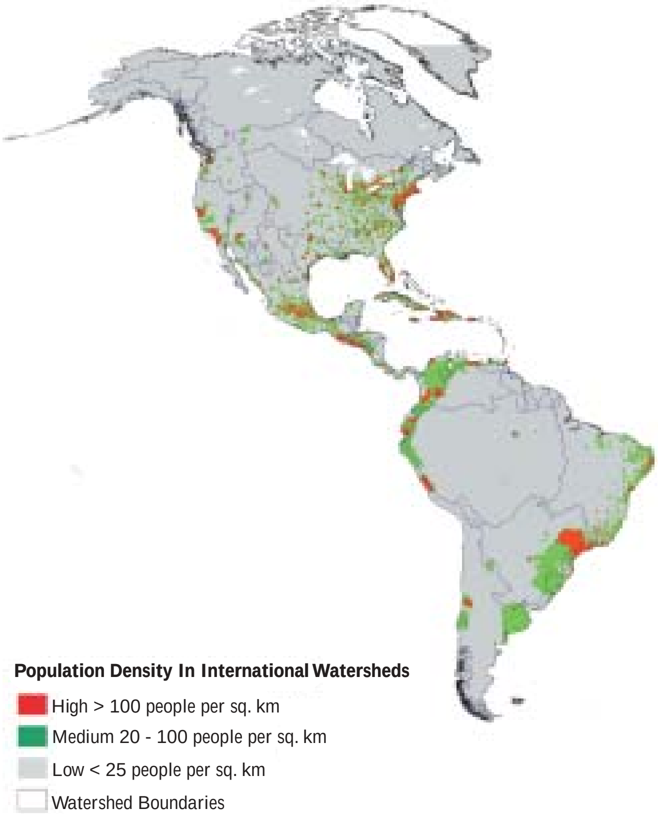


Table 2: Threats to Freshwater Ecosystems From Human Activities

Human Activity	Impacts On Aquatic Ecosystems	Functions At Risk
Population and Consumption Growth	Increases in water diversion, water pollution, acid rain, cultivated land and potential for climate change.	Virtually all aquatic ecosystem functions
Infrastructure Development (e.g. dams, dikes, levees, river diversions)	Loss of ecosystem integrity alters timing and quantity of river flows, water temperature, nutrient and sediment transport and delta replenishment, and blocks fish migrations.	Water quantity and quality, habitats, flood-plain fertility, sports, fisheries, maintenance of deltas and their economies
Land Conversion and Poor Land Use (e.g. wetland drainage, deforestation).	Eliminates key component of aquatic environment, loss of functions, integrity, habitats and biodiversity, alters runoff patterns, inhibits natural recharge, fills water bodies with silt.	Natural flood control, habitat for fisheries and waterfowl, recreation, water supply, water quantity and quality, transport
Overharvesting and Overexploitation	Depletes living resources, ecosystem functions and biodiversity (e.g. ground-water depletion, loss of fisheries).	Food production, sport and commercial fisheries, habitats, water supply, water quantity and quality
Introduction of Exotic Species	Eliminates native species, alters production and nutrient cycling, loss of biodiversity.	Water quality, sport and commercial fisheries, fish and wildlife habitat, transport
Release of Chemical and Biological Pollutants to Water, Land and Air	Pollution of water bodies alters chemistry and ecology of rivers, lakes and wetlands.	Water supply, habitat, fisheries, recreation
Greenhouse Gas Emissions Inducing Climate Change	Potential dramatic changes in runoff patterns from increases in temperature and changes in rainfall patterns.	Water supply, hydropower, transportation, fish and wildlife habitat, pollution dilution, recreation, fisheries, flood control

Source: Daily, G. (1997)

Map 5: Population Density In International Watersheds, North, Central And South America



growing threats from water scarcity, contamination of water supplies, and decreases in ecosystem health. Of particular concern are watersheds in India, China, and parts of central Africa.

Assuming current patterns continue into the future, increased infrastructure development will continue to alter timing and quantity of river flows and block fish migrations. Unsustainable withdrawals of water will lead to depletion of groundwater and biodiversity. Degradation of catchments will result in increasing erosion and flooding. Changing patterns of international trade will have significant,

Map 6: Population Density In International Watersheds, Europe And Asia

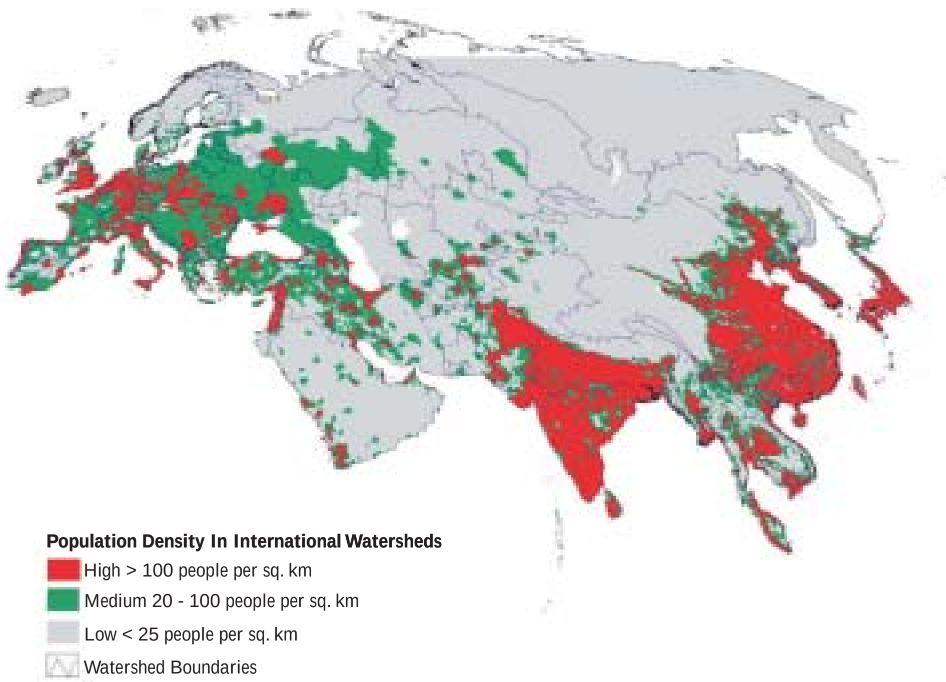


Table 3 : Number Of Reported Disaster Events And Fatalities In Selected Countries

Country	Number Of Reported Events	Persons Killed
USA	242	3418
India	114	50777
Bangladesh	86	150242

Source: CERD (2000)

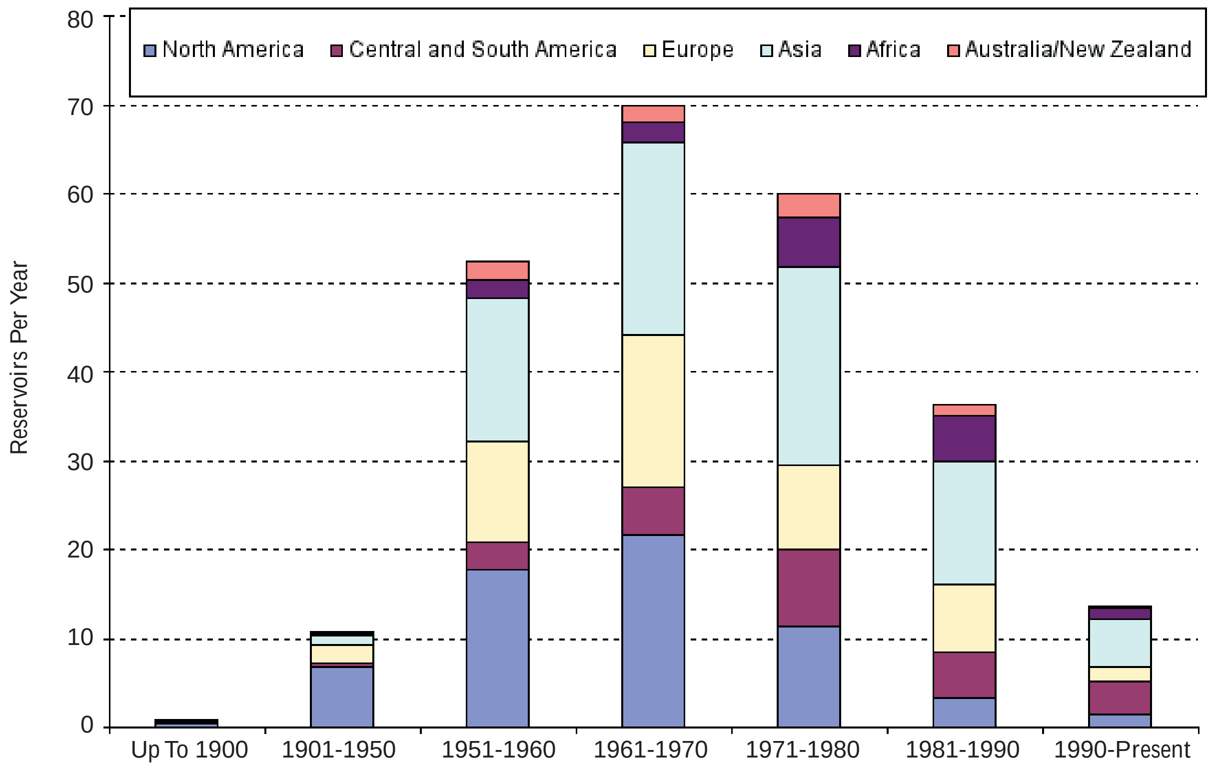
but uncertain impacts on environmental goods and services. Wetlands, dramatically reduced in numbers, will no longer provide flood abatement. The loss of species and habitats will dramatically reduce the world's biological diversity, and resulting declines in fish production will further exacerbate demands for protein from livestock production and agriculture. Many rivers are already open sewers that no longer contain fish and other life forms, but transport pollutants directly to degraded coastal and marine ecosystems.[23]

People in developing countries will especially suffer indirect effects of continued water resources degradation. They have more difficulty accessing global markets for goods and services and are often especially sensitive to changes in local land and water conditions. At the same time, such populations have fewer resources for avoiding, mitigating, or adapting to severe events. As Table 3 shows, the number of people killed in Bangladesh from reported disasters is 50 times higher than in the U.S., yet there were only a third as many reported events.

Subsistence farmers often depend on floods to replenish the soil and nutrients of floodplains and pasture, to clean streams, and aid in fish migration and production. The loss of freshwater biodiversity threatens the economic survival of fishing communities.

Developed countries will be affected as well. While population growth in most of these countries is low, consumption patterns and economic growth continue to be major drivers of environmental degradation. Agricultural production relies heavily on monocultures that use large inputs of pesticides and fertilizers. Industrial production has a heavy dependence on fossil fuels and nuclear energy, which places pressures on water resources for cooling and for large-scale hydropower, which places pressures on free-flowing aquatic ecosystems.

Figure 8: Average Number Of Large Reservoirs Built Per Year, By Time Period



Source: A.B. Avakyan and V.B. Iakovleva (1998)

Table 4: Number Of Reservoirs Larger Than 0.1 km³, By Continent, Time Series

	Up to 1900	1901-1950	1951-1960	1961-1970	1971-1980	1981-1990	1990-Present	Total
North America	25	342	178	216	113	34	7	915
Central and South America	1	22	30	54	88	51	19	265
Europe	9	104	113	172	94	76	8	576
Asia	5	47	161	215	222	138	27	815
Africa	1	15	21	24	57	52	6	176
Australia / New Zealand		10	21	18	27	12	1	89
Totals	**41**	**540**	**524**	**699**	**601**	**363**	**68**	**2,836**
Cumulative Totals	**41**	**581**	**1,105**	**1,804**	**2,405**	**2,768**	**2,836**	

Source: Avakyan, A.B. and V.B. Iakovleva (1998)

Heavy production and use of agricultural and industrial chemicals contaminates soils, rivers, and groundwater basins.

If water demands continue to grow as they have grown in the past, land will continue to be converted for agricultural, industrial, and human use, and water will continue to be abstracted away from natural ecosystems. Invasive plant and animal species are increasingly affecting waterways, disrupting entire ecosystems, and reducing freshwater biodiversity. Only modest investments are being made, however, to remove existing dams and to rehabilitate degraded wetlands, floodplains, and deltas.

Ecosystem integrity is defined as the interactions between the hydrologic cycle, biophysical, chemical, and ecological processes that support the functioning of an ecosystem and the health of the species supported by that ecosystem. To preserve ecosystem integrity it is essential to maintain the hydrological characteristics of catchments, including the flow regime, the connection between pieces of the system (such as upstream and downstream segments), and the links between groundwater and

Table 5: Volume Of Reservoirs Larger Than 0.1 km³, By Continent, Time Series

	Cubic Kilometers							
	Up to 1900	1901-1950	1951-1960	1961-1970	1971-1980	1981-1990	1991-1996	Total
North America	8.4	344.7	254.4	534.0	339.0	176.9	34.7	1,692.1
Central and South America	0.3	8.8	28.8	96.9	251.5	349.1	236.1	971.5
Europe	3.3	121.7	175.0	189.4	103.6	49.3	2.7	645.0
Asia	1.7	17.9	293.6	640.0	484.1	321.5	221.6	1,980.4
Africa	0.1	15.0	381.1	364.4	173.7	56.6	9.8	1,000.7
Australia / New Zealand		10.6	20.1	15.5	42.4	5.9	0.3	94.8
Totals	**13.8**	**518.7**	**1,153.0**	**1,840.2**	**1,394.3**	**959.3**	**505.2**	**6,384.5**
Average Annual Additions (km³/yr)10.4	**115.3**	**184.0**	**139.4**	**95.9**	**84.2**			

Source: Avakyan, A.B. and V.B. Iakovleva (1998)

Table 6: Wetlands Loss From Selected OECD (Organisation for Economic Cooperation and Development) Countries

Country	Period	Percent Wetland Loss
France	1900-1993	67
Germany	1950-1985	57
Greece	1920-1991	63
Italy	1938-1994	66
Netherlands	1950-1985	55
Spain	1948-1990	60
United States	1970-1985	54
World	**1900-1998**	**50**

Source: IUCN (2000)

surface waters. Below, several of these critical concerns are discussed in more detail.

3.1 Infrastructure Development

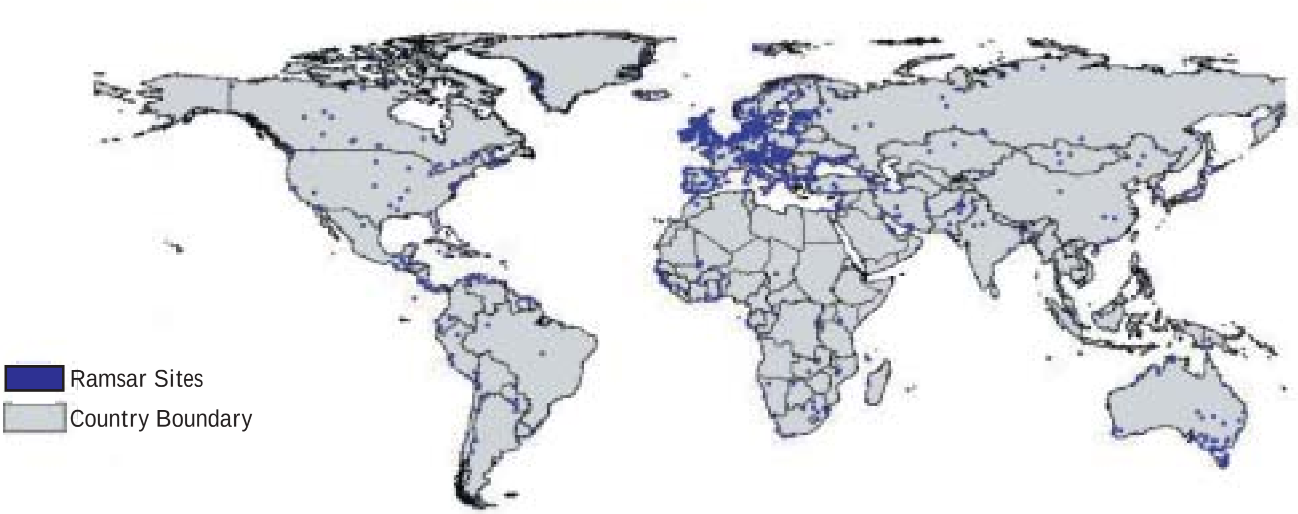
One of the greatest threats to ecosystem integrity is development of physical infrastructure on free-flowing rivers, such as dams, dikes and levees. In North America, Europe, and the former Soviet Union, for example, three-quarters of the 139 largest river systems are strongly or moderately affected by water regulation resulting from dams, interbasin transfers, or irrigation withdrawals.[24] The decline in discharge of the Indus and Brahmaputra rivers due to dam construction is contributing to the destruction of mangrove systems in the deltas of these rivers – a scenario common to many other river systems as well.

The data on construction of large dams over the past century is presented in Tables 4 and 5, and in Figure 8. Nearly 3,000 dams and reservoirs larger than 0.1 cubic kilometers have been built since 1900, but the rate of construction of new facilities is no longer growing. Since 1980, many new large facilities have been postponed or canceled. Similarly, the average volume of reservoirs being built has dropped substantially in the past decade (Table 5).

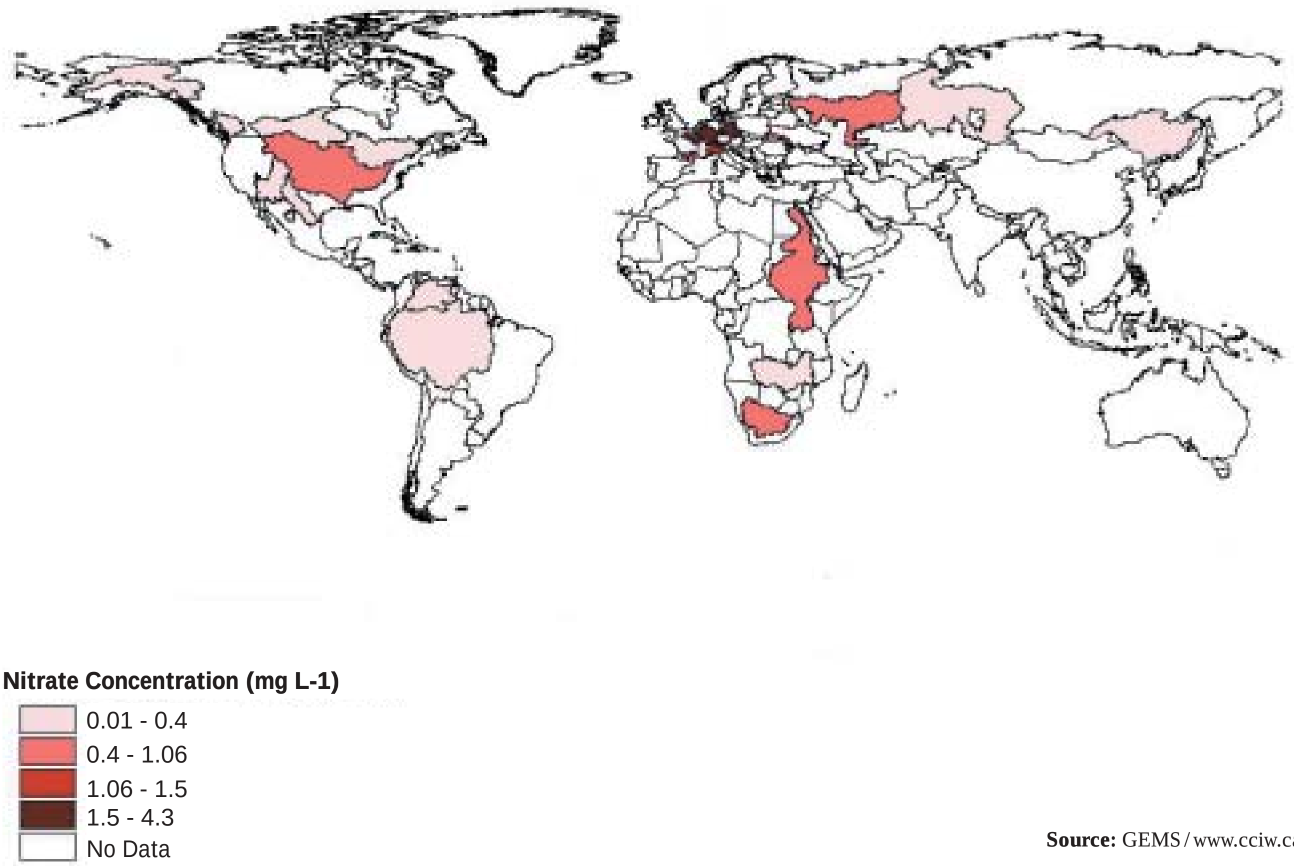
3.2 Habitat Destruction Caused By Land Conversion

Another important threat to ecosystem integrity comes from land conversion and urbanization. Aquatic ecosystems provide food and habitat for diverse plant and animal communities and contribute to biodiversity. Migrating species depend on the distribution of various habitats for refuge and survival. Wetlands, for example, support over 10,000 species of fish and over 4,000 species of amphibians. Some of the richest habitats for freshwater species include foothill streams, estuarine marshes, peat swamps and ancient lakes. Over the last century, the loss of wetland habitats has been severe in many developed countries, as shown in Table 6, caused mainly by conversion to urban and agricultural land.

Map 7: Wetlands Of International Importance



Map 8: Nitrate Concentrations For Major Watersheds



Source: GEMS / www.cciw.ca

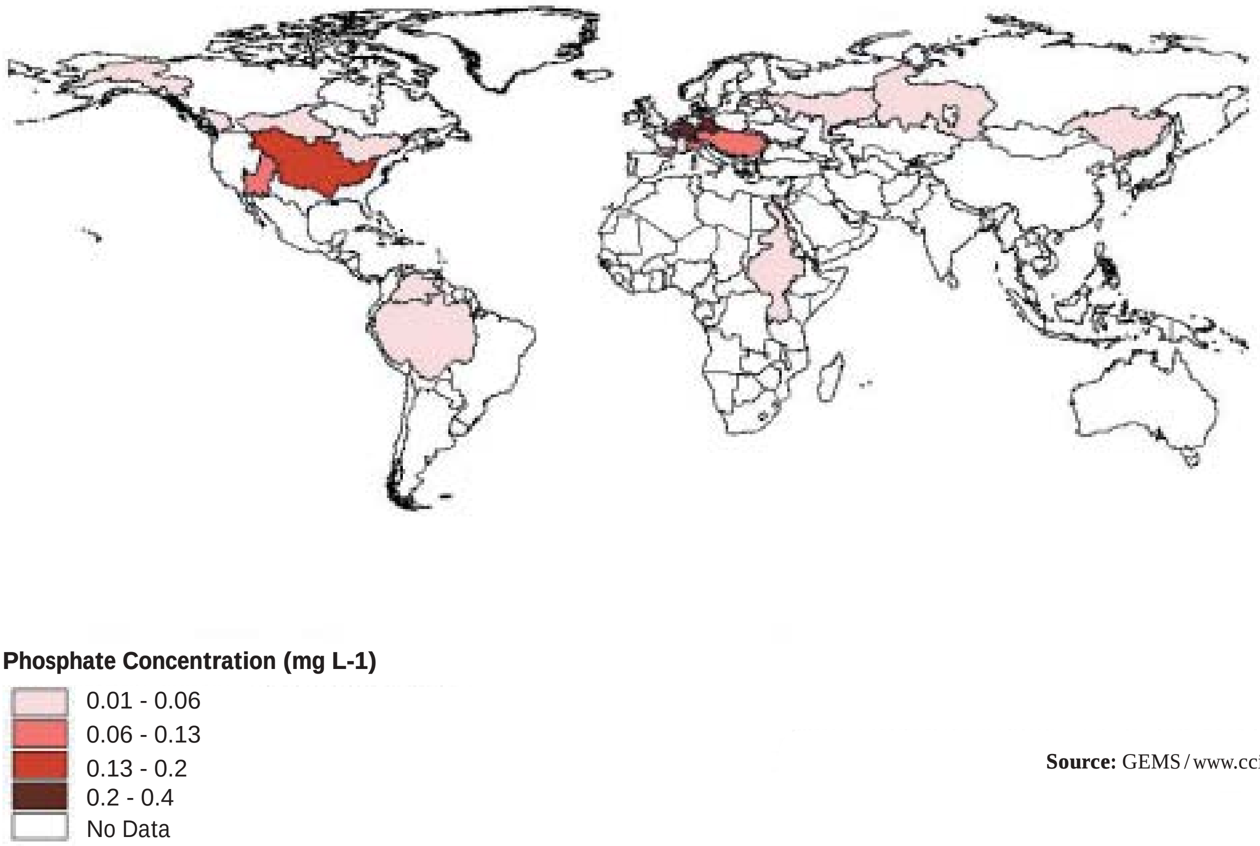
Deforestation increases peak flows and reduces low flows, contributing to flooding during some months and water shortages in others. Recent flooding in Europe and the United States has shown that building on floodplains reduces their capacity to store and attenuate floodwaters, increasing the risk of death and property damage. Table 6 lists the percentage of wetlands thought to be lost in developed countries of the OECD. Many of them have lost between 50 and 60 percent or more. Worldwide, half of all wetlands are estimated to have been lost to land conversion.[25] Map 7 shows protected wetlands worldwide. As this map indicates, there are many parts of the world with few officially protected wetlands.

3.3 Pollution Of Water Bodies From Industry, Agriculture, And Urban Use

Industrial and urban pollutants, agricultural runoff, and atmospheric deposition all have severe impacts on aquatic ecosystems. Water quality is currently improving in some areas, but water contamination continues to pose serious threats to human and environmental health. Persistent Organic Pollutants (POPs) originating from pesticides and herbicides, for example, continue to be used in large quantities. These chemicals become concentrated in people and other top predators, causing reproductive and developmental abnormalities in humans and animals. Non-point agricultural runoff puts excessive nutrients in surface and groundwater. In the United States, for example, 22 per cent of wells in agricultural areas contain nitrate levels in excess of the federal limit. In many developing countries, water quality is degrading due to pollution from inadequate disposal of human or animal wastes.

The Global Environmental Monitoring program (GEMs) has been monitoring water quality and various water pollutants for many years. Extensive data are available on specific pollutants in specific watersheds (see http://www.cciw.ca/gems/atlas-gwq/gems_tbl.htm) for more details. Maps 8 and 9 show the watersheds where nitrate and phosphorus concentrations have been a problem, though there are many regions of the world for which reliable data on water quality are still not available.

Map 9: Phospate Concentrations For Major Watersheds



Source: GEMS / www.cciw.ca

3.4 Resource Overexploitation

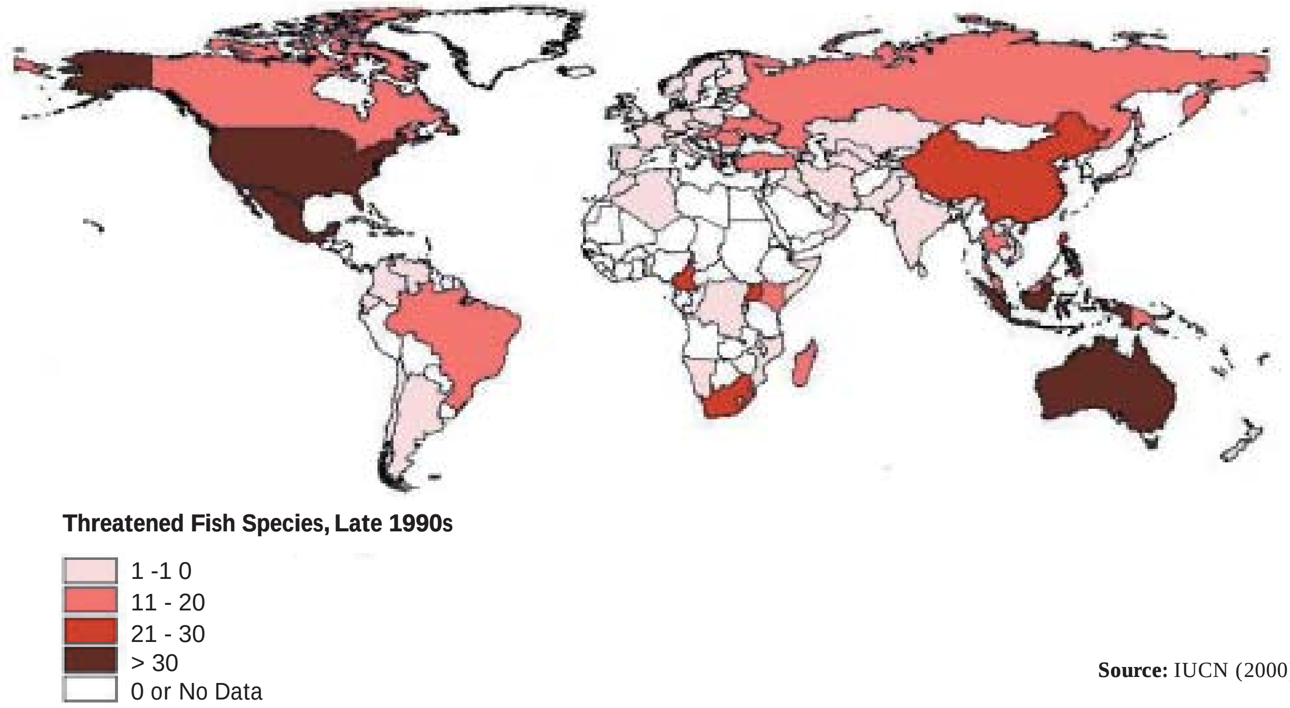
Freshwater withdrawals continue to increase in most parts of the world. Unsustainable withdrawals occur where abstraction exceeds the total renewable supply. In many areas of the world, groundwater withdrawals for domestic and agricultural use are leading to falling groundwater levels of as much as 0.5 to 5 meters per year. In coastal areas, this overdraft can lead to saltwater intrusion and the contamination of the remaining resource. In other areas, local wetlands depend on high water tables and overuse of groundwater destroys these vulnerable areas. Massive withdrawals of water from the Colorado River, for example, have led to wetlands loss, fish deaths, and loss of habitat for birds and other species.[26]

Water itself is not the only freshwater system to be overexploited: freshwater fish populations have come under increasing threat in several regions. Fish are a major source of animal protein throughout the world, especially in many tropical and subtropical countries. Between 1961 and 1996 worldwide freshwater fish catches increased fivefold (from 9 to 45 million metric tonnes).[27] The greatest growth has been in developing countries, particularly those in Asia, where over the same period there was nearly an eight-fold increase. The very significant increase in the human exploitation of the natural fish resource in recent decades, and the recent local decrease in catches, indicate that freshwater fishes are being exploited at, or above, sustainable levels.[28] Farm-raised fish production has also increased dramatically, with a subsequent rise in threats to wild fish populations in adjacent freshwater and coastal ecosystems, and concerns over water quality degradation.

3.5 Loss Of Freshwater Biological Diversity

A disproportionate fraction of the world's species lives in freshwater ecosystems. While the oceans comprise 70 percent of the earth's surface, only 1 percent is covered with inland waters. Yet the oceans contain only 7 percent of the animal species alive today while 12 percent of all animal species live in freshwater.[29] Freshwater fish comprise 40% of all recognized fish species and freshwater mollusks comprise 25% of all mollusks.[30] Freshwater biodiversity tends to be greatest in tropical regions with a high number of species, such as in northern South America, Central Africa, and Southeast Asia.

Map 10: Threatened Fish Species, By Country, Late 1990s



Source: IUCN (2000)

The loss of freshwater biodiversity is poorly monitored except for some larger, commercial species. Available data suggest that between 20 and 35% of freshwater fish are vulnerable or endangered. In addition, of the more than 3,500 species currently threatened worldwide, 25% are fish and amphibians.[31] Habitat destruction, particularly that caused by water infrastructure development (e.g. dams, dikes), is a major cause of freshwater biodiversity loss. Other factors include pollution, invasive species, and overharvesting. Map 10 shows those countries with officially listed threatened species of fish.

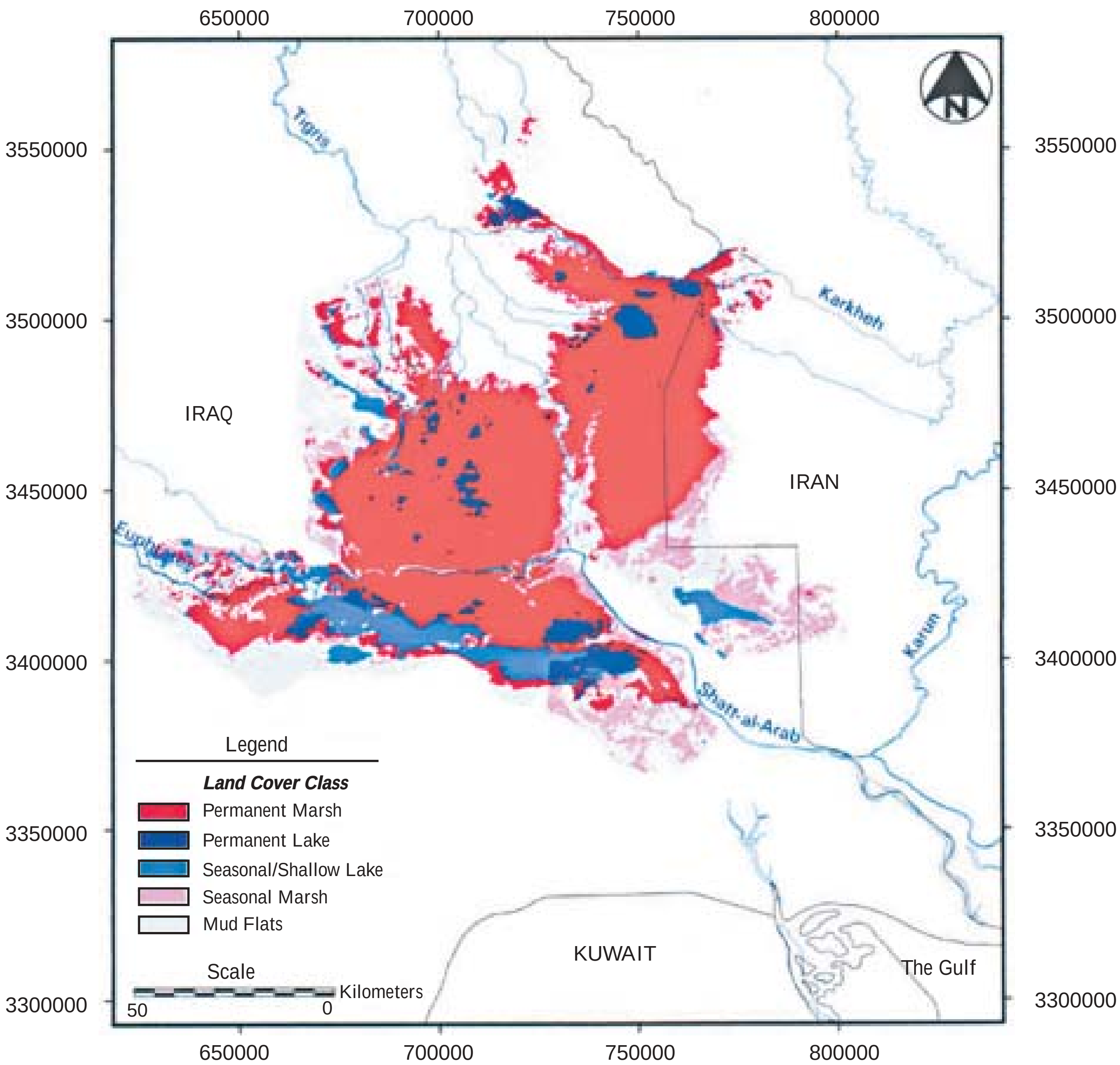
Table 7: Human Modification Of Freshwater Ecosystems

Alteration	1680	1800	1900	1950 to 60	1981 to 90	1990s
Waterways altered for navigation	<200 km	3,125 km	8,750 km		>500,000 km	
Canals	5,000 km	8,750 km	21,250 km	63,125 km		
Large Reservoir (Volume in km^3)			14	1,685	5,879	6,384
Large Reservoir (Numbers)			41	1,105	1,777	2,836
Large Dams (>15 m)				5,749		41,413
Wetlands loss *				160,600 km^2		

* Includes available information for drainage of natural bogs and grasslands as well as disposal of agricultural runoff. There are no comprehensive data for wetland loss for the world.

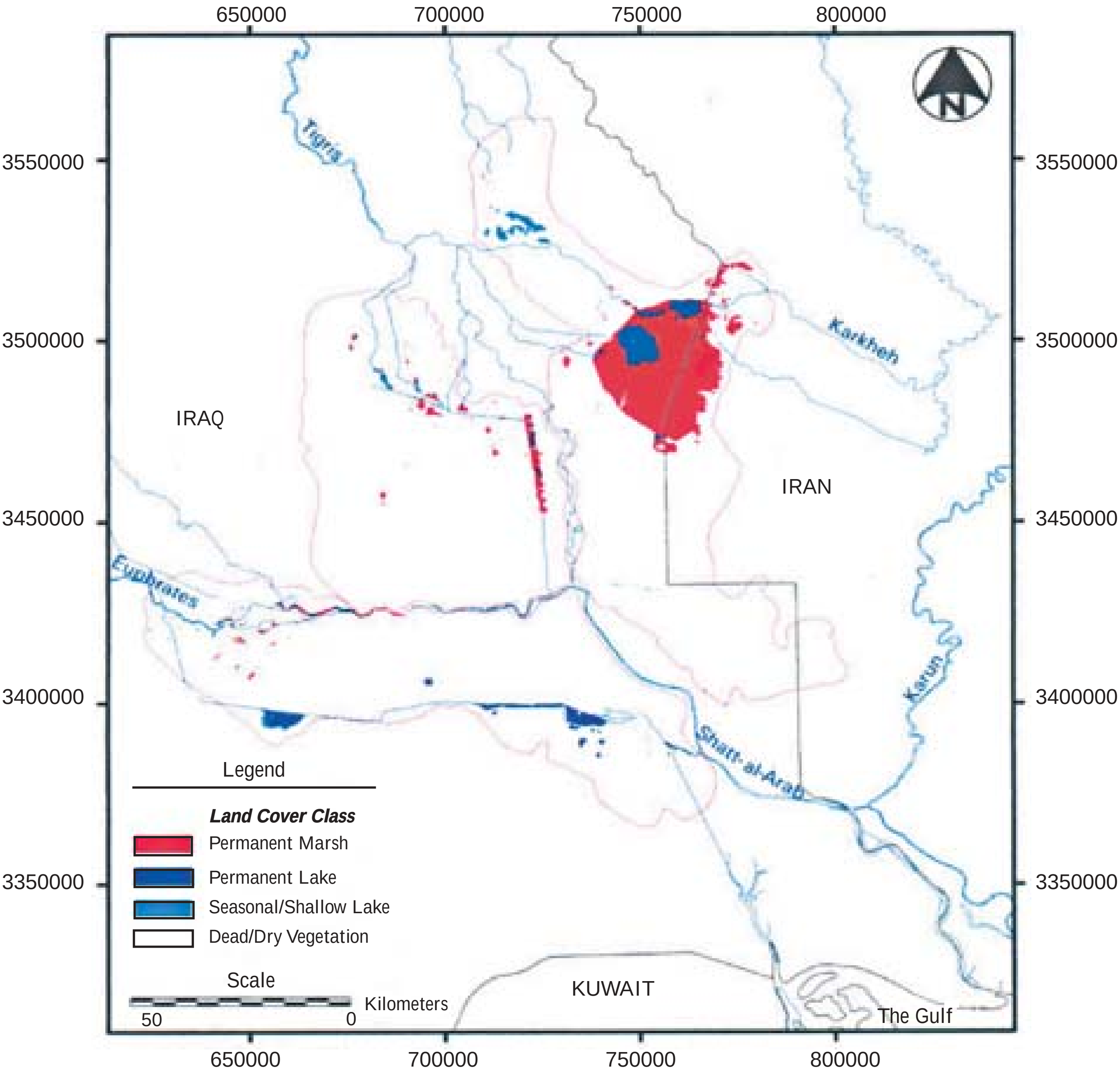
Sources: Naiman, R.J., J.J. Magnuson, D.M. McKnight, and J.A. Stanford (editors) (1995), WRI (1999), Avakyan, A.B. and V.B. Iakovleva (1998)

Map 11: Mesopotamian Wetlands - 1973



The satellite images taken in 1973 and 2000 provide a synoptic illustration of the great changes that have taken place in the Mesopotamian marshlands, located at the confluence of the Tigris and Euphrates in southern Iraq and extending partially into Iran. In the early 1970's the Mesopotamian marshlands were one of the world's great wetlands, covering an estimated original area of 15,000 - 20,000 km^2 (Map 11). They were an important center of biodiversity, played a vital role in the intercontinental migration of birds and had long supported unique human communities. Water reservoirs created by large dams upstream, as well as drainage activities in the marshlands themselves, have significantly reduced the quantity of water entering the marshes. Together these factors have led to the collapse of the ecosystem: the Landsat image of March 2000 shows that most of the wetlands have disappeared (Map 12). (UNEP / DEWA / GRID - Geneva)

Map 12: Mesopotamian Wetlands - 2000



4 Freshwater Contamination And Pollution

From Human Developments

Major water quality challenges face the world and these challenges are growing. As population has increased over the past century, it has become increasingly difficult to maintain adequate supplies of clean water to urban centers and rural environments have become increasingly polluted from agricultural and industrial activities. Heavy metals and syntehtic organics are also a growing problem, deserving far more attention than they've received. However, insufficient research has been done on them and, because of this, will not be discussed in detail in this chapter.

Water quality is closely linked to water use and to the state of economic development. In the 1800s and early 1900s, contamination of surface water with human wastes caused serious health problems (such as typhoid and cholera) in large cities in Europe and North America. As these cities began to build sewer networks and expanded waste-treatment facilities, the incidence and prevalence of water-related diseases in developed areas dropped significantly. In recent decades, however, the rapid growth of urban population in Latin America and Asia has outpaced the ability of governments to expand sewage and water infrastructure. While waterborne diseases have been virtually eliminated in the developed world, outbreaks of cholera and other gastro-enteric diseases still occur with alarming frequency in the developing countries (see Section 2).

Ironically, while industrialized nations have greatly eliminated water-related diseases, industrial and agricultural chemicals are now heavily affecting regional water quality. Eutrophication of surface waters from human and agricultural wastes is affecting large parts of the world. Acidification of lakes by air pollution threatens aquatic life in many areas. These water quality problems threaten aquatic ecosystems and necessitate costly remediation before water can be released or reused. Groundwater resources, once thought to be better protected than surface waters, have suffered nitrification from agricultural practices and have become widely contaminated with chemicals, many of which are known to have public health implications.

J. Isaac/www.fao.org

4.1 Water Quality Monitoring

There are serious gaps in water quality monitoring. One of the more comprehensive programs, the Global Environmental Monitoring System (GEMS), was initiated in 1974 to promote and coordinate the collection of environmental data at national, regional, and global scales (http://www.cciw.ca/gems/summary94/intro.html). GEMS aims at assisting governments to develop monitoring systems for their own use, to improve the validity and comparability of environmental data globally, and to provide for the collection and assessment of environmental data. GEMS maintains major programs for climate-related monitoring, monitoring of natural resources, monitoring of the oceans, and health-related monitoring. GEMS partners include WHO, UNESCO, WMO and UNEP. The objectives of the project are:

- to collaborate with Member States in the establishment of new water monitoring systems and to strengthen existing ones;

- to improve the validity and comparability of water quality data within and between Member States, and
- to assess the incidence and long-term trends of water pollution by selected persistent and hazardous substances (http://www.cciw.ca/gems/summary94/intro.html).

Member States routinely monitor the quality of their water resources at selected locations and provide the data for global syntheses and dissemination. Wherever possible, the stations for the global network were selected from existing national or local networks. Where such stations did not exist, new ones were established. Priority was given to water bodies (rivers, lakes and groundwater aquifers) that are major sources of water supply for municipalities, irrigation, livestock, and selected industries. A number of stations were also included to monitor international rivers and lakes, rivers discharging into ocean and seas, and water bodies not yet affected by human activities (baseline stations).

The first stage of the project (1977-1981) established a skeleton network of approximately 300 monitoring stations on rivers, lakes, and in groundwater aquifers. At that time it was estimated that a total of about 1,200 stations might ultimately be required to achieve representative global coverage. Measurement of water quality variables at these stations include natural as well as anthropogenic constituents.

UNEP, Nairobi, and WHO, Geneva, implement GEMS/Water with the assistance of WHO Regional Offices. Technical support is provided by two WHO regional centers for environmental health. In addition, institutes have been designated as regional reference laboratories for implementing the analytical quality assurance component of the project. WMO has concentrated on network design criteria and hydrological monitoring methods.

By January 1998, the responsible national authorities in 71 countries had formally designated a total of 612 stations. As of January 1998, there was active participation and data submissions from 64 countries for a total of 538 stations. There are 368 river stations, 78 lake stations, and 92 groundwater aquifers in the active files (http://www.cciw.ca/gems/atlas-gwq/gems2.htm). The water-quality variables to be measured at each station fall into three categories:

(i) 13 basic physical, chemical and microbiological variables;

(ii) globally significant variables comprising such pollutants as heavy metals and pesticides; and

(iii) various site-specific optional variables.

4.2 Water Quality Problems

The quality of natural waters varies tremendously over both time and space. These variations depend on climate, hydrologic conditions, soils, and other characteristics. For example, dissolved oxygen concentration – an important parameter for aquatic life – varies with temperature as well as the concentration of certain pollutants. Salinity is affected by natural soil characteristics, flow dynamics, and agricultural practices. Water quality measures therefore can vary in response to both natural events and human actions.

Humans can also affect water quality over very large scales, such as through persistent pesticide contamination, atmospheric transport of pollutants, and increases in carbon dioxide concentrations. The adequacy of water quality for human use depends on both the absolute quality of the water as well as the purpose for which the water is needed. Water required for drinking needs to be far cleaner than water for irrigation or certain industrial uses. Anthropogenic pollution may be categorized as municipal, industrial, and agricultural. Municipal waste is composed of human excreta and generally contains numerous pathogenic microorganisms but few chemical contaminants. Industrial wastes vary tremendously and contain both organic and inorganic chemicals, heavy metals, and other wastes. Agricultural pollution includes phosphorus and nitrogen from fertilizers as well as numerous organic pesticides.[32] Below, some of the more important water quality contaminants of growing concern are described.

4.2.1 Microbiological Contamination

Microbiological contamination of freshwater remains the most pressing water quality concern globally. Estimates of the occurrence of waterborne diseases are uncertain and variable, but the WHO reports 250 million new cases of waterborne diseases each year, with between three and five million deaths.[33] The actual degree of diseases and death caused by water-related diseases in the developing world is largely unknown, since most illnesses are never diagnosed, reported, or treated (see Section 2).

The vast majority of these cases occur in tropical countries where climatic conditions and inadequate water supply and sanitation combine to spread disease. Freshwater bodies polluted by faecal discharges from humans, livestock, pets, and wild animals may contain a variety of pathogens such as bacteria (Shigella, Salmonella, Cholera Vibrio, Escherichia), viruses, and protozoans.

Waterborne diseases are principally transmitted through the contamination of drinking water supplies with pathogens from human or animal excreta. Uninfected people then ingest the contaminated water. Typhoid and cholera were among the first diseases identified as waterborne, and they remain among the most important diseases in this class.[34]

Seven species of parasite are of particular concern, though over 30 species have been identified that infect the human intestine. These include amoebiasis, giardiasis, ascariasis, hookworm, trichuriasis (whipworm), Taenia solium taeniasis, and strongyloidiasis.[35] The parasite responsible for amoebiasis and trichuriasis are both estimated to infect 500 million people worldwide. Ascaris is estimated to infect over a billion people.[36]

Waterborne diseases can be controlled through improved water quality. The industrialized nations made tremendous progress in the 19th and 20th centuries in the protection and treatment of water supplies, ultimately bringing both cholera and typhoid fever under control. Outbreaks of water-related diseases today arise mostly from pathogens resistant to chlorine.

Water-based diseases, including schistosomiasis and dracunculiasis, are also widespread. Together, these two diseases affect nearly 200 million people and certain kinds of major water projects encourage the spread of the disease vectors.

Detection of waterborne pathogens is difficult; therefore water-quality surveys use various indicators of faecal contaminations such as total coliforms and faecal coliforms. Bacterial counts, expressed in number per 100 ml, may vary over several orders of magnitude at a given station. They are the most variable of water quality measurements. In rivers that are relatively free of sewage discharges, total faecal counts are less than 100/100 ml. Most of the GEMS stations in Europe reflect a marked contamination with counts between 1,000 and 10,000/100 ml with occasional peaks exceeding 100,000/100 ml. In rivers that receive untreated sewage, coliform counts can well exceed 100,000/100 ml. The lower values from region to region may reflect methodological and reporting differences. As populations grow, microbial contamination will remain a critical water quality concern and special measures for both monitoring such contamination and reducing waterborne pathogens are warranted.

4.2.2 Dissolved Oxygen

Oxygen is critical for aquatic life and a standard measure of water quality. For fish, salmonid species need oxygen concentrations greater than 5 mg/l; cyprinids (carp family) need more than 2 mg/l. Oxygen is needed to modify and reduce pollutant loads in rivers. Dissolved oxygen in natural running waters should be close to 100 percent saturation, that is, between 9 and 11 mg/l, depending on temperature. Oxygen depletion is usually caused by bacterial degradation of organic matter (http://www.cciw.ca/gems/atlas-gwq).

The potential for oxygen consumption is typically referred to as Biological Oxygen Demand over a five-day period (BOD_5) and by the oxidization of chemical bonds (Chemical Oxygen Demand — COD). Oxygenation of water occurs naturally through turbulence, atmospheric exchange, and vertical mixing in lakes.

The GEMs program regularly measures BOD_5 levels at many places. Global BOD_5 levels at GEMS stations average 2 mg/l, which indicates modest levels of organic pollution. Much higher values occur at some locations, especially those downstream of discharges of municipal wastewater, wastes from food processors, and certain industrial effluents. South American stations show the lowest BOD levels. The Xi Jiang (Pearl River) shows natural variability of BOD_5 ranging from 0.3 to 1.2 mg/l for 12 years of record. Such low levels are rarely found in the GEMS/WATER database. The Xi Jiang also demonstrates how higher values of BOD_5 are associated with low flow of a river when effluents are least diluted. Growing threats from municipal waste discharges have been inadequately addressed and monitoring should be expanded.

4.2.3 Salts (Sodium and Chloride)

Sodium and chloride both originate from natural weathering of rock, atmospheric transport of oceanic minerals, and many anthropogenic sources. The WHO drinking water guideline for Cl^- is 200 mg/l. Concentrations of sodium and chloride have risen by a factor of 10 to 20 in many rivers during the past century, as a direct result of human activities that both increase salt inputs and reduce freshwater flows. Since 1889 there has been a five-fold increase in Cl^- concentrations at the water intake (Ivry) for the City of Paris (http://www.cciw.ca/gems/atlas-gwq/gems10.htm#2). Sometimes, single large sources can lead to major water-quality problems, though often, many small sources are responsible. For example, the Rhine River suffers from two major salt sources — the Alsace potash mines and the Lorraine salt mines, both located in France. The brine from these sites is discharged to the Rhine downstream of Basel and to the Mosel River, respectively. The Alsace source (15,000 tonnes NaCl/day) represents 30 % of the Cl^- flux measured at the German/Netherlands border. Other contributions are mostly urban and industrial from the Ruhr area. Since the opening of the potash mines, 100 years ago, Cl^- levels and fluxes have increased by a factor of 15 to 20 (http://www.cciw.ca/gems/atlas-gwq). The WHO standard for drinking water has often been exceeded in this watershed.

These forms of pollution are now beginning to be seen in many developing country watersheds as well. In the Nile basin, chloride concentrations are low in the upstream Lake Victoria tributaries and they increase as one moves downstream toward Egypt. Chloride concentrations increase at Khartoum from evaporation in southern Sudan. Below the Aswan Dam, the Nile collects both sodium and chloride from municipal and industrial wastes and agricultural runoff, further raising concentrations. A similar pattern of rising concentrations can be seen in the Orange River in southern Africa, which has both large point sources and many smaller areal sources.

Other rivers in developing countries may have chloride concentrations relatively unaffected by human activities. In the upstream reaches of the Krishna River, India, for example, chlorides originate from aerosols driven inland by westerly winds from the oceans. Some African waters are characterized by very low Cl^- concentrations, including the Senegal, Niger, Zaire, and Chari rivers (http://www.cciw.ca/gems). Early and consistent monitoring of such rivers can provide early warning of threats.

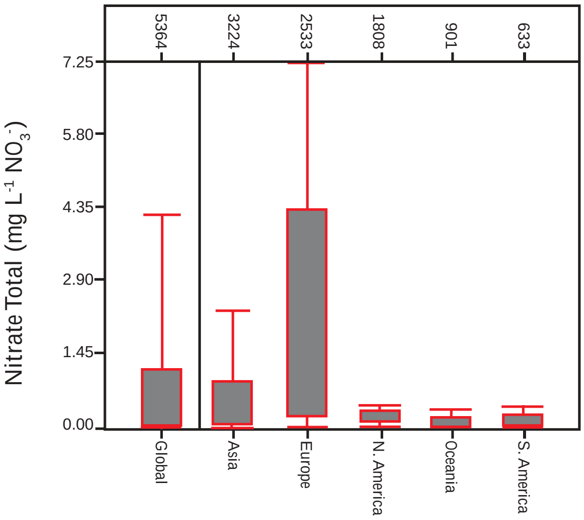
In arid and semi-arid areas of the world, evapotranspiration leads to an increase in the salt content of surface waters and to an increase in the sodium and calcium concentrations. Many rivers flow through arid regions, including the Colorado, Rio Grande, Orange, Nile, Indus, and Murray. Salinity of the Colorado River as it reaches the U.S.-Mexican border can be very high, and a water quality standard was negotiated between the two countries in the 1970s. As more water is abstracted from the Colorado, and similar rivers in semi-arid regions, salt content often increases. About 50 percent of arid land is located in regions where there is no flow to the ocean. In these regions, rivers flow into lakes and inland seas such as the Aral, Caspian, Chad, Great Salt Lake, and Titicaca, which have no outlets and which further concentrate salts through evaporation. These basins are particularly vulnerable to human use of water, as shown by the massive impacts on the Aral Sea basin in the former Soviet Union.

4.2.4 Phosphorous and Nitrogen

Nitrogen and phosphorus both occur in the environment naturally. Human mobilization of these elements in agricultural fertilizer, municipal sewage, and animal wastes, however, can cause major problems. They serve as important water-quality indicators of the impacts of human activities. Runoff containing these nutrients from agricultural lands, dairy and poultry farms, and the discharge of municipal waste to rivers and lakes can lead to eutrophication of surface waters. Measurements of phosphorus and nitrogen, primarily in the oxidized forms of phosphate (PO_4^{-3}) and nitrate (NO_3^-), are useful indicators of population and agricultural impact.

Measurements indicate that the nitrate content of fresh water has been rising in many countries since the 1960s. Water-quality experts estimate that about one-third of the total dissolved nitrogen in rivers comes from water pollution.[37] Figure 9 shows nitrate levels in continental waters. Most South American rivers show low levels of nitrates — less than 0.88 mg/liter of NO_3^-. Similar levels are found in northern Canadian rivers, some Siberian rivers, and most African rivers, but levels are growing. Nitrate pollution caused by agricultural chemicals is also becoming a major problem for groundwater quality in many parts of the world. In the United States, a sampling network established by the U.S. Geological Survey showed that in more than one-third of the regions analyzed, 25 percent of groundwater wells had nitrate concentrations that ex-

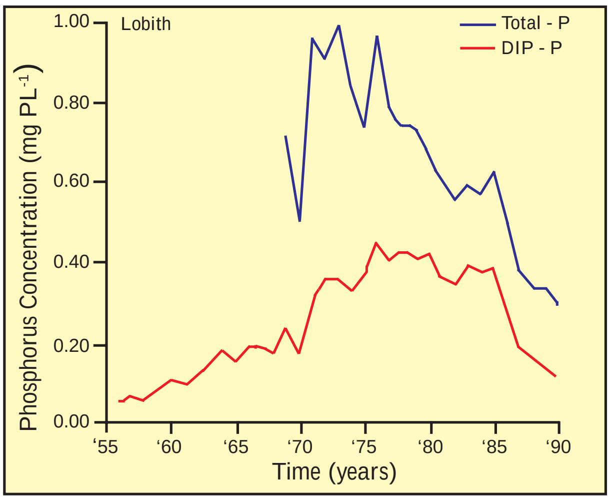
Figure 9: Statistical Distribution Of Nitrate For Major Global Watersheds



ceeded background levels. In 5 percent of the regions, more than one-quarter of all wells exceeded the federal drinking water standard for NO_3^- N. Similarly, nitrate levels in Danish ground water wells tripled between the 1940s and 1990s.[38]

Excessive nutrient concentrations, usually of phosphorus, can lead to eutrophication of lakes. Eutrophication, especially in extreme cases, leads to algal blooms, which are often followed by low oxygen levels when the algal material decays. High concentrations of algae cause taste and odor problems in drinking water, and some types of algae are toxic to animals. Phosphate concentrations and seasonal ranges are sensitive to domestic wastes and to intensive agricultural activities when phosphorus-based fertilizers are used. About half of the phosphate in urban sewage originates from phosphate-

Figure 10: Mean Annual Concentration Of Phosphorus Species For The Rhine (Ref.31)
DIP is Dissolved Inorganic Phosphorus
(Reproduced by permission)



containing detergents and about half from human and animals wastes. Higher concentrations of phosphate observed in some of the rivers of Western Europe are indicative of municipal waste loading that has not received adequate treatment to remove phosphorus.

Experience with pollution control efforts in North America and Europe has shown that, in some cases, bodies of water adversely affected by excessive levels of nutrients can be successfully restored to health by controlling inputs of nutrients. Efforts to reduce nutrient loadings in rivers can also have positive results. In the 1960s programs to collect and treat sewage in the Rhine basin were begun. Controls on PO_4^{-3} (see Figure 10) and NH_4^+ have been successful but NO_3^- concentrations have continued to increase because of the use of nitrogen-based fertilizers in the basin. This increase occurs in many Western European rivers such as the Thames and Seine.[39] In an increasing number of watersheds, the WHO standard for drinking water (50 mg NO_3^- per liter) will be reached. Maps 8 and 9 show major international watersheds with high nitrate and phosphate concentrations.

4.2.5 Acidification

The natural acidity of rainwater is increased by the presence of sulfur dioxide (SO_2) and nitrogen oxides (NO_X). These pollutants originate mainly from fossil-fuel combustion and are carried by winds over long distances from urban, mining, power plants, and industrial sources. During rainfall the pollutants precipitate as sulfuric and nitric acids. Acidified waters are characterized by a major decrease in biological density and diversity.

Regions at risk from acid rain have been estimated by combining both the source areas (use of sulfur-bearing coal, major cities, oil refineries, various industries) and the occurrence of sensitive soils found in wet and humid regions (see http://www.cciw.ca/gems/atlas-gwq/gems12.htm).

The presence of geologically sensitive areas downwind of existing major emission sources lead to three problem areas where acidification is a major issue: southern Scandinavia, northeastern USA/eastern Canada, and China. Regions that are experiencing rapid increases in emissions may have acid rain problems in the future, including Nigeria, India, Venezuela, southern Brazil, and southeast Asia.

5 Climate Change

The Earth's climate is intrinsic to everything important to society - the production of food and energy, human and ecosystem health, the functioning and characteristics of the hydrologic cycle, and much more. Natural and human-induced changes in the Earth's climate will thus have widespread implications for society. This section addresses the future risks of climate change for water resources and complex developed water systems. Assessing the impacts of climatic changes cannot be a static activity – new information is constantly being made available, new methods and models are being developed and tested, and policies related to water management and planning are dynamic and changing. In the coming years, researchers will continue to work to improve our understanding of the implications of climatic changes for the world's water.

Total precipitation worldwide averages 580 cubic kilometers per year. Much of this precipitation falls on the oceans or quickly evaporates back into the atmosphere, but the remainder provides a renewable supply of surface water and groundwater that is many times larger than current consumptive use. In addition, vast amounts of water are stored in lakes, reservoirs, and groundwater aquifers, providing reliable, high-quality supplies for much of the world's population.

A fundamental characteristic of the natural water cycle is that average figures hide important regional and temporal variations. Water may be plentiful in places and times when it is not needed, but sparse in other regions and times that may need it. Despite its average abundance and renewability, fresh water can be a scarce resource almost anywhere in the world. It can also be present in excess, causing floods that kill or injure large numbers of people and destroy property.

The design and evaluation of alternative water investments and management strategies currently assume that future precipitation and runoff can be adequately described by assuming the future will continue to look like the past. The increasing likelihood that a human-induced greenhouse warming will affect the variability and availability of water quality and supplies as well as the increasing demand for water raises doubts about this assumption and the most appropriate water policies for the future.[40]

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Presenting a clear picture of information on the impacts of climate change is a major challenge when the extent of our knowledge is continuously evolving. Decision-makers must weigh their potential actions and responses to the risks of climate change before all the uncertainties can be resolved – indeed, all the uncertainties will never be resolved because of the nature of the problem. As a result, imperfect information must be synthesized, evaluated, and presented in a responsible and informative manner.[41] Compounding the vast uncertainties associated with a naturally stochastic system like the Earth's hydrologic cycle are complicating human factors ranging from rates of population growth to the speed and scope of technological innovation and the flexibility and changeability of human institutions and policies. Adding predictions of the behavior of the Earth's climate in the future as greenhouse gas concentrations in the atmosphere increase imposes even more complexities and uncertainties.

Uncertainty can range from a lack of absolute sureness to speculation or informed guesses. Some uncertainties can be quantified; others must remain qualitative. Such uncertainties are not unique to the problem of climate change. Scientists in laboratories must deal with statistical variation, measurement error, natural variability, and subjective judgment. The science of climate change involves some even worse complexities having to do with the global and regional scales of impacts, the long time periods involved, and the impossibility of reproducing climatic conditions in a testable, laboratory situation. Yet the issue of climate change is not a purely scientific one: it also involves socioeconomic factors and public policy questions that further complicate assessment. Sidebar 1 summarizes some of the uncertainties associated with the implications of climate change for water resources. The greatest uncertainties arise from the difficulty of knowing how the driving forces affecting the global climate system will change. For example, estimating future greenhouse gas concentrations alone requires making projections of uncertain human and economic behaviors. Then, even if we could reliably determine atmospheric gas concentrations over time, converting these conditions into climatic changes involves modeling some of the most complex geophysical behaviors on Earth. Interested readers are directed to the comprehensive discussions of these issues in the IPCC reports.[42]

Acknowledging the many uncertainties involved is vital, but a great deal has also been learned in recent years about possible risks facing local, national, and international water systems. Prudent planning requires that a strong international climate and water research program should be maintained, that decisions about future water planning and management be flexible, and that expensive and irreversible actions be avoided in climate-sensitive areas. Nearly two decades of serious research into the implications of climate change for water resources has improved our understanding of possible impacts, points of vulnerability, and critical issues and some clear and consistent results have been identified. Taken all together, the current state-of-the-science suggests a wide range of concerns that should be addressed by national and local water managers and planners, climatologists, hydrologists, policymakers, and the public.

5.1 Recent Scientific Assessments

The debate about whether or not climatic change is a real problem is not over, but the nature of that debate is beginning to change. Instead of arguing about the complex details of atmospheric science and modeling, increasing attention is being given to trying to understand possible consequences for society and the kinds of responses that make sense despite the many remaining uncertainties. This is particularly true in the area of water resources, where many decisions depend explicitly on the assumptions we make about future climatic conditions. Long-term water planning choices, the design and construction of new water-supply infrastructure, agricultural planting patterns, urban water allocations and rate structures, and reservoir operating rules all depend on climatic conditions.

There is a broad scientific consensus that global climatic change is a real problem and that it will alter the hydrologic cycle in a variety of important ways.[43] Beginning in the late 1980s enormous efforts by scientists from many different backgrounds have vastly improved our understanding of the atmospheric system and its behavior. Uncounted peer-reviewed studies, scientific meetings and symposia, and both large- and small-scale research projects in dozens of scientific fields have explored many of the questions that must be answered in order to better understand climate. One major piece of this effort is the Intergovernmental Panel on Climate Change (IPCC), a multi-year scientific assessment of climate change under the auspices of the World Meteorological Organization and the United Nations Environment Programme, with the cooperation of over 120 nations and most of the world's leading climatologists. The first IPCC report was released in 1990, a reassessment was released in 1996, and the third assessment will be released in mid-2001. The 1996 study concluded:

Sidebar 1: Important Uncertainties And Complexities In The Research Process

A wide range of uncertainties result from the difficulty of predicting the future rates of greenhouse gas emissions and interested readers should look at the reports of the Intergovernmental Panel on Climate Change.

- Most research on the hydrologic implication of the greenhouse effect begins with estimations of regional atmospheric or surface variables such as temperature and precipitation derived from a long-term general circulation model (GCM) simulation. Large uncertainties result from estimates of how increased greenhouse gas concentrations will affect the climate. GCMs generally do a better job of representing large-scale atmospheric dynamics than temperature and precipitation and they are run at spatial scales far coarser than hydrologists would like. Biases of several degrees C are not uncommon in attempts to reproduce seasonal temperature variations and there is considerable variation among GCM estimates of the future direction, magnitude, and timing of changes in precipitation. Detailed information on the promise and limitations of GCMs can be found in IPCC Working Group 1 report.

- The next step in the research sequence involves going from the large scale of the GCMs, which often have grid cells of about 40,000 km^2, to the river-basin scale. "Downscaling" introduces new uncertainties about the relationships between large-scale climate data and smaller-scale dynamics of the atmosphere, how those dynamics affect the hydrology of a watershed, and the proper translation of coarse hydrologic data to finer resolution.

- Climate information is then fed into hydrologic models calibrated and tested with observed streamflow and meteorological data at the river basin level. These models produce estimates of runoff, soil moisture, and other conditions under a range of climate scenarios. The hydrologic modeling errors introduced at this point are relatively modest compared to those introduced by the GCM simulations and downscaling.

- The resulting hydrological data are then used with models of water-management systems to evaluate the differences in system performance under different climate scenarios. Applying the climate-adjusted hydrology to water-resource system models calibrated and designed to operate with historical streamflows introduces additional uncertainties.

- Finally, the impacts of future climatic changes on water resources will depend on many non-scientific factors, including regional demographic factors, water policies, prices, and rules for operating complex systems. Such factors can help systems cope with possible climate changes or they can make the system more vulnerable. Because we cannot know how water managers will react in advance, or even if they will, the ultimate impacts of climate change will depend on choices and value judgments as well as scientific information and data.

Sources: Wood, A.W., D.P. Lettenmaier, and R.N. Palmer. 1997. Assessing climate change implications for water resources planning, Climatic Change, Vol. 37, pp. 203-228; Frederick, K.D., D.C. Major, and E.Z. Stakhiv. 1997. Special Issue: Climate Change and Water Resources Planning Criteria. Climatic Change. Volume 37, No. 1; Gleick, P.H. 2000b. <u>Water: The Potential Consequences of Climate Variability and Change</u>. A Report of the National Assessment Water Sector. U.S. Global Change Research Program. U.S. Department of the Interior and the Pacific Institute for Studies in Development, Environment, and Security, Oakland, California.

"We are certain of the following:

- emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. [44]

"We calculate with confidence that:

- Continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead. The longer emissions continue to increase at present day rates, the greater reductions would have to be for concentrations to stabilise at a given level. [45]

The Intergovernmental Panel on Climate Change also stated in 1996 that "freshwater resources in many regions of the world are likely to be significantly affected," and that many current freshwater problems will be made worse by the greenhouse effect. This second assessment report urged water managers to begin "a systematic reexamination of engineering design criteria, operating rules, contingency plans, and water allocation policies" and states with "high confidence" that "water demand management and institutional adaptation are the primary components for increasing system flexibility to meet uncertainties of climate change." [46] This emphasis on demand management rather than construction of new facilities marks a change in traditional water management approaches, which in the past have relied on the construction of large and expensive infrastructure.

Several other major efforts have also explored the implications of climate change for water resources. For example, the Second World Climate Conference, held in Geneva in late 1990, concluded:

> "The design of many costly [water management] structures to store and convey water, from large dams to small drainage facilities, is based on analyses of past records of climatic and hydrologic parameters. Some of these structures are designed to last 50 to 100 years or even longer. *Records of past climate and hydrological conditions may no longer be a reliable guide to the future. The design and management of both structural and non-structural water resource systems should allow for the possible effects of climate change.*" (Italics added)[47]

A separate study of the American Association for the Advancement of Science (AAAS) published in 1990 focused explicitly on the implications of global climate changes for the water resources of the United States. This study, chaired by Drs. Roger Revelle and Paul Waggoner concluded:

> "Among the climatic changes that governments and other public bodies are likely to encounter are rising temperatures, increasing evapotranspiration, earlier melting of snowpacks, new seasonal cycles of runoff, altered frequency of extreme events, and rising sea level...*Governments at all levels should reevaluate legal, technical, and economic procedures for managing water resources in the light of climate changes that are highly likely.*" (Italics from original.) [48]

In mid-1998, a new assessment of the implications of climate change for the United States (the "National Assessment") was begun. One component of this assessment is a new look at the impacts on water resources, including both hydrology and water management and planning. This effort brought together water managers and water utility planners with climatologists, hydrologists, and others in the community of water scientists. The final water report of the U.S. National Assessment stated:

> "The scientific evidence that humans are changing the climate is increasingly compelling. Complex impacts affecting every sector of society, including, especially, the nation's water resources, now seem unavoidable… In many cases and in many locations, there is compelling scientific evidence that climate changes will pose serious challenges to our water systems…It is vital that uncertainties not be used to delay or avoid taking certain kids of actions now."[49]

5.2 Summary Of The Effects Of Climate Changes On Water Resources

Among the expected impacts of climatic changes on water resources are higher global and regional temperatures, increases in global average precipitation and evaporation, changes in the regional patterns of rainfall, snowfall, and snowmelt, changes in the intensity, severity, and timing of major storms, and a wide range of other geophysical effects. These changes will also have many secondary impacts on freshwater resources, altering both the demand and supply of water, and changing its quality.

5.2.1 Temperature, Evaporation, and Precipitation

There is a high degree of confidence that global average temperatures will rise as greenhouse gas concentrations rise; indeed, there is already strong empirical evidence that anthropogenic warming has begun. Regional temperatures will also increase, though some areas may experience short-term cooling effects due to the complex behavior of the climate system. Evaporation of water from land and water surfaces will increase as global and regional temperatures rise. More evaporation will result in more precipitation on average, though regional precipitation patterns will continue to be very complex and variable. Reviews of state-of-the-art climate models suggest that global average evaporation and precipitation may increase by 3 to 15 percent for an equivalent doubling of atmospheric carbon dioxide concentration. The greater the warming, the larger these increases.

Over the last two decades, improvements in modeling of the climate have begun to permit more realistic estimates to be made of regional evaporation and precipitation patterns. Increases in precipitation are expected to occur more consistently and intensely throughout the year at high latitudes. With a doubling of atmospheric CO_2 concentrations, models show moister atmospheres (i.e., increases in specific humidity), and greater precipitation in high latitudes and tropics throughout the year and in mid-latitudes in winter. In many of the model estimates, summer rainfall decreases slightly over much of the northern mid-latitude continents. Other changes in mid-latitudes remain highly variable and ambiguous. Information on changes in precipitation in subtropical arid regions is very scanty but even small changes in these arid zones can have significant implications for ecological and human systems. While the intensity of precipitation is very important for water management, little is known about how extremes might change.

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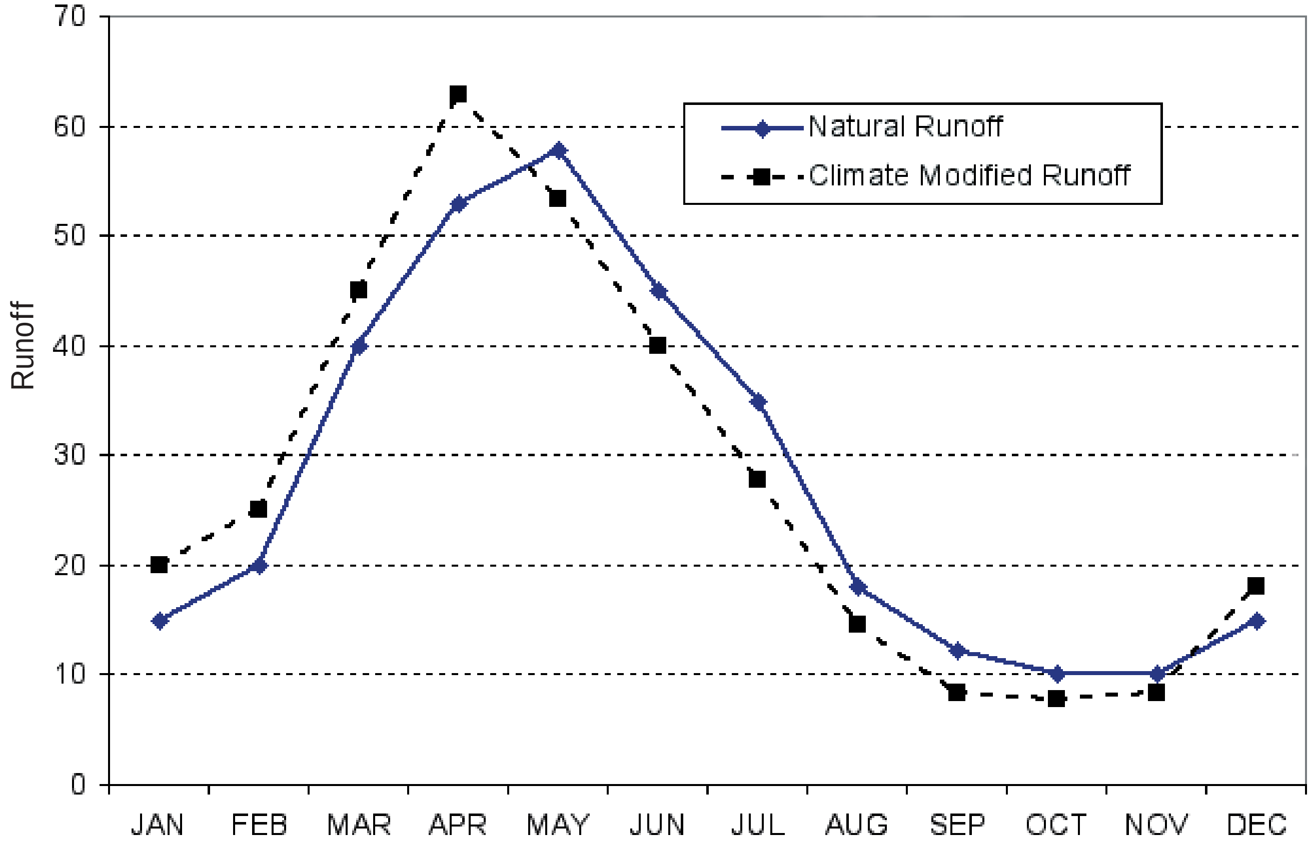
5.2.2 Changes in Snowfall and Snowmelt

One of the most important hydrologic impacts of climatic change will be snowfall and snowmelt changes in high-altitude watersheds or areas with strong snowmelt runoff characteristics. In these watersheds, changes in temperature are expected to lead to important changes in water availability and quality and complicate the management of reservoirs and irrigation systems.

In basins with substantial snowfall and snowmelt, temperature increases will have three effects. They increase the ratio of rain to snow in cold months, they decrease the overall duration of snowpack season, and they increase the rate and intensity of warm season snowmelt. As a result of these three effects, average winter runoff and average peak runoff increase, peak runoff occurs earlier in the year, and there is a faster and more intense drying of warm-season soil moisture. Because of these effects, far more attention needs to be paid in some regions to the risk of floods, rather than droughts. One of the greatest concerns about the effect of higher temperatures is, therefore, the increased probability and intensity of flood flows. Earlier snowmelt will also have implications for reservoir storage capacity and operation, and for the availability of stored water for domestic and agricultural use

Figure 11: Hypothetical Natural And Modified Average Hydrograph For Basins With Snowfall And Snowmelt



Source: Gleick (2000)

later in the year. Figure 11 shows how a hypothetical hydrograph may change as temperatures changes snowfall and snowmelt dynamics in a watershed.

5.2.3 Variability, Storms, and Extreme Events

The climate varies naturally on all time-scales because of processes internal (such as ocean dynamics) and external (such as solar variability) to the climate system. These processes will continue to exert an important influence on the climate system even as changes induced by rising concentrations of greenhouse gases are felt. Existing variability of climate has profound impacts on humans, primarily through the costs of flood and drought events or through the cost of implementing options and building infrastructure to prevent them. In recent years there have been new efforts to understand how natural patterns of variability, such as El Niño, affect water resources.[50] This research consistently notes that the hydrological "baseline" used by water planners and systems designers cannot be assumed to be constant, even without climate changes. It also helps to identify vulnerabilities of existing systems to hydrologic extremes and provides information that should be useful to those interested in the issue of adaptation and coping.

As CO_2 and other trace gas levels change and circulation of the atmosphere adjusts, storm frequency and intensity may change as well. The connection between elevated greenhouse gas concentrations and variability is inadequately studied and the few available results should be considered speculative. There are some model studies that suggest that the variability (as measured, for example, by the interannual standard deviation) of the hydrologic cycle increases when mean precipitation increases and vice-versa. In one model study, the total area over which precipitation fell decreased, even though global mean precipitation increased, implying more intense local storms and, perhaps, increased runoff as well.[51] A study released in 1999 suggests that the frequency of El Niño events may increase due to greenhouse warming.[52] In particular, their results reveal a world where the average condition is like the present-day El Niño condition in that events typical of El Niño will become more frequent. The model also showed a stronger interannual variability, meaning that year-to-year variations may become more extreme under enhanced greenhouse conditions. More frequent or intense El Niños could alter precipitation and flooding patterns in many regions.

Some model projections of CO_2-forced climate change suggest that storms in a climate-changed world should, on average, be fewer in number, weaker in intensity, and be displaced northward in position. Enhanced warming at high latitudes near the surface may lead to reduced meridional temperature gradients in the lower troposphere and hence fewer storms. In contrast, more warming at the surface than aloft and a wetter atmosphere arising from increased latent heating should result in reduced atmospheric stability, increased convection, and a more vigorous hydrologic cycle, which might support more storms and perhaps more intense storms as well.[53] Some other model studies have suggested that higher CO_2 levels might produce more intense storm events.[54]

These conflicting conclusions are consistent with the 1996 IPCC summary "In the few analyses available, there is little agreement between models on the changes in storminess that might occur in a warmed world. Conclusions regarding extreme storm events are obviously even more uncertain." These contradictory results support the need for higher spatial resolution models with better cloud processes. Progress in such efforts should be regularly revisited in later assessments.

5.2.4 Snowpack, Glaciers, and Permafrost

Snow accumulation is an important source of runoff and water supply in many parts of the world. Despite all of the uncertainties about how increased greenhouse gas concentrations may affect precipitation, there is very high confidence that higher temperatures will result and, as discussed in the following section, are likely already occurring. The greatest increases in temperature are expected to be in higher latitude regions because of the dynamics of the atmosphere and feedbacks among ice, albedo, and radiation. A growing amount of research has established that higher temperatures will lead to dramatic changes in the snowfall and snowmelt dynamics in mountainous watersheds. Higher temperatures will have several major effects: they will increase the ratio of rain to snow, delay the onset of the snow season, accelerate the rate of spring snowmelt, and shorten the overall snowfall season, leading to more rapid and earlier seasonal runoff. They can also lead to significant changes in the distribution of permafrost and the mass balances of glaciers.

As early as the mid-1980s and early 1990s, regional hydrologic modeling of global warming impacts suggested with increasing confidence that higher temperatures will affect the timing of runoff in these regions and studies have now shown that all watersheds with significant snow dynamics are likely to be affected.[55] Indeed, over the past two decades, this has been one of the most persistent and well-established findings on the impacts of climate change for water resources.

Other regional effects are important to note. Alaska, Canada, Greenland, Siberia, Scandinavia, and other high latitude regions have extensive glaciers and permanently frozen soil (permafrost). Global warming will have direct and indirect impacts on these resources. Davidovich and Ananicheva simulated the behavior of Alaskan glaciers under temperature increases and concluded that they will experience significant retreat but also an increase in mass due to increased winter snow accumulation.[56] This result is similar to that of Oerlemanns et al. who showed in a mass balance of 12 valley glaciers and ice sheets that most climate-change scenarios lead to glacial retreat.[57] In the absence of any change in precipitation, a temperature rise of 0.4 degrees C per decade would virtually eliminate all twelve glaciers by 2100. Even a 0.1 degree C increase per decade led to reductions in glacier volume of 10 to 25 percent.

Thawing of permafrost in interior regions will increase rates of soil moisture infiltration and the amount of water stored in aquifers and the active layer of the soil. This will generally result in decreased flood peaks and increased base level runoff. The reduction of peak flow caused by increased infiltration of rain into the aquifer is likely to be offset, however, by increased frequency and quantity of precipitation. Similarly, the increase in base-level flow may be offset by increased rates of evapotranspiration and by decreasing volumes of melt water from glaciers. Base level flow reductions associated with recession of glaciers will be most severe in basins with small glaciers that disappear during a warmer climate.

H.D. Nygren / www.noaa.gov

A range of other impacts in the high latitudes is also possible. As glaciers become smaller, flow variability may increase, with reductions in the reliability of hydro power generation. Base flows in summer are also critical to transportation – higher base flows mean longer shipping seasons. Increased winter base flow under warmer climate may increase icing along roads, streams, and culverts, increasing maintenance costs. As permafrost thaws, water tables under hills retreat and wells may have to be drilled deeper or in new locations. Loss of permafrost has already led to subsidence and damage to roads requiring extensive and expensive road repairs in Alaska.[58] Less extensive permafrost, increased depth to the water table, and increased groundwater fluxes will enhance the performance of sewage disposal systems that discharge to the subsurface. Increased stream flow and decreased ice cover will enhance aeration and dilution of surface-discharged effluent.

5.2.5 Runoff

Changes in future runoff depend on changes in a wide range of factors, most notably precipitation and temperature. These climatic variables have a direct effect on runoff from surface systems. Many different approaches have been used to evaluate possible impacts to runoff, but great uncertainties remain about specific regional results because of uncertainties in how regional precipitation will change.

In most model studies, the changes in runoff resembled the overall nature of the changes in precipitation, in large part because precipitation is the primary factor in determining runoff, with increased flows in higher latitude regions and decreases in sub-tropical areas. Significantly higher temperatures coupled with small increases in precipitation can lead to reductions in regional runoff, while smaller temperature increases and large increases in precipitation can lead to large runoff increases. Several different conclusions can be drawn from these results. First, the great differences in results show the difficulty of making accurate "predictions" of future runoff – regional results should be viewed with considerable caution. Second, runoff is extremely sensitive to climatic conditions. Significant increases in precipitation will probably lead to increases in runoff: such increases can either worsen or lessen water management problems, depending on the region and the nature of the problem. Third, far more work is needed, on a regional scale, to understand how climate will affect water resources.[59] Until the large-scale climate models can provide better and more consistent projections of regional changes in temperature and precipitation, they will be of limited value to water planners, who would like more specific information as to the direction of the climate-induced changes in water supplies.

Many more detailed estimates of changes in runoff due to climate change have been produced using regional hydrologic models of specific river basins.[60] By using anticipated, hypothetical, or historical changes in temperature and precipitation and models that include realistic small-scale hydrology, modelers suggest with high confidence that some significant changes in the timing and magnitude of runoff will result from quite plausible changes in climatic variables. With some exceptions, however, there is little confidence in specific regional forecasts. Human and natural ecosystems are highly dependent upon river flows and any changes caused by the greenhouse effect would be cause for concern. Specific regional impacts will depend on both the future climate changes as well as the economic, institutional, and structural conditions in any region.

In arid and semi-arid regions, it is well established that relatively modest changes in precipitation can have proportionally large impacts on runoff. Even in the absence of changes in precipitation patterns, higher temperatures resulting from increased greenhouse gas concentrations lead to higher evaporation rates, reductions in streamflow, and increased frequency of droughts.[61] In such cases, increases in precipitation would be required to maintain runoff at historical levels.

In cold and cool-temperate zones, which are found in most mid- to high-latitude areas and large areas of mountains, a major proportion of annual runoff comes from spring snowmelt. The major effect of warming in these regions is a change in the timing of streamflow, including both the intensity and timing of peak flows. A declining proportion of total precipitation falls as snow as temperatures rise, more winter runoff occurs, and remaining snow melts sooner and faster in spring.

Shifts in runoff timing in basins with snowfall and snowmelt have been found in all studies that looked at daily or monthly runoff. These studies show with high confidence that increases in winter runoff, decreases in spring and summer runoff, and higher peak flows will occur if temperatures rise. Because the temperature projections of the GCMs are more certain than the impacts on precipitation, temperature-induced shifts in the relative amounts of rain and snow and in the timing of snowmelt in mountainous areas are considered highly likely.

There is also a risk of increased flooding. The authors of the 1995 IPCC report conclude that the "flood related consequences of climate change may be as serious and widely distributed as the adverse impacts of droughts."

> "there is more evidence now that flooding is likely to become a larger problem in many temperate regions, requiring adaptations not only to droughts and chronic water shortages, but also to floods and associated damages, raising concerns about dam and levee failure." [62]

Ironically, some regions may experience increases in both droughts and floods if climate becomes more variable. In the western United States, for example, where winter precipitation falls largely as snow, higher temperatures will increase the amount of rain and decrease the amount of snow, contributing to high winter and spring runoff — the period of time when flood risk is already highest. At the same time, summer and dry-season runoff will decrease because of a decline in snowpack and accelerated spring melting.

5.2.6 Soil Moisture

Soil moisture is a crucial hydrologic variable of particular interest to ecologists and farmers. Precipitation, that does not evaporate back into the atmosphere, transpires immediately from vegetation and is captured by humans for direct use, or runs off into rivers, lakes, or the ocean infiltrating the soil, where part of it may filter down to groundwater. The amount of water stored in the soils is influenced by vegetation type, soil type, evaporation rates, and precipitation intensity. Soil moisture is critically important in both supporting agricultural production and defining natural vegetative type and extent. Any changes in climate that alter precipitation patterns and the evapotranspiration regime will directly affect soil-moisture storage, runoff processes, and groundwater recharge dynamics. In regions where precipitation decreases, soil moisture may be significantly reduced. Even in regions with precipitation increases, soil moisture on average or over certain periods may still drop if increases in evaporation owing to higher temperatures are even greater or if the timing of precipitation or runoff changes. Where precipitation increases significantly, soil moisture is likely to increase, perhaps by large amounts.

5.2.7 Lake Levels And Conditions

While most research has focused on rivers and runoff, some studies have looked at the impacts of climate change on lakes. Lakes are known to be sensitive to a wide array of changes in climatic conditions: variations in temperature, precipitation, humidity, and wind conditions can alter evaporation rates, the water balance of a basin, ice formation and melting, and chemical and biological regimes.[63]

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Closed (endorheic) lakes are extremely sensitive to the balance of inflows and evaporative losses. Even small changes in climate can produce large changes in lake levels and salinity.[64]

In work done on the impacts of climate changes on the Great Lakes, including Lake Erie, lake levels were forecast to drop under several GCM-generated scenarios, decreasing hydropower revenues, increasing navigation costs, reducing cold-water fish habitat, and reducing the costs of flooding and shoreline erosion.[65] Climate change causes lake ice cover to decrease or even disappear entirely. Ice-free boundaries shift northward. Summer lake temperatures increase, leading to inhibited mixing of thermal layers. Higher evaporation and changes in precipitation lead to changes in net moisture depending on the model used.

Other effects of increased temperature on lakes were higher thermal stress for cold-water fish, higher trophic states leading to increased productivity and lower dissolved oxygen, degraded water quality, increased summer anoxia, and a loss of productivity in boreal lakes. Among the effects of loss of ice cover were increased growth of warm-water fish (though productivity may be curtailed by lack of food supply) and decreased winter anoxia. Decreases in lake levels coupled with decreased flows from runoff and groundwater may exacerbate temperature increases and loss of thermal refugia and dissolved oxygen. Increased net evaporation may increase salinity of lakes. Researchers also note that climate variability may amplify or offset changes in the mean state under climate changes and may ultimately be more important that changes in average conditions.[66]

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5.2.8 Groundwater

Groundwater accounts for a substantial fraction of global freshwater use. In some areas of the U.S., northern China, India, Mexico, and elsewhere, current levels of groundwater use are already unsustainable.[67] Declining aquifer levels and higher pumping lifts have increased water costs. Groundwater overdrafts in coastal areas of the world have led to saltwater intrusion into the aquifers. Very little work has been done on the impacts of climate changes for specific groundwater basins, or for general groundwater recharge characteristics or water quality. Recharge and withdrawal rates are relatively balanced in some watersheds and any decrease in recharge rates could have a major effect on the long-term sustainability of a basin. Aquifers are replenished by rainfall above the rate of evaporation and where soils are sufficiently saturated to permit additional storage to flow into subsurface basins. Changes in recharge will result from changes in effective rainfall as well as a change in the timing of the recharge season. Increased winter rainfall, expected for some mid-continental, mid-latitude regions could lead to increased groundwater recharge. Actual recharge will also depend on the period over which soils are frozen. Higher temperatures could increase the period of infiltration. Higher evaporation or shorter rainfall seasons, on the other hand, could mean that soil deficits persist for longer periods of time, shortening recharge seasons.[68]

A study of a semi-arid basin in Africa concluded that a 15 percent reduction in rainfall could lead to a 45 percent reduction in groundwater recharge.[69] Similar sensitivities were seen in two studies of the effects of climate changes on groundwater in Australia, where proportionally larger decreases in groundwater levels were seen for a given reduction in precipitation.[70] Groundwater-streamflow interactions under conditions of climate change were studied in a mountainous basin in central Greece and large impacts were seen in spring and summer months because of temperature-induced changes in snowfall and snowmelt patterns.[71] Sea-level rise will affect groundwater aquifers and coastal ecosystems. Rising sea level will cause an increase in the intrusion of salt water into coastal aquifers, depending on the groundwater gradients and pumping rates. Shallow aquifers are at greatest risk, together with aquifers supporting large amounts of human use.

5.2.9 Direct Effects On Ecosystems

As described in Section 3, ecosystems are fundamentally dependent on water resources: healthy ecosystems depend on receiving appropriate amounts of water, of certain quality, at certain times. The composition of ecosystems depends on climatic conditions such as temperature, precipitation, and storm patterns. Humans, in turn, are dependent upon ecosystem processes: for example, primary productivity and inputs from watersheds support food webs, yielding fish for commercial and recreational purposes; and decomposition and biological uptake removes organic materials and nutrients, purifying water. Ecosystem processes are affected by temperature and flow regimes and will be affected by changes in climatic conditions.[72]

The direct effects of climate change on ecosystems will be complex, depending on the nature of the change, the system affected, and the nature and scope of intentional interventions by humans. Previous assessments have established a wide range of possibly severe impacts, including changes in the mix of plant species capable of thriving in a region, lake and stream temperatures, lake levels, mixing regimes, declining wetlands area, water residence times, water clarity, possible extinction of endemic fish species, thermocline depth and productivity, invasions of exotic species, fire frequency, permafrost melting, altered nutrient exchanges and food web structure, and more.[73]

Researchers express concern not only for the actual impacts of climate change, but for the limited ability of natural ecosystems to adapt or cope with those changes over the short time frame in which the impacts are likely to occur. This limited ability to adapt may lead to irreversible impacts such as extinctions. While some research has been done on these issues, far more is needed.

5.2.10 Other Impacts

Climate change will have many other effects on water resources, including effects on hydroelectric generation, direct and indirect impacts on human health and water quality, navigation and shipping, agriculture, and water quality. Climate changes can affect the viability of disease vectors like mosquitoes or the viability and transport of water-borne pathogens like Cryptosporidium. Cryptosporidium has been responsible for an increasing number of drinking water advisories in developed nations in recent years and led to more than 100 deaths and 400,000 illnesses in Milwaukee in 1993. Hantavirus, a disease spread by deer mice, has been linked to ENSO related climatic variability. Higher rainfall has led to increased rodent populations and increases in contact between humans and rodents. The distribution of Vibrio cholerae, the bacteria responsible for cholera, is affected by climatic conditions, including El Niño, temperature, and ocean salinity.[74] Over 740,000 cases of dengue fever were reported for 1998 by Pan American Health Organizations countries, more than twice the total for 1997. Efforts are just beginning to explore the complex connections among climate, water, and human health.

Water-borne shipping is an important means of transportation for certain regions and industries. River and lake navigation and shipping are sensitive to flows, water depth, ice formation, and other climatic factors. A warming would increase the potential length of the shipping season on some northern lakes and rivers that typically freeze in winter. Decreases in river flows would reduce the periods when navigation was possible, increase transportation costs, or increase the conflicts over water allocated for other purposes.

The quality of water resources can be as important or even more important than water quantity. Water quality affects natural ecosystems, human health, and economic activities. At the same time, human activities directly affect water quality. Global climate changes will have a wide range of effects on the quality of freshwater systems by changing temperatures, flows, runoff rates and timing, and the ability of watersheds to assimilate wastes and pollutants. Higher flows of water could reduce pollutant concentrations or increase erosion of land surfaces and stream channels, leading to higher sediment, chemical, and nutrient loads in rivers.

Changes in storm flows will affect urban runoff, which already has adverse water quality impacts on discharges to the oceans. Lower flows could reduce dissolved oxygen concentrations, reduce the dilution of pollutants, and increase zones with high temperatures. For almost every body or source of water, land use and agricultural practices have a significant impact on water quality. Thus, changes in these practices, together with technical and regulatory actions to protect water quality, can be critical to future water conditions. The net effect on water quality for rivers, lakes, and groundwater in the future thus depends not just on how climatic conditions might change but also on a wide range of other human actions. Some of these impacts have been evaluated in the IPCC assessments, but more work is needed.

5.2.11 Socioeconomic Costs and Benefits of Changes in Water Supply and Demand

All of the physical, ecological, and institutional impacts of climate change will entail social and economic costs and benefits. On top of the uncertainties described above in evaluating both climate changes and potential impacts, evaluating the economic implications of the diverse impacts is fraught with difficulties, and few efforts to quantify them have been made. Ultimately, however, efforts to comprehensively evaluate costs will be necessary in order to help policymakers and the public understand the implications of both taking and not taking actions to either reduce the impacts of climate change or adapt to the changes that will come.

Several steps are needed to evaluate socioeconomic effects of climate change. First, estimates of the nature and magnitude of the impacts of climate change are necessary. Second, these impacts need to be put into common units, typically monetary, with a comprehensive discussion of the limits of doing so. Third, the costs of taking various actions must be evaluated, together with the effects of options to reduce expected impacts.

The socioeconomic impacts of a greenhouse warming look very different depending on which projections are used. Some researchers have argued that the effects of climate change on municipal and industrial water use will generally be small compared with the expected rates of growth of water use, but in the U.S. new research is beginning to suggest the opposite may be true. The impacts of climate change could in some cases exceed, sometimes significantly, impacts due to demographic and economic changes.[75] While climate impacts on water use could be large in some areas, research to date indicates that climate-induced changes in demands would mostly be modest compared to changes in water supplies. Some water-scarce regions could benefit from increased precipitation and runoff while others are forced to adjust to less water. Water abundant areas might suffer from further increases in runoff but benefit from reductions.

5.3 Coping and Adaptation

Climate change is just one of a number of factors putting pressure on the hydrological system and water resources. Population growth, changes in land use, restructuring of the industrial sector, and demands for ecosystem protection and restoration are all occurring simultaneously. Current laws and policies affecting water use, management, and development are often contradictory, inefficient, or unresponsive to changing conditions. In the absence of explicit efforts to address these issues, the societal costs of water problems are likely to rise as competition for water grows and supply and demand conditions change. There are many opportunities for reducing the risks of climatic variability and change for water resources. We note the applicability here of the precautionary approach taken in many international agreements, including the United Nations Framework Convention on Climate Change:

> "Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures … should be cost-effective so as to ensure global benefits at the lowest possible cost."[76]

Water managers have a long history of adapting to changes in supply and demand. Their efforts have largely focused on minimizing the risks of natural variability and maximizing system reliability.

Tools for achieving these goals have traditionaly included supply-side options such as new dams, reservoirs, and pipelines, but demand-side options, such as improving efficiency, modifying water-use processes, or changing land use practices, are receiving increasing attention. This work is going on largely independent of the issue of climate change, but it will have important implications for the ultimate severity of climate impacts. Among the new tools water agencies and managers are exploring are (1) incentives for conserving and protecting supplies, (2) opportunities for transferring water among competing uses in response to changing supply and demand conditions, (3) economic changes in how water is managed within and among basins, (4) evaluating how "re-operating" existing infrastructure can help address possible changes, and (5) new technology to reduce the intensity of water use to meet specific goals.

5.3.1 Water Planning and Management

Decisions about long-term water planning, the design and construction of new water-supply infrastructure, the type and acreage of crops to be grown, urban water allocations and rate structures, reservoir operation, and water-supply management all depend on climatic conditions and what humans do to respond and adapt to those conditions. In the past, these decisions relied on the assumption that future climatic conditions would have the same characteristics and variability as past conditions, and U.S. water-supply systems were designed with this assumption in mind. Dams are sized and built using available information on existing flows in rivers and the size and frequency of expected floods and droughts. Reservoirs are operated for multiple purposes using the past hydrologic record to guide decisions. Irrigation systems are designed using historical information on temperature, water availability, and soil water requirements.

This reliance on the past record now may lead us to make incorrect – and potentially dangerous or expensive – decisions. Given that risk, one of the most important coping strategies must be to try to understand what the consequences of climate change will be for water resources and to begin planning for those changes. The academic community has advocated this position for a decade. An earlier two-year study by the Climate and Water Panel of the American Association for the Advancement of Science on the implications of global climate changes for the water resources of the United States concluded:

> "Among the climatic changes that governments and other public bodies are likely to encounter are rising temperatures, increasing evapotranspiration, earlier melting of snowpacks, new seasonal cycles of runoff, altered frequency of extreme events, and rising sea level...*Governments at all levels should reevaluate legal, technical, and economic procedures for managing water resources in the light of climate changes that are highly likely.*" [Italics in original.] [77]

The Second World Climate Conference concluded in 1991 that:

> "The design of many costly structures to store and convey water, from large dams to small drainage facilities, is based on analyses of past records of climatic and hydrologic parameters. Some of these structures are designed to last 50 to 100 years or even longer. *Records of past climate and hydrological conditions may no longer be a reliable guide to the future. The design and management of both structural and non-structural water resource systems should allow for the possible effects of climate change.*" (Italics added) [78]

Similarly, the IPCC urged water managers to begin "a systematic reexamination of engineering design criteria, operating rules, contingency plans, and water allocation policies" and states with "high confidence" that "water demand management and institutional adaptation are the primary components for increasing system flexibility to meet uncertainties of climate change." [79] This emphasis on planning and demand management rather than construction of new facilities marks a change in traditional water-management approaches, which in the past have relied on the construction of large and expensive infrastructure.

In 1997, the American Water Works Association, the largest professional association of water utilities and providers in the United States, published a set of recommendations from its Public Advisory Forum.[80] Among the recommendations to water managers were the following:

- While water management systems are often flexible, adaptation to new hydrologic conditions may come at substantial economic costs. Water agencies should begin now to re-examine engineering design assumptions, operating rules, system optimization, and contingency planning for existing and planned water-management systems under a wider range of climatic conditions than traditionally used.
- Water agencies and providers should explore the vulnerability of both structural and non-structural water systems to plausible future climate variability, not just past climatic variability.
- Governments at all levels should re-evaluate legal, technical, and economic approaches for managing water resources in the light of possible climate changes.
- Cooperation of water agencies with the leading scientific organizations can facilitate the exchange of information on the state-of-the-art thinking about climate change and impacts on water resources.
- The timely flow of information from the scientific global change community to the public and the water-management community would be valuable. Such lines of communication need to be developed and expanded.

One of the main implications of climate changes for water management is a shift toward improved decision-making under uncertainty and flexible management approaches.

5.4 Climate Summary

As the new century begins, the public, water planners and managers, and policymakers face many challenging factors. Changes in population, economic conditions, technology, policies, and the relative values of society will be important determinants of future water supply and demand. On top of these complexities, human-induced changes in

Sidebar 2: The Dublin Principles

In January 1992, 500 representatives from 100 countries and 80 international and non-governmental organizations met in Dublin, Ireland to prepare for the Earth Summit in Rio de Janeiro in June 1992. At the closing session of the Dublin Conference (the "International Conference on Water and the Environment (ICWE)), the participants adopted the "Dublin Statement." That statement offered specific recommendations and activities based on four guiding "principles" – now called the Dublin Principles. The Dublin Principles state that:

- "Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment.
- Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels.
- Women play a central part in the provision, management and safeguarding of water.
- Water has an economic value in all its competing uses and should be recognized as an economic good."

For the full text of the Dublin Statement, see http://www.wmo.ch/web/homs/icwedece.html.

our basic climatic conditions must also be taken into account. More than twenty years of research and more than a thousand peer-reviewed scientific papers have firmly established that a greenhouse warming will alter the supply and demand for water, the quality of water, and the health and functioning of aquatic ecosystems.

The detailed nature of future climate changes and their impacts remain uncertain. These uncertainties are obstacles to introducing climate impacts into investment or operational decisions. The first line of defense for protecting water resources must therefore be a strong and consistent research and monitoring program to continue to evaluate climate-related risks. Where climate changes are minor or where other factors dominate, the impacts on water resources may be low. In some regions and for some issues, climate changes may even reduce the risks imposed by growing populations, industrialization, and land-use changes.

A growing body of evidence, however, shows that water resources are sensitive to both climate and to how these complex water systems are managed. In many cases and in many locations, there is compelling scientific evidence that climate changes will impose serious challenges on water systems. Of particular concern are climate changes that cause impacts that are larger than other expected changes, different in nature than expected changes, or imposed on top of existing long-term challenges. In these instances, the marginal economical, ecological, and social costs to society could be substantial.

The world has made an enormous investment in dams, reservoirs, aqueducts, water treatment facilities, and other concrete structures. Other parts of the world depend on the vagaries of the hydrologic system – on rains that may or may not come. The relative socioeconomic and environmental impacts of both climatic and non-climatic impacts on the supply and demand for water will depend in large part on the ability to foresee major changes, to adapt to such changes, to be flexible in the face of probable surprises, and to be innovative in the management and allocation of water.

6 Summary: Early Warnings

Of Future Threats

Moving toward a better understanding of sustainable water use requires first and foremost a new dialogue on the ultimate ends to be served by water management. In the past, an official water-related goal might have been to expand irrigation by a certain area over a five-year period. Behind this target, however, is the more fundamental aim of food security, which can be met in a variety of ways — some of which include expanding irrigation, and some of which do not. Thus a key aspect of moving toward sustainable resource use is to shift from the water supply expansion or growth approach to one that focuses on ultimate ends and the alternative ways of achieving them.

In addition, twentieth century water planning has been preoccupied almost exclusively with supporting increasing levels of economic and agricultural development. It has given relatively little attention to issues of equity and the water needs of the poor, to the health of the aquatic environment, to the integrity of communities and cultures, and to the welfare of future generations. Although not always clearly defined, the concept of sustainability embodies an ethic that embraces resource efficiency, distributional equity (among present and future generations), ecosystem protection, and public participation. And these fundamental principles, in turn, must guide water planning and policymaking for the new era that lies ahead. This new water ethic means that water policy and management decisions can no longer be made strictly by economists and engineers – a principle that echoes the second Dublin Principle (Sidebar 2). Water planning must involve a public dialogue that will address, among other things, which "needs" and "wants" can and should be satisified, how to protect the common good aspects of water (such as recreational, cultural, and community values) while supporting the local economy and jobs, and how available supplies should be allocated. It will address such questions as: How much water is needed for satisfying the domestic use of a family in a dense urban center or in a rural agricultural community? Should people be able to use as much water as they can pay for? Under what situations should water be delivered to farmers at rates below full operating and capital costs? How much water is needed to maintain environmental quality and services? How much water should be available and at what quality for the use of future generations? Only by looking ahead, anticipating future threats, and developing ways of reducing those threats, can we hope to meet our coming needs.

Identifying emerging threats to water resources is a challenging task. Surprises are always possible – even likely. Data are often missing, in error, or inaccessible. And humans have ways of confounding even the most careful assessments. Each of the problems presented here is an expression of concern about the long-term sustainable use of water: the worry that current uses of water cannot be maintained in light of future anticipated demands and growing water contamination; the continuing concern about the health implications of failing to provide basic water services to billions of people; and the growing realization that the functioning of the entire hydrologic system, as we currently understand it, is threatened by uncertain but potentially large changes in global water cycles. In this context, integrating new concerns over "sustainable development" with regional and global freshwater problems becomes a critical challenge for water policymakers and the public.

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Figure 7: Gleick (2000)

Figure 8: A.B. Avakyan and V.B. Iakovleva. 1998. Status of global reservoirs: The position in the late twentieth century.

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Figure 11: Gleick (2000)