periods. Since the atmospheric circulation is very complicated, only the general pattern can be identified.

The atmosphere is divided vertically into various zones. The atmospheric circulation described above occurs in the *troposphere*, which ranges in height from about 8 km at the poles to 16 km at the equator. The temperature in the troposphere decreases with altitude at a rate varying with the moisture content of the atmosphere. For dry air the rate of decrease is called the *dry adiabatic lapse rate* and is approximately 9.8°C/km. The *saturated adiabatic lapse rate* is less, about 6.5°C/km, because some of the vapor in the air condenses as it rises and cools, releasing heat into the surrounding air. These are average figures for lapse rates that can vary considerably with altitude. The *tropopause* separates the troposphere from the *stratosphere* above. Near the tropopause, sharp changes in temperature and pressure produce strong narrow air currents known as *jet streams* with velocities ranging from 15 to 50 m/s (30 to 100 mi/h). They flow for thousands of kilometers, and have an important influence on air-mass movement.

The oceans exert an important control on global climate. Because water bodies have a high volumetric heat capacity, the oceans are able to retain great quantities of heat. Through wave and current circulation, the oceans redistribute heat to considerable depths and even large areas of the oceans. Redistribution is east–west or west–east, and is also across the midaltitudes from the tropics to the subartic, enhancing the overall poleward heat transfer in the atmosphere. Waves are predominately generated by wind. Ocean circulation is illustrated in Figure 1.7.

Oceans have a significant effect on the atmosphere; however, an exact understanding of the relationships and mechanisms involved are not known. The correlation between ocean temperatures and weather trends and midlatitude events has not been solved. One trend is the growth and decline of a warm body of water in the equatorial zone of the eastern Pacific Ocean, referred to as El Niño (meaning "The Infant" in Spanish, alluding to the Christ Child, because the effect typically begins around Christmas). The warm body of water develops and expands every five years or so off the coast of Peru, initiated by changes in atmospheric pressure resulting in a decline of the easterly trade winds. This reduction in wind reduces resistance, causing the eastwardly equatorial countercurrent to rise. As El Niño builds up, the warm body of water flows out into the Pacific and along the tropical west coast of the Americas, displacing the colder water of the California and Humboldt currents. One of the interesting effects of this weather variation is the South Oscillation, which changes precipitation patterns—

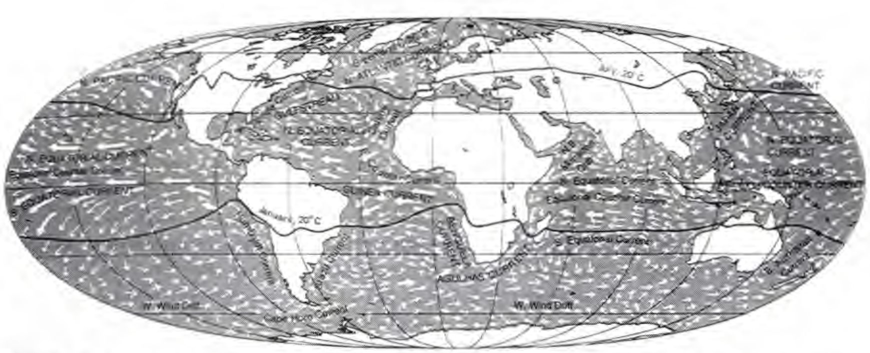


FIGURE 1.7 The actual circulation of the oceans. Major currents are shown with heavy arrows. *(Marsh, 1987.)*

resulting in drier conditions where there would normally be substantial precipitation, and in wetter conditions in areas of normally little precipitation.

1.2.5 Global Climates

The global climate must be viewed as operating within a complex atmosphere-land-ocean-ice system. Climate classification can be made in the form of a genetic classification, as that proposed by Strahler (1969). He considers the three major climates as: (1) low-latitude climates, which are controlled by equatorial and tropical air masses, (2) middle-latitude climates, which are controlled by both tropical and polar air masses, and (3) high-latitude climates, which are controlled by polar and artic air masses. These are subdivided into 15 climatic regions as shown in Fig. 1.8.

1.3 WATER IN THE EARTH ATMOSPHERE SYSTEM

1.3.1 Origin of Water

Venus, Earth, and Mars all have atmospheres with solar-forced circulations. Earth's atmosphere is made up mainly of nitrogen and oxygen, which is controlled by biological processes. The atmospheres on Venus and Mars both have carbon dioxide, controlled by abiotic processes. The clouds on each of these planets, however, have far different constituents—Venus has sulfuric acid, Earth has water, and Mars has dust.

Two classes of theories, evolutionary and genetic, have been used to explain water on Earth. Genetic theory contends that the chemical equilibrium of accreting gas and dust in the solar nebula led to the formation of solid constituents rich in hydrated minerals in Venus, Mars, and Earth. The water in these minerals, and other volatiles, were released to varying degrees over time in the formation of planetary atmospheres. The source of water was the outgassing of water vapor from the earth's interior through the extrusion of material by volcanoes and ocean upwellings over geological time. Once released from the earth's interior, the *juvenile water* condensed, because the combined temperature and pressure at the earth's surface were ideal for water to exist in liquid form. Venus and Mars had different results. Higher accretion temperatures and tectonic activities on Venus led to outgassing followed by irreversible photodissociation of any water into hydrogen, which escaped to space, and oxygen, which reacted with surface elements. Carbon dioxide created a runaway greenhouse effect, resulting in a dry surface with a temperature of 464°C (National Research Council, 1991). Outgassing on Mars has been limited by lower accretion temperatures and no tectonic activity. There is, however, evidence of surface erosion by flowing liquid, possibly water, the source of which is unknown. Mars's atmosphere is thin and cold (–53°C), which has led to seasonal polar caps of frozen carbon dioxide and the possibility of extensive frozen subsurface water (National Research Council, 1991).

The evolutionary theory contends that the planets began with similar volatiles, and that subsequent events led to their current composition. Some of these events may have even included meteorite impacts (National Research Council, 1991).

Earth probably once had a carbon dioxide atmosphere that was reduced by unique processes, such as biological processes. Probably the most unique thing about

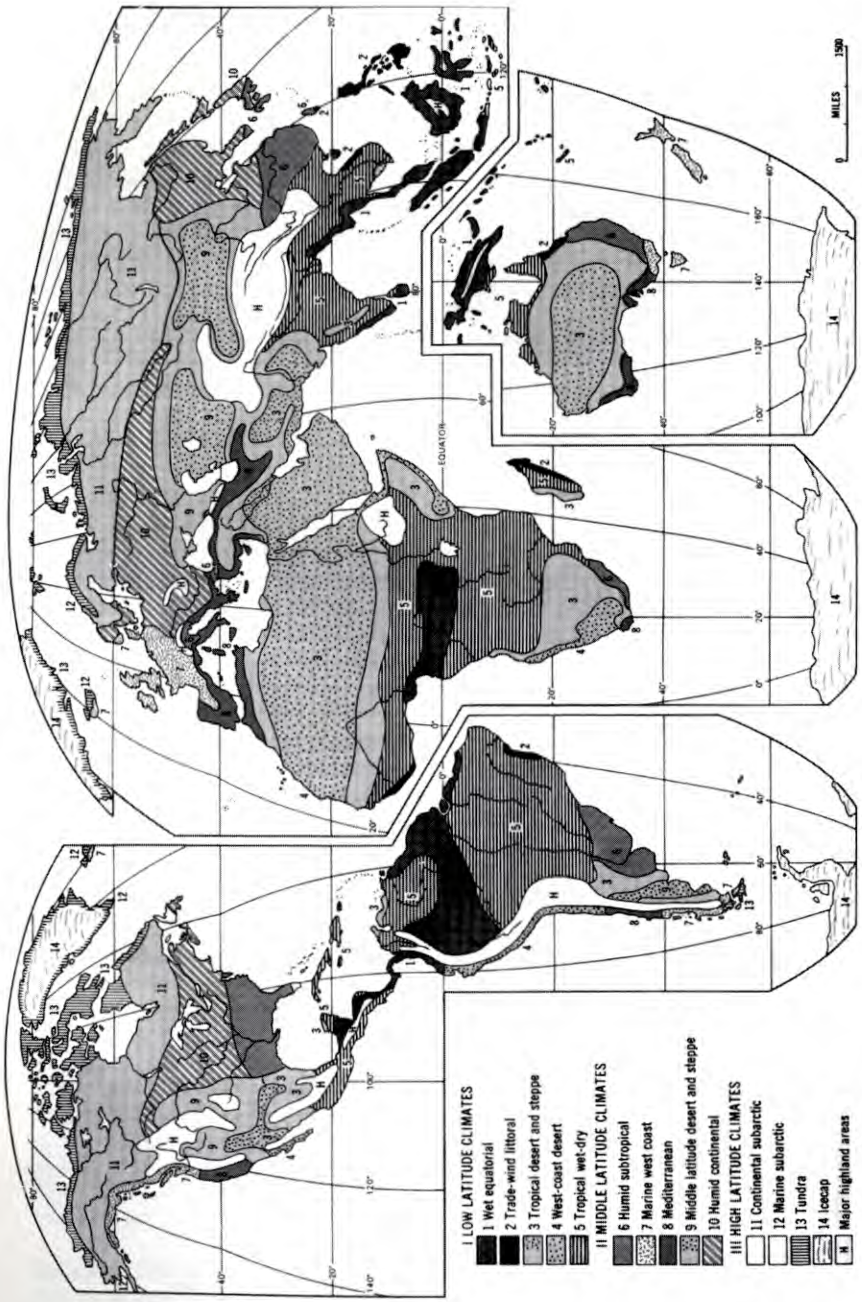


FIGURE 1.8 Simplified world map showing the distribution of Strahler's genetic climatic regions. *(Strahler, 1969.)*

the earth–atmosphere system is the ability for all three phases of water (solid, liquid, and vapor) to coexist, which is certainly unique among the terrestrial planets. Figure 1.9 illustrates the planetary positions on the phase diagram of water.

1.3.2 What Is Water?

The water molecule is a unique combination of hydrogen and oxygen atoms, with electrons being shared between them as shown in Fig. 1.10. The symmetry of the distribution of electrons leaves one side of each molecule with a positive charge, resulting in an electrostatic attraction between molecules. Water molecules can form four such relatively weak hydrogen bonds. The hydrogen, or polar, bonds of water molecules are much weaker than the covalent bonds between hydrogen and oxygen within the molecule. These polar bonds cause water molecules to cluster in tetrahedral patterns, as shown in Fig. 1.11 for ice. In the solid state, the tetrahedral arrangement of the bonding produces a tetrahedral crystalline structure. In the fluid state, increases in temperature weaken the hydrogen bonding.

Ice processes heat energy from the vibration of atoms and molecules in the fixed structure. As ice warms, the vibrations increase to the point where the tetrahedral structure breaks down and the ice melts. The molecules of the liquid phase are closer than in the solid state, as illustrated in Fig. 1.11, making water slightly more dense than ice at its melting point. Molecules of water in the liquid phase vibrate faster as temperature rises. Once the vibrations are great enough, some molecules are thrown off (or escape) the liquid surface, forming a gaseous or vapor phase, called evaporation. This evaporation consumes a large amount of energy, called *latent heat of vaporization.* The phase changes for water are: (1) *evaporation*—liquid to vapor, (2) *condensation*—vapor to liquid, (3) *sublimation*—vapor to solid or solid to vapor,

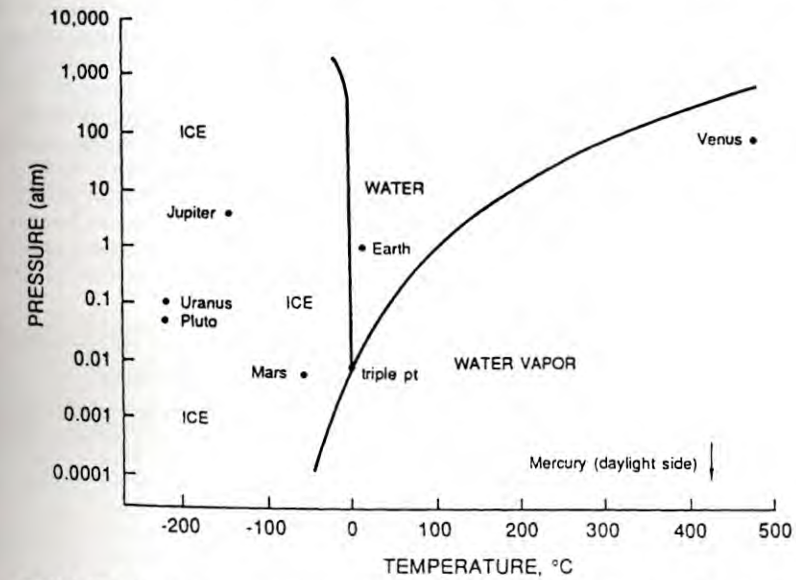


FIGURE 1.9 Planetary positions on the phase diagram of water. *(National Research Council, 1991.)*

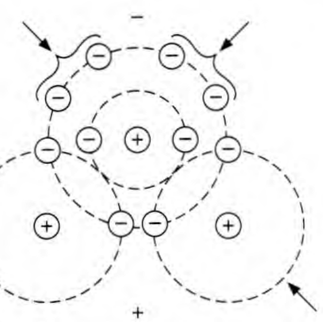


FIGURE 1.10 The Water Molecule. *(After Sutcliffe, 1968.)*

(4) melting—solid to liquid, and (5) freezing—liquid to solid.

The physical properties of water are unique compared to substances with similar molecular mass. Water has the highest specific heat of any known substance, which means that temperature change within it occurs very slowly. Water has a high viscosity and a high surface tension compared to most common liquids, which is caused by the hydrogen bonding. This produces capillary rise of water in soils and causes rain to form into spherical droplets. Physical properties of water in the solid and liquid phases vary with temperature. In these states the variation in density differs more significantly than in most liquids. Water in the gaseous phase (*water vapor*) exerts a partial pressure in the atmosphere, referred to as its *vapor pressure*. In the atmosphere above a liquid water surface, water molecules are constantly being exchanged between the air and the water. For a drier atmosphere, the rate of uptake of molecules is greater than the rate of return to the surface. At a state of equilibrium, when the number of molecules leaving the surface is equal to the number arriving, saturation of the vapor pressure of air has been reached. Additional water molecules to the air are balanced by deposition on the water surface. Table 1.2 lists some common physical constants of pure water. The latent heat of vaporization is about 8 times larger than is necessary to melt ice, and about 600 times larger than its heat capacity (the energy necessary to raise water temperature by 1°C). Evaporation is then the dominant component of energy balance in the hydrologic cycle. About 23 percent of the solar radiation reaching the earth is absorbed by evaporating water (Maidment, 1993). The latent heat of water is larger than for any other liquid.

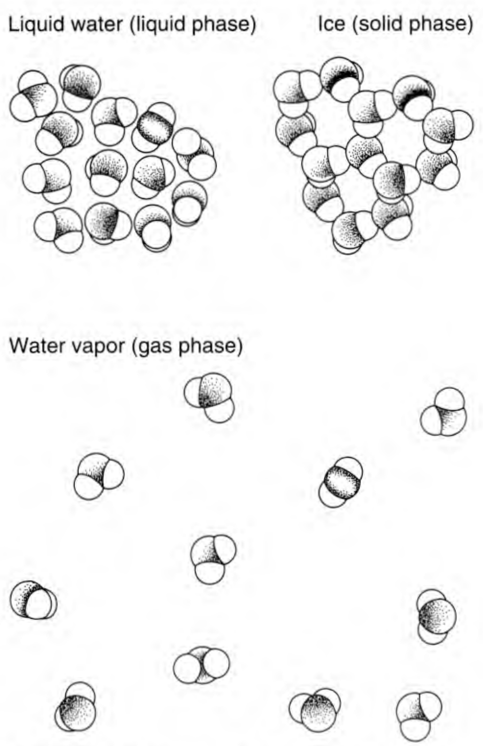


FIGURE 1.11 The three states of water. *(After Sutcliffe, 1968.)*

1.3.3 Earth's Hydrologic Cycle

The National Research Council (1991) report defines the *hydrologic cycle* as "the pathway of water as it moves in its various phases through the atmosphere, to the Earth, over and through the land, to the ocean, and back to the atmosphere" as shown in Fig. 1.12. During the cycle, which has no beginning or end, a single water molecule may assume various states, returning to the hydrologic pathway as new chemical compounds are mixed with various solid and liquid substances. As shown in the figure, water evaporates from the oceans and the land surface to become part of the atmosphere; water vapor is transported and lifted in the atmosphere until it condenses and precipitates on the land or oceans; precipitated water may be intercepted by vegetation, become overland flow over the ground surface, infiltrate into the ground, flow through the soil as subsurface flow, and discharge into streams as surface runoff. Large amounts of the intercepted water and surface runoff returns to the atmosphere through evaporation. Infiltrated water may percolate deeper to recharge groundwater, and later emerge in springs, or seepage into streams, to form surface runoff. Finally, this water may flow out to the sea or evaporate into the atmosphere. Throughout this cycle, water may take on many quality aspects.

The hydrologic cycle can also be viewed on a global scale, as shown in Fig. 1.13. Our knowledge of the amount of water in space and in the earth's mantle is very limited. There is evidence that space and the earth's mantle both exchange water with the primary crustal, ice, the atmosphere, and the ocean. The hydrologic cycle can also be viewed as a global geophysical process, as shown in Fig. 1.14. Water vapor and methane molecules are diffused into space, causing loss of the hydrogen in water. These hydrogen atoms subsequently escape by photochemistry. The addition of

TABLE 1.2 Physical Constants of Pure Water

Specific heat, 15°C	4.18 J g^{-1} deg^{-1}
Latent heat of melting	334.4 J g^{-1}
Latent heat of vaporization, 15°C	2462 J g^{-1}
Surface tension	7340 mN m^{-2} cm^{-1}
Tensile strength	1418.5 kN m^{-2} cm^{-2}
Melting point, 1013 mb	0°C
Boiling point, 1013 mb	100°C

Source: Sutcliffe, 1968.

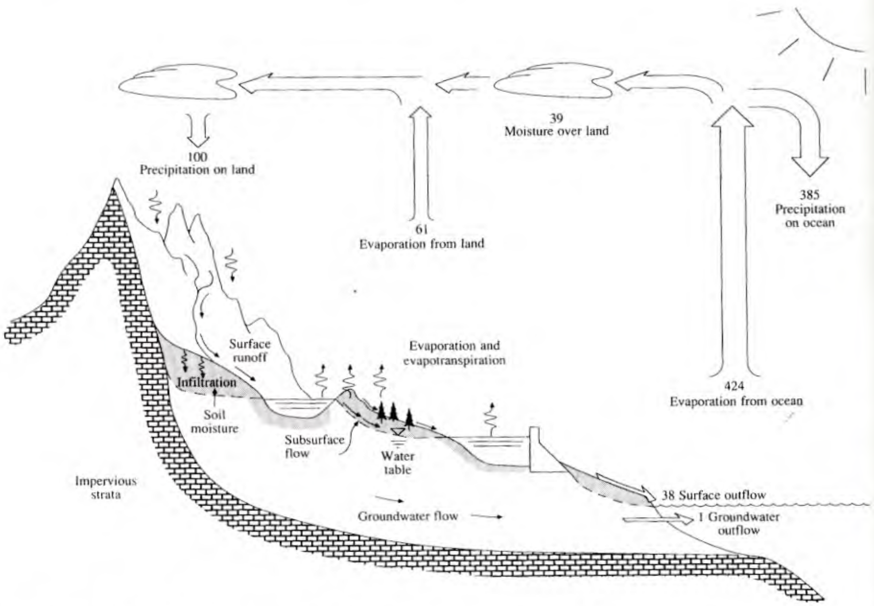


FIGURE 1.12 Hydrologic cycle with global annual average water balance given in units relative to a value of 100 for the rate of precipitation on land. *(Chow, et al., 1988.)*

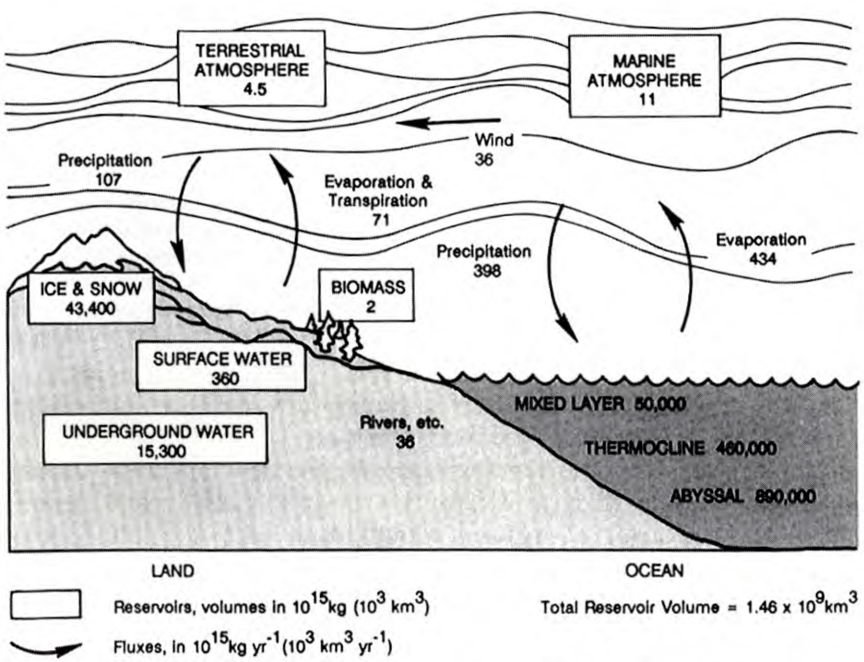
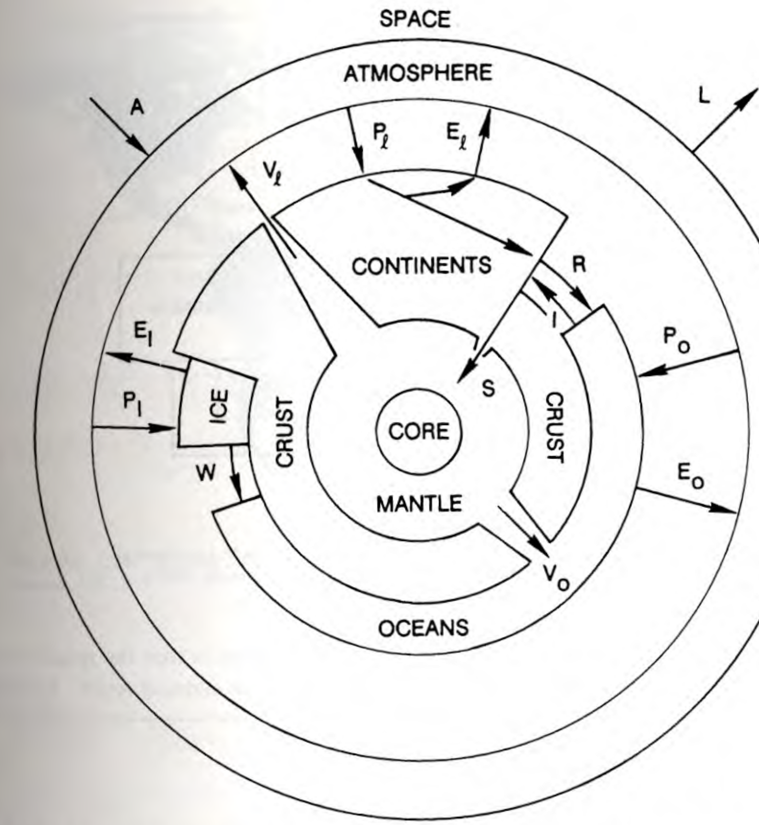


FIGURE 1.13 The hydrologic cycle at global scale *(National Research Council, 1986.)*



A	=	Additions of water from space	P_I	=	Precipitation on ice
E_o	=	Evaporation from oceans	P_ℓ	=	Precipitation on land
E_I	=	Evaporation (i.e., sublimation) from ice	R	=	Runoff from continents
E_ℓ	=	Evapotranspiration from land	S	=	Subduction of water-containing crust
I	=	Intrusion of seawater into continental aquifers	V_o	=	Volcanic venting to oceans
L	=	Loss of water to space	V_ℓ	=	Volcanic venting to atmosphere
P_o	=	Precipitation on oceans	W	=	Wastage of ice sheets to ocean

FIGURE 1.14 The hydrologic cycle as a global geophysical process. Enclosed areas represent storage reservoirs for the earth's water, and the arrows designate the transfer fluxes between them. *(National Research Council, 1991.)*

water from space is a controversial issue. Volcanic activity vents water vapor to the atmosphere and liquid vapor to the ocean. Water recirculates on a geological time scale by the subduction of water-containing crustal material.

This fascinating phenomena called the hydrological cycle is being changed by human activities. We have begun to realize the effects on nature and our environment brought about by these changes in the hydrologic cycle. This realization is changing our contemporary views of the interactive role of people in the hydrologic cycle. Figure 1.15 illustrates the classical and modern view points of the role of people in the hydrologic cycle. Human activities are an integral and inseparable part of

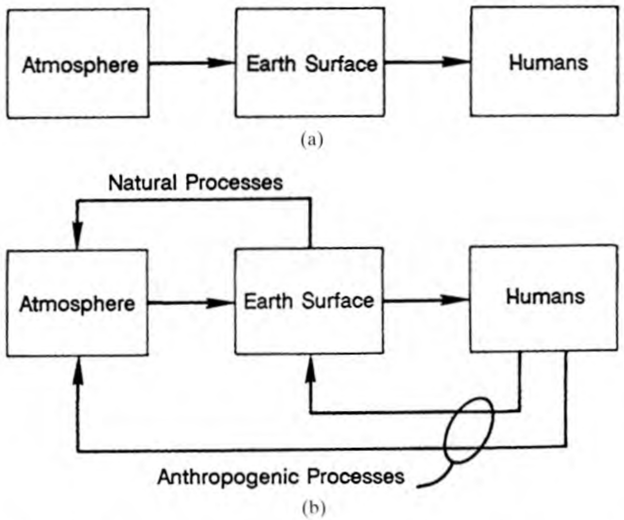


FIGURE 1.15 The role of humans in the hydrologic cycle. (*a*) classical viewpoint; (*b*) modern viewpoint. *(National Research Council, 1982.)*

the hydrologic cycle. One of our most important realizations is that the quality of water in this cycle is of as much concern as the quantity.

1.4 AVAILABILITY OF WATER ON EARTH

Figure 1.16 illustrates the variation in average annual precipitation for the world's land areas. Data on global water resources are presented in Table 1.3. The oceans contain 96.5 percent of the water on Earth, whereas freshwater reserves are only 2.53 percent (or 35 million km^3) of the total 1.384 billion km^3. A large fraction of the freshwater (24 million km^3, or 68.7 percent) is ice and permanent snow cover in the Antarctic and Arctic region. The main sources of water for human consumption, freshwater lakes and rivers, contain on the average about 90,000 km^3 of water (0.26 percent of the total global freshwater reserves). The atmosphere contains only 12,900 km^3, which is 0.001 percent of the total water, or 0.04 percent of the freshwater.

It is also of interest to review the data for annual runoff and water consumption by physiographic and economic regions of the world, as listed in Table 1.4. The total water withdrawn for use in 1990 was 9.3 percent of the total surface runoff. Unrecoverable consumptive use was 5.2 percent. By year 2000, these values could be 11.6 percent and 6.5 percent respectively (Shiklomanov, 1993).

The dynamics of actual water availability in different regions of the world is particularly interesting in understanding the water balance on Earth. As illustrated in Table 1.5, during the 30-year period from 1950 to 1980, the actual level of per capita water supply decreased rather significantly in many regions of the world, due to population increases. Significant impacts were in North Africa, North China and Mongolia, Central Asia, and Kazakhstan. In addition to the regions listed above, by year 2000 low water availability per capita is anticipated in central and southern Europe,

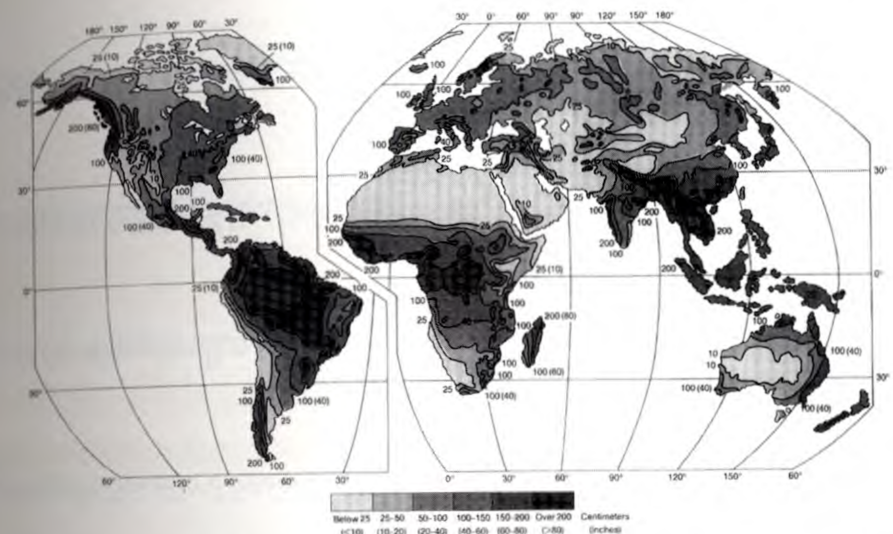


FIGURE 1.16 Average annual precipitation for the world's land areas, excepting Antarctica. *(Marsh, 1987.)*

TABLE 1.3 Water Reserves on Earth

	Distribution area, 10^3 km^2	Volume, 10^3 km^3	Layer, m	Percentage of global reserves: Of total water	Of freshwater
World ocean	361,300	1,338,000	3,700	96.5	—
Groundwater	134,800	23,400	174	1.7	—
Freshwater		10,530	78	0.76	30.1
Soil moisture		16.5	0.2	0.001	0.05
Glaciers and permanent snow cover	16,227	24,064	1,463	1.74	68.7
Antarctic	13,980	21,600	1,546	1.56	61.7
Greenland	1,802	2,340	1,298	0.17	6.68
Arctic islands	226	83.5	369	0.006	0.24
Mountainous regions	224	40.6	181	0.003	0.12
Ground ice/permafrost	21,000	300	14	0.022	0.86
Water reserves in lakes	2,058.7	176.4	85.7	0.013	—
Fresh	1,236.4	91	73.6	0.007	0.26
Saline	822.3	85.4	103.8	0.006	—
Swamp water	2,682.6	11.47	4.28	0.0008	0.03
River flows	148,800	2.12	0.014	0.0002	0.006
Biological water	510,000	1.12	0.002	0.0001	0.003
Atmospheric water	510,000	12.9	0.025	0.001	0.04
Total water reserves	510,000	1,385,984	2,718	100	—
Total freshwater reserves	148,800	35,029	235	2.53	100

Source: Shiklomanov, 1993.

TABLE 1.4 Annual Runoff and Water Consumption by Continents and by Physiographic and Economic Regions of the World

Continent and region	Mean annual runoff		Aridity index, R/LP	Water consumption, km³/yr					
				1980		1990		2000	
	mm	km³/yr		Total	Irretrievable	Total	Irretrievable	Total	Irretrievable
Europe	310	3,210		435	127	555	178	673	222
North	480	737	0.6	9.9	1.6	12	2.0	13	2.3
Central	380	705	0.7	141	22	176	28	205	33
South	320	564	1.4	132	51	184	64	226	73
European USSR (North)	330	601	0.7	18	2.1	24	3.4	29	5.2
European USSR (South)	150	525	1.5	134	50	159	81	200	108
North America	340	8,200		663	224	724	255	796	302
Canada and Alaska	390	5,300	0.8	41	8	57	11	97	15
United States	220	1,700	1.5	527	155	546	171	531	194
Central America	450	1,200	1.2	95	61	120	73	168	93
Africa	150	4,570		168	129	232	165	317	211
North	17	154	8.1	100	79	125	97	150	112
South	68	349	2.5	23	16	36	20	63	34
East	160	809	2.2	23	18	32	23	45	28
West	190	1,350	2.5	19	14	33	23	51	34
Central	470	1,909	0.8	2.8	1.3	4.8	2.1	8.4	3.4
Asia	330	14,410		1,910	1,380	2,440	1,660	3,140	2,020
North China and Mongolia	160	1,470	2.2	395	270	527	314	677	360
South	490	2,200	1.3	668	518	857	638	1,200	865
West	72	490	2.7	192	147	220	165	262	190
Southeast	1,090	6,650	0.7	461	337	609	399	741	435
Central Asia and Kazakhstan	70	170	3.1	135	87	157	109	174	128
Siberia and Far East	230	3,350	0.9	34	11	40	17	49	25
Trans-Caucasus	410	77	1.2	24	14	26	18	33	21
South America	660	11,760		111	71	150	86	216	116
Northern area	1,230	3,126	0.6	15	11	23	16	33	20
Brazil	720	6,148	0.7	23	10	33	14	48	21
West	740	1,714	1.3	40	30	45	32	64	44
Central	170	812	2.0	33	20	48	24	70	31
Australia and Oceania	270	2,390		29	15	38	17	47	22
Australia	39	301	4.0	27	13	34	16	42	20
Oceania	1,560	2,090	0.6	2.4	1.5	3.3	1.8	4.5	2.3
Land area (rounded off)		44,500		3,320	1,450	4,130	2,360	5,190	2,900

Source: Shiklomanov, 1993.

the southern European part of the former Soviet Union, Southeast Asia, and West, East, and South Africa (Shiklomanov, 1993). The very high natural nonuniformity in the distribution of water supply throughout the earth is increasing with time, as a result of the extremely rapid rate of human economic activities and population change. Data for year 2000 presented in Table 1.5 does not consider the possible anthropogenic global-scale climatic changes through the year 2000.

1.5 INGREDIENTS FOR WATER RESOURCES

The management of water resources can be subdivided into three broad categories: (1) *water-supply management,* (2) *water-excess management,* and (3) *environmental restoration.* All modern multipurpose water resources projects are designed and built for water-supply management and/or water-excess management. In fact, throughout human history all water resources projects have been designed and built for one or both of these categories. A *water resources system* is a system for redistribution, in space and time, the water that is available to a region to meet societal needs (Plate, 1993). Water can be utilized from *surface water systems,* from *groundwater systems,* or from *conjunctive/ground surface water systems.* When discussing water resources, we must consider both the quantity and the quality aspects. As pointed out earlier in this chapter, the hydrologic cycle must be defined in terms of both the water quantity and the water quality. Because of the very complex water issues and problems that we face today, many fields of study are involved in the solution of these problems. These include the biological sciences, engineering, physical sciences, and social sciences. Figure 1.17 attempts to present the wide diversity of disciplines involved in water resources.

TABLE 1.5 Dynamics of Actual Water Availability in Different Regions of the World

Continent and region	Area, 10^6 km^2	Actual water availability, 10^3 m^3/yr per capita				
		1950	1960	1970	1980	2000
Europe	10.28	5.9	5.4	4.9	4.6	4.1
North	1.32	39.2	36.5	33.9	32.7	30.9
Central	1.86	3.0	2.8	2.6	2.4	2.3
South	1.76	3.8	3.5	3.1	2.8	2.5
European USSR (North)	1.82	33.8	29.2	26.3	24.1	20.9
European USSR (South)	3.52	4.4	4	3.6	3.2	2.4
North America	24.16	37.2	30.2	25.2	21.3	17.5
Canada and Alaska	13.67	384	294	246	219	189
United States	7.83	10.6	8.8	7.6	6.8	5.6
Central America	2.67	22.7	17.2	12.5	9.4	7.1
Africa	30.10	20.6	16.5	12.7	9.4	5.1
North	8.78	2.3	1.6	1.1	0.69	0.21
South	5.11	12.2	10.3	7.6	5.7	3.0
East	5.17	15.0	12	9.2	6.9	3.7
West	6.96	20.5	16.2	12.4	9.2	4.9
Central	4.08	92.7	79.5	59.1	46.0	25.4
Asia	44.56	9.6	7.9	6.1	5.1	3.3
North China and Mongolia	9.14	3.8	3.0	2.3	1.9	1.2
South	4.49	4.1	3.4	2.5	2.1	1.1
West	6.82	6.3	4.2	3.3	2.3	1.3
Southeast	7.17	13.2	11.1	8.6	7.1	4.9
Central Asia and Kazakhstan	2.43	7.5	5.5	3.3	2.0	0.7
Siberia and Far East	14.32	124	112	102	96.2	95.3
Trans-Caucasus	0.19	8.8	6.9	5.4	4.5	3.0
South America	17.85	105	80.2	61.7	48.8	28.3
North	2.55	179	128	94.8	72.9	37.4
Brazil	8.51	115	86	64.5	50.3	32.2
West	2.33	97.9	77.1	58.6	45.8	25.7
Central	4.46	34	27	23.9	20.5	10.4
Australia and Oceania	8.59	112	91.3	74.6	64.0	50.0
Australia	7.62	35.7	28.4	23	19.8	15.0
Oceania	1.34	161	132	108	92.4	73.5

Source: Shiklomanov, 1993.

1.6 FUTURE DIRECTIONS FOR WATER RESOURCES

1.6.1 Water Development

As we approach the twenty-first century, we are questioning the viability of our patterns of development, industrialization and resources usage. We are now beginning to discuss the goals of attaining an equitable and sustainable society in the international community. Looking into the future, a new set of problems face us, including the rapidly growing population in developing countries, uncertain impacts of global climate change, possible conflicts over shared freshwater resources, thinning of the

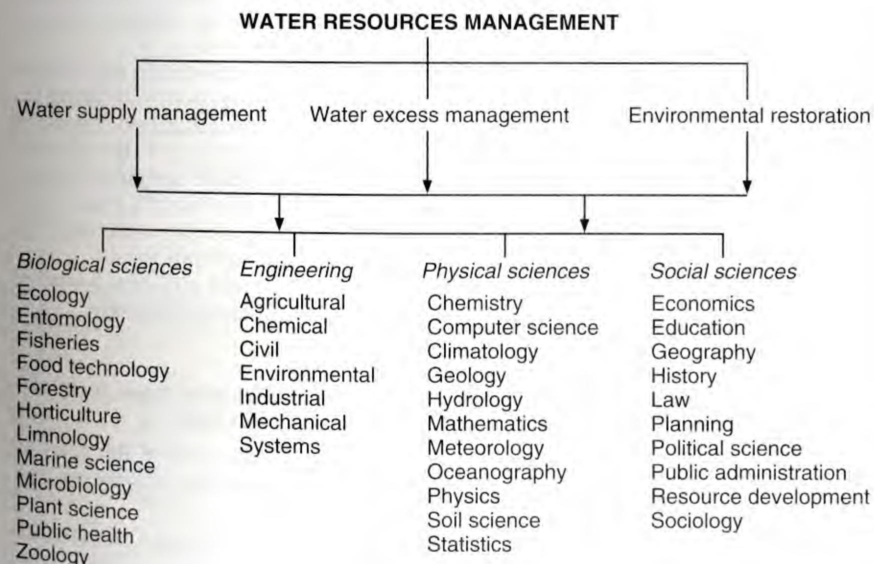


FIGURE 1.17 Ingredients for water resources management.

ozone layer, destruction of rain forests, threats to wetlands, farmland, and other renewable resources, and many others.

During the 1980s, the United Nations sponsored the International Water Supply and Sanitation Decade. Data in Table 1.6 present the water supply and sanitation coverage for developing regions for 1980 and 1990. The striking fact is that four-fifths of the world's population is covered by this table, including 100 percent of the population of developing countries. Many factors interfere with the improvement of water supplies and the provision of sanitation services in developing countries. Some constraints for developing countries include an insufficient number of trained professionals, insufficient funding, inadequate operation and maintenance, ineffective logistics, inadequate cost-recovery framework, inappropriate institutional framework, insufficient health education effects, intermittent water service, and lack of planning and design.

The future population will have a direct and very significant impact on future water availability, use, and quality. By year 2000 the total population on Earth may exceed 6 billion people, and by year 2050, possibly 10 billion, according to estimates by the United Nations. In discussing the impacts of population it must be recognized that the total population and growth rates are very different in developing countries and developed countries. For developed countries, the rate is under 1 percent per year, whereas it exceeds 2 percent per year in developing countries, and in some parts of Africa, Asia, and the Middle East, it exceeds 3 percent per year (Gleick, 1993). The consequence is that over 90 percent of future population increases will be in developing countries, where access to clean water, sanitation services, and other amenities for a satisfactory quality of life are inadequate.

Over the past decade, the total population in urban areas grew tremendously, due to massive migrations to the larger urban areas in developing countries. Most of these urban areas have never had adequate clean water and sanitation services. There is no doubt that during the next decade, as the population-growth rate in these urban areas in developing countries increases, the situation will worsen. Because the total amount of freshwater is fixed, these growing populations will continuously reduce the water available per capita (see Table 1.5).

It is interesting to note that throughout the world, poor rural women spend 60 to 90 hours per week gathering wood, collecting water, preparing food, and caring for children (Gleick, 1993). The United Nations has shown that the education of women can improve child health, and often leads to improved availability of water and sanitation. Educating people about family planning and public health can also be effective in tackling the future problems of water availability. The world's population must be stabilized, as it cannot continue to grow indefinitely. At the same time, we must work to reduce the enormous suffering caused by what already exists.

Al Gore (1992), in his book *Earth in the Balance,* proposed a Global Marshall Plan which includes the following five goals to save the global environment:

1. Stabilizing the world population
2. The rapid creation and development of environmentally appropriate technologies, also referred to as a Strategic Environment Initiative (SEI)
3. A comprehensive and ubiquitous change in the economic rules of the road by which we measure the impact of our decisions on the global environment—a new global economics
4. The negotiation and approval of a new generation of international agreements
5. The establishment of a cooperative plan for educating the world's citizens about our global environment

TABLE 1.6 Water Supply and Sanitation Coverage for Developing Regions, 1980 and 1990

	1980				1990			
Region/sector	Population, 10^6	Percent coverage	Number served, 10^6	Number unserved, 10^6	Population, 10^6	Percent coverage	Number served, 10^6	Number unserved, 10^6
Africa								
Urban water	119.77	83	99.41	20.36	202.54	87	176.21	26.33
Rural water	332.83	33	109.83	223.00	409.64	42	172.06	237.59
Urban sanitation	119.77	65	77.85	41.92	202.54	78	160.01	42.53
Rural sanitation	332.83	18	59.91	272.92	409.64	26	106.51	303.13
Latin America and the Caribbean								
Urban water	236.72	82	194.11	42.61	324.08	87	281.95	42.13
Rural water	124.91	47	58.71	66.20	123.87	62	76.80	47.07
Urban sanitation	236.72	78	184.64	52.08	324.08	79	256.02	68.06
Rural sanitation	124.91	22	27.48	97.43	123.87	37	45.83	78.04
Asia and the Pacific								
Urban water	549.44	73	401.09	148.35	761.18	77	586.11	175.07
Rural water	1,823.30	28	510.52	1,312.78	2,099.40	67	1,406.60	692.80
Urban sanitation	549.44	65	357.14	192.30	761.18	65	494.77	266.41
Rural sanitation	1,823.30	42	765.79	1,057.51	2,099.40	54	1,133.68	965.72
Western Asia (Middle East)								
Urban water	27.54	95	26.16	1.38	44.42	100	44.25	0.17
Rural water	21.95	51	11.19	10.76	25.60	56	14.34	11.26
Urban sanitation	27.54	79	21.76	5.78	44.42	100	44.42	0.00
Rural sanitation	21.95	34	7.46	14.49	25.60	34	8.70	16.90
Totals for these regions								
Urban water	933.47	77	720.77	212.70	1,332.22	82	1,088.52	243.70
Rural water	2,302.99	30	690.25	1,612.74	2,658.51	63	1,669.79	988.72
Urban sanitation	933.47	69	641.39	292.08	1,332.23	72	955.22	377.00
Rural sanitation	2,302.99	37	860.64	1,442.35	2,658.51	49	1,294.72	1,363.79

Source: Gleick, 1993.

These five goals are all interrelated, so they should be pursued simultaneously. An integrating goal would be "the establishment, especially in the developing world, of the social and political conditions most conducive to the emergence of sustainable societies."

1.6.2 Research Directions

The Carnegie Commission on Science, Technology, and Government (1992) defined environmental research as directed to maintaining environmental quality, including monitoring, testing, evaluation, prevention, mitigation, assessment, and policy analysis. Their definition includes:

- Investigations designed to understand the structure and function of the biosphere, and the impact that human activities have on it
- Research to understand the conditions necessary to support human existence without destroying the resource base
- Research to define the properties and adverse effects of toxic substances on human health and the environment
- The development of technologies to monitor pollutants and their impacts
- The development of pollution-control technologies
- The economic and social research directed at understanding the many complex, interrelated factors that influence environmental quality

The Commission concluded that the present research and development system in the United States has basically been a "catch up, clean up" dominated approach. They felt that the research and development system is diffuse, reactive, and focused on short-range, end-of-the-pipe solutions. The mechanism to coordinate and integrate the research products are weak. In the future there must be more effort put into: (1) environmental biology, (2) interdisciplinary studies, (3) understanding ecological processes, (4) understanding the interrelation of land, water, and biota in landscapes, and (5) there needs to be better integration of economic, social, and political studies of environmental issues with the natural sciences.

The Committee on Opportunities in Hydrologic Sciences of the NRC (1991) developed priority categories of scientific opportunity under the premises that: "(1) the largest potential for such contribution lies in the least explored scales and in making the linkages across scales, and (2) hydrologic science is currently data-limited." The unranked research areas of highest priority are: (1) chemical and biological components of the hydrologic cycle, (2) scaling of dynamic behavior, (3) land surface–atmosphere interaction, (4) coordinated global-scale observation of water reservoirs and the fluxes of water and energy, and (5) hydrologic effects of human activity.

The research area of chemical and biological components of the hydrologic cycle includes:

- Understanding the interaction between ecosystems and the hydrologic cycle
- Understanding the pathways of water through soil and rock through the use of aqueous geochemistry to reveal the historical states for climate research, and to reconstruct the erosional history of continents

- Combining efforts in aquatic chemistry, microbiology, and physics of flow to reveal solute transformation, biochemical functioning, and the mechanism for both contamination and purification of soils and water

Scaling of dynamic behavior involves research:

- To quantify predictions of large-scale hydrologic processes under the three-dimensional heterogeneity of natural systems, which are orders of magnitude larger in scale than idealized one-dimensional laboratory conditions
- To quantify the inverse problem by disaggregating conditions at large scale to obtain small scale information, e.g. in the parameterization of subgrid-scale processes in climate models

Understanding land surface–atmosphere interactions has become somewhat urgent, because of the accelerating human-induced changes in land surface characteristics globally, on issues ranging from the mesoscale upward to continental scales. A better understanding of the following are needed:

- Our knowledge of the time and space distribution of rainfall, soil moisture, groundwater recharge, and evapotranspiration
- Knowledge of the variability and sensitivity of local and regional climates to alterations in land surface properties

Coordinated global-scale observation of water reservoirs and the fluxes of water and energy is needed for a better understanding of the state and variability of the global water balance. Two programs that will help in this effort are the World Climate Data Program (WCDP) to assemble historical and current data, and the World Climate Research Program (WCRP), which is planning a global experimental program to place future observations on a sound and coordinated effort, called the Global Energy and Water Cycle Experiment (GEWEX).

The Global Energy and Water Cycle Experiment (GEWEX), proposed to begin in the late 1990s, is designed to verify large-scale hydrologic models and to validate global-scale satellite observations. This initiative of the World Climate Research Program addresses four scientific objectives:

1. Determine water and energy fluxes by global measurements of observable atmosphere and surface properties.
2. Model the hydrologic cycle and its effects on the atmosphere and ocean.
3. Develop the ability to predict variations of global and regional hydrologic processes and water resources and their response to environmental change.
4. Foster the development of observing techniques, and data management and assimilation systems suitable for operational applications to long-range weather forecasting and to hydrologic and climate predictions.

A central goal of the GEWEX program is to develop and improve modeling of hydrologic processes, and to integrate surface and ground water processes on the catchment scale into fully interactive global land–atmosphere models.

Hydrologic effects of human activity research should focus on the quantitative forecasts of anthropogenic hydrologic change, which is largely indistinguishable from the temporal variability of the natural system.

In summary, as asked by the Carnegie Commission (1992), "Can scientists and engineers generate the kind of large-scale and highly focused effort that took us into space and apply it to developing the understanding necessary to protect our global environment?" An international effort will be required to meet the environmental challenges that we face today. Obtaining a sustainable development will require a wide range of research advances.

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CHAPTER 3
WATER ECONOMICS

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3.1 *INTRODUCTION AND OVERVIEW*

It is fitting that attention be turned to the subject of managing water. The water resource in its varied forms supplies important benefits to humankind, both commodity benefits and environmental values. However, throughout the world, significant water management problems abound, and in many areas are rapidly becoming worse (Clarke, 1993; Gleick, 1993). Growing populations and incomes are imposing ever-increasing demands for water for agricultural, industrial, and residential uses on limited surface and groundwater supplies. These same forces add to the pollution discharged to the world's waterways, and to the encroachment of human activities onto lowlands vulnerable to flooding, or onto important natural ecosystems.

The subject of water resource management seems to be viewed by many of its practitioners and the public (not to mention the organizers of this volume) to be mainly an interesting hydrologic-engineering problem made inconveniently messy by the mysterious and unpredictable activities of humankind. One task of this chapter is to demonstrate an alternative perspective: That the significant challenges of water management as we approach the twenty-first century are much more issues of "people-coordination" than of physical or technical water management, and that economics and other social sciences have an important role to play in addressing these issues.

Economists study the ways in which individuals and societies respond to the scarcity of means available for achieving a multiplicity of wants. Ideally, economic analysis is designed to anticipate and assess the impact of alternative policies over the longer term and on all affected parties, not only on those immediately affected. Water, and the resources required to both exploit and protect it, are increasingly scarce; hence, it is in the interest of the public to apply economic criteria to water management decisions.

Two principal theses underlie the presentation in this chapter. First, the outward manifestations of water problems—shortages, pollution, conflicts over entitlements to use water, environmental degradation—are but symptoms. To a great extent, the actual problems arise from underlying economic policy failures: Water is underpriced, and its uses are underregulated and/or beset with counterproductive incentives. Second, while human behavior may be inherently more difficult to understand than physical or biological relationships, sufficient regularities can be found in aggregate human interactions with the water resource to help in describing recurring and systematic patterns of water use, diagnosing the sources of water-related problems, and prescribing improved water allocations and the institutional arrangements for achieving them.

This chapter presents for the noneconomist and the nonspecialist in water economics an interpretive survey of how economists currently approach problems arising from managing water, including allocation, pricing, pollution control and natural hazard management. The breadth of the subject matter, combined with the limits of space, dictate that the style is more a literature review than the "how to" character of analyses found in other chapters of this volume. A previous survey (Young and Haveman, 1985) emphasized earlier concerns addressed by water economists, principally the design and application of economic feasibility (cost-benefit) tests for investments in water supply structures. (See also Kneese, 1988). This chapter focuses primarily on literature and issues receiving the most attention during the past ten years—water allocation, water quality, and floodplain management—although interest in these issues arose and significant work occurred much earlier.

A proposition stated earlier is that water management problems have become primarily people-coordination problems. Accordingly, this chapter stresses economic approaches to design of institutional arrangements (i.e., interrelated sets of organizations and rules or laws) which serve to coordinate the activities of people who use or benefit from water resources, so as to achieve the maximum value from scarce water, environmental, and other resources.

The balance of the chapter is divided, as are the activities of economists themselves, into two major categories. *Positive* economics, taken up in Sec. 3.3, is concerned with observable facts and recurring relationships—it seeks to describe, explain, and predict economic phenomena. For example, what are the effects of changing prices, incomes, policies, or technologies on water consumption patterns? Or, what role does water play in regional economic growth? *Normative* economics is concerned not only with matters of fact, but with criteria for policy and questions of optimal policy. For example, *should* a particular water supply project be undertaken? Are markets *preferable* to a government administrative agency in accommodating changing patterns of demand for water? *Should* pollution be discouraged, and if so, with what type of policies? Normative economics employs the empirical studies of positive economics, and combines them with value judgments reflecting notions about the ideal society to derive policy recommendations. The concluding portions of the chapter, Secs. 3.4 to 3.8, address normative analyses, focusing on three specific issues: Water allocation, water quality management, and flood hazard management. The remainder of this introductory section introduces some of most important concepts used by economists in the study of water allocation and management.

3.1.1 The Economist's Approach

A few key concepts identify the economist's particular view on the way an economy functions, and how policies should be designed. (See Rhoads, 1985, for a sympathetic review and critique.) An extract from Gary Becker's Nobel Lecture (1993, pp. 385–386) provides a starting point.

> It is a *method* of analysis, not an assumption about particular motivations. . . . The analysis assumes that individuals maximize welfare *as they conceive it*, whether they be selfish, altruistic, loyal, spiteful or masochistic. Their behavior is forward-looking, and is assumed to be consistent over time. In particular, they try as best as they can to anticipate the uncertain consequences of their actions. . . . While this approach to behavior builds on an expanded theory of individual choice, it is not mainly concerned with individuals. It uses theory at the micro level as a powerful tool to derive implications at the group or macro level. [Emphasis in the original.]

One of the most important economic concepts is that of *opportunity costs*, which refers to the benefits foregone when a scarce resource is used for one purpose instead of its next best alternative use. It is important to recognize that spending and regulatory decisions that use scarce resources impose costs in the form of foregone alternatives—that is, opportunities that can no longer be undertaken.

Another significant concept identified with the economic approach is *marginalism*. In the context of resource allocation decisions, marginalism emphasizes the importance of considering incremental gains relative to incremental costs. Rather than setting spending decisions on ranking of problems by their seriousness, spending should be prioritized on the basis of the marginal potential gains relative to incremental costs.

Closely linked with marginalism are the notions of *diminishing returns* and *resource substitutibility*. Diminishing returns refers to the fact that, on the producers' side, increases in the use of a given input (when all other inputs are held constant) lead to decreasing increments of product. Similarly, for consumers, additions to consumption yield decreasing increments of utility or satisfaction. Resource substitutibility means that consumers and producers are not limited to fixed proportions of resource use in their consumption or production activities. Changing relative prices, or scarcities, make it attractive to substitute plentiful resources for scarce ones. Farmers may take more care and expend more labor in crop irrigation under scarce water conditions than they would under conditions of relative plenty, or householders might replace inefficient plumbing fixtures as water prices rise.

Water was involved in one of the most famous intellectual conundrums in the history of economic thought: The water–diamond paradox. This problem was resolved in the eighteenth century by what came to be known as the distinction between value in use and value in exchange. Although its price is low, water has enormous value *in use* to humans, because it is necessary to existence. Diamonds, in contrast, are not at all essential, but have high value *in exchange* (on the market). Final resolution of the paradox came with the additional distinction between total and marginal values. The total utility of water clearly exceeds that of diamonds. However, the marginal utility of diamonds is greater than the marginal utility of water. Because diamonds are scarce (the marginal costs of acquiring more are high) and the marginal utility for diamonds is high, diamonds are priced higher than is water.

Another important idea is that *incentives matter.* Based on the belief that individuals act to maximize welfare as they see it, economists expect that the individual producer or consumer will adjust behavior when incentives change. Since the time of Adam Smith over two centuries ago, an emphasis on designing institutions so as to make private interests more consistent with public goals has been a main attribute of the economist's approach. Paying attention to private interests in designing government programs will frequently permit important goals to be achieved more cheaply.

Economics has been characterized as the study of *unintended consequences* of human action in that part of the social system encompassing production, exchange, and consumption of goods and services (O'Driscoll, 1977). Economics goes beyond direct observation. The nonspecialist can recognize the immediate effect of policy decisions: A policy of holding water prices below costs makes the resource less expensive and improves the economic well-being of some consumers. In this case, other consumers must pay part of the costs. An investment in a reliable, high-quality water supply may provide increased employment and income to the regional economy. However, economists attempt to also address the hidden impacts of these policies, and illuminate considerations not readily recognized as aspects of these problems. Low-cost water will lead to overuse and waste of the resource, while the financing of an investment in water supply implies foregone employment and income elsewhere in the economy.

Nonmarketed goods and services valuation is an important aspect of environmental and resource economics. Economists recognize that people value things—including many important services of the earth's water supply—that they do not purchase through a market, or that they may value for reasons independent of their own purchase and use. Further, not everything that reduces utility—such as pollution—is costed in markets. Although practitioners of the dismal science are sometimes equated with Oscar Wilde's cynic (who knows the price of everything and the value of nothing), environmental economists in fact spend much of their professional efforts attempting to estimate the public's value (often called a *shadow price*) for nonmarketed goods and services. The modern economic paradigm assumes that values of goods and services rest on underlying demand and supply relationships, that are usually, but not always, reflected in market prices. Economics is not just the study of markets, but more generally, the study of preferences and human behavior (Hanemann, 1994).

The principal strengths of the economic approach to rational policymaking are its focus on assessing the consequences—both beneficial and adverse—of policy actions and its attempts to be sensitive to the particular facts of decision situations. By expressing consequences in terms of a common denominator of money value, it provides a method of resolving tradeoffs among competing and valued ends, including taking account of the economic costs (foregone benefits) of achieving those ends.

It would be pleasing to be able to assure the reader that resource economists all speak with the same voice on how economics is applied to research and policy issues. As with the discipline taken as a whole, and indeed, in common with other social sciences, resource economists exhibit a spectrum of methodological perspectives, as well as diverse ideological views, on the appropriate role for private and government entities in managing natural and environmental resources. Moreover, there are important differences across the profession regarding the uses and limits of economics as a policy tool (see Randall, 1985 for a full discussion). In contrast to the perceived mainstream focus on markets and prices, *institutionalists*, from a policy stance skeptical of market mechanisms, have emphasized the importance of studying the distributive effects of economic institutions. Many of their concerns, however, have been coopted into mainstream environmental and resource economics practice. Some economists in the institutionalist tradition reject the mainstream's primary emphasis on economic efficiency as a criterion for policy analysis, emphasizing the importance of other values, such as income distribution (e.g., Bromley, 1991). Others have focused on the limitations of market allocation systems for dealing with potential long-term environmental problems (Costanza, et al., 1990). On the other hand are the *Individualists* or *Austrians*, who emphasize the role of individual liberties as well as economic efficiency, and urge decentralization, property rights, and markets for resolving water and environmental problems (e.g., Anderson and Leal, 1991).

3.2 WHY IS WATER POLICY DESIGN SO DIFFICULT? ECONOMIC AND RELATED CONSIDERATIONS

Water *is* indeed different. A number of special characteristics distinguish water from most other resources or commodities, and pose significant challenges for the design and selection of water allocation and management institutions. These unique characteristics are considered here under four headings: Water supply, water demand, social attitudes, and legal-political considerations.

3.2.1 Physical and Hydrologic Characteristics

3.2.1.1 Mobility. Water, usually a liquid, tends to flow, evaporate, and seep as it moves through the hydrologic cycle. Mobility presents problems in identifying and measuring specific units of the resource. Due to its physical nature, and for other reasons, water is what economists call a *high-exclusion cost* resource, implying that the exclusive property rights which are the basis of a market or exchange economy are relatively difficult and expensive to establish and enforce.

3.2.1.2 Uncertainty in Supply. Water supplies, although generally renewable, are typically relatively variable and unpredictable in time, space, and quality. Local water availability usually changes systematically throughout the seasons of the year (with climatic variations) and over longer cyclical swings. Forecasts of significant global climate change—from both natural and human causes—raise concerns about longer-term supply trends. Problems for humankind are encountered at the extremes of the probability distributions of supply (floods and droughts). Too much or too little water can, of course, yield adverse effects on human societies. Flooding from excess rainfall or snowmelt is an important hazard in many areas, imposing significant costs, and most governments have undertaken programs for flood control. At the opposite extreme, droughts can have a major negative impact on an economy, particularly those relying heavily on agriculture.

3.2.1.3 Solvent Properties. Water is a nearly universal solvent which, together with plentiful supply, creates an inexpensive capacity for absorbing wastes and pollutants, and for diluting them and transporting them to less-adverse locations. Managing the assimilative capacity of the hydrologic system is, then, understood as the management of a scarce collective or public asset. In many situations, water quality considerations are increasingly as important as direct use and other public benefits.

3.2.1.4 Pervasive Interdependency Among Users. The physical nature of water, combined with supply variability, causes a unique but unpredictable degree of interrelationship among water users. Water is rarely completely consumed (i.e., lost to evaporation) in the course of human consumption or production activities. So-called "water uses" generally result in return flows to an aquifer or stream. In crop irrigation, for example, it is not unusual to find that fifty percent or more of water diverted returns, in the form of surface or subsurface drainage, to the hydrologic system, while an even larger proportion is typically returned from municipal and industrial withdrawals. Other, particularly downstream, users are greatly affected (for good or ill) by the quantity, quality, and timing of releases or return flows by upstream users. These interdependencies lead to effects called *externalities*, (or *spillover* or *third party* effects), which are uncompensated side effects of individual activities. In such cases, the full costs of economic activity are not recognized in individual producer or consumer decisions, and outcomes for the society will be suboptimal.

3.2.1.5 ***Site-Specificity of Water Problems.*** Because of water supply variations, and also due to localized demand-side considerations, problems with water resources are typically rather site-specific. The relative supplies of surface and groundwater at any location depend, of course, on climatic variations (rainfall and snowpack), as well as on the available aquifer storage. Water demand and quality issues are likewise specific to population size and economic development level. The implication of these facts is that water management problems tend to be specific to areas, and policy treatment often needs to be adapted to local conditions.

3.2.1.6 ***Economies of Large Size.*** The capture, storage, and delivery of water—especially surface water—exhibits economies of large size (falling unit costs). When costs decline over the range of existing demands, a single supplying entity is the most economically efficient organizational arrangement. This is a classical natural monopoly situation—the least-cost supply is with a single producing organization. Accordingly, public regulation or ownership is often invoked to avoid monopolistic pricing. (Groundwater seems to present a different story, as most size economies are achieved at relatively small outputs. Moreover, such size economies as are observed may be offset by increased pumping costs, and rising third-party spillover costs, due to water-table drawdown.)

3.2.1.7 ***Distinctive Attributes of Groundwater Supplies.*** Groundwater aquifers are an important source of water throughout the world. An aquifer is defined as a geologic formation actually, or potentially, containing water in its pores or voids, which can be removed economically and used as a water supply. Several differences in supply attributes from surface water can be identified for groundwater, including a slow rate of flow and extra difficulties in accurately knowing the potential yield and quality of an aquifer. This point will be elaborated upon somewhat in Section 3.5.

3.2.2 Water Demand—Characteristics from Users' Perspectives

3.2.2.1 ***Preliminary Remarks on Water Demand.*** People obtain many types of value and benefits from water. Because each benefit type usually calls for specialized management approaches, it will be useful to classify the types of value into five classes. These are: (1) commodity benefits, (2) waste assimilation benefits, (3) public and private aesthetic and recreational values, (4) species and ecosystem preservation, and (5) social and cultural values. The first three of these are treated here as economic considerations, because they are characterized by increasing scarcity, and the associated problems of allocation among competing uses to maximize economic value. The final pair, preservation and sociocultural issues, are discussed separately as noneconomic values.

It may be most useful to begin by recognizing that the economic characteristics of water demand varies across the continuum from *rival* to *nonrival* goods. A good or service is said to be *rival* in consumption, if one person's use in some sense precludes or prevents uses by other individuals or businesses. Goods that are rival in consumption are the types that are amenable to supply and allocation by market or quasi-market processes, and are often called *private* goods. The opposite end of the continuum is occupied by goods that are *nonrival* in consumption, meaning that one person's use does not preclude enjoyment by others. Goods that are nonrival are often called *public* or *collective* goods. Because nonpayers cannot be easily excluded, private firms will not find it profitable to supply nonrival goods. Water for agricultural or industrial use tends toward the rival end, while the aesthetic value of a beautiful stream is nonrival.

The significance of nonrivalry can be better understood by noting its association with high exclusion costs (Schmid, 1989). *Exclusion cost* refers to the resources required to keep those not entitled from using the good or service. Water is frequently a high-exclusion-cost good because of its physical nature: When the service exists for one user, it is difficult to exclude others. In such cases, it is hard to limit the use of the good to those who have helped pay for its costs of production. (The refusal of some beneficiaries to pay their share of the provision of a public good, from whose benefits they cannot be excluded, is called the *free rider* problem. To circumvent the problem, public goods must normally be financed by general taxes, rather than by specific charges.)

3.2.2.2 ***Variety and Economic Characteristics of Water Uses.*** The first type of benefit is the *commodity benefit:* Those derived from personal drinking, cooking, and sanitation, and those contributing to productive activities on farms and in businesses and industries. What are here called *commodity values* are distinguished by the fact of being rival in use, meaning that one person's use of a unit of water necessarily precludes use of that unit by others. Commodity uses tend to be private goods or services.

Some additional distinctions will be helpful in continuing the discussion of commodity-type uses. Those uses of water which normally take place away from the natural hydrologic system may be called *withdrawal* (or *offstream*) uses. Since they typically involve at least partial consumption (evaporation), they may further be distinguished as *consumptive* uses. Other economic commodity values associated with water may not require it to leave the natural hydrologic system. This group may be labelled *instream* water uses—hydroelectric power generation and waterways transportation are important examples. Since instream uses often involve little or no physical loss, they are also called *nonconsumptive* uses. Although instream uses do not "consume" much water, in the sense of evaporating it to the atmosphere, they do often require a change in the time and/or place of availability—as with releases from a hydropower reservoir—and therefore exhibit some aspects of the rivalness of a private good.

The second general class of economic benefit of water use is the value of waste disposal. Bodies of water are significant assets because of their assimilative capacity, meaning that they can carry away wastes, dilute them, and, for some substances, aid in processing wastes into less undesirable forms. The assimilative capacity of water is closer to being a public or collective (rather than private) value, because of the difficulty in excluding dischargers from utilizing these services.

A third type of economic benefit from water is its value for recreation, aesthetics, and fish and wildlife habitat. Once regarded as luxury goods inappropriate for governmental concern, these benefits are increasingly important. The citizens of developed countries more and more often choose water bodies for recreational activities. In developing nations, as income and leisure time grow, water-based recreation is also increasingly important to the citizens, and often provides a basis for attracting the tourist trade. As is waste assimilation, recreational and aesthetic values are nearer the public-good end of the spectrum. Enjoyment of an attractive water body does not necessarily deny similar enjoyment to others. However, congestion at special sites, such as waterfalls, may adversely affect total enjoyment of the resource. Significant instream values are also found as habitat for wildlife and fish.

The economic value of water can also extend to *nonuse* values. In addition to valuation of goods and services which are actually used or experienced, it is observed that people are willing to pay for environmental services they will neither use nor experience. Nonuse values are benefits received from knowing that a good exists, even though the individual may not ever directly experience the good. Voluntary contribution toward preserving an endangered fish species is an illustrative example. Many resource economists argue that nonuse values should be included with use values, so as to more accurately measure total environmental values.

Some environmentalists object to policies which acknowledge the commodity aspects of water, because they fear this will lead to sacrifice of important public benefits. However, it will likely be more fruitful to recognize both the commodity and environmental characteristics of water demand, and design policies with this duality in mind.

3.2.2.3 Water Is a Low-Valued Commodity. The economic value per unit weight or volume of water tends to be relatively low, placing water among commodities which economists call *bulky*. Capital and energy costs for transportation, lifting, and storage tend to be high relative to economic value at the point of use. (For example, in crop irrigation, much of the water applied may yield direct economic value—profit after production costs—of less than US$0.04 per ton.) Extensive water-conserving technologies (closed conduits, recycling, and metering) as well as incentives for conservation (marketable property rights, increasing-block pricing) are presently found only where water is recognized as scarce and valuable. (Although water may be low valued, it nevertheless may be underpriced relative to cost of supply or opportunity costs.)

3.2.2.4 Variability in Demand. As on the supply side, variability is also important on the demand side. Agricultural needs oscillate, responding to temperature and rainfall patterns over seasons of the year and over longer cycles. Residential and industrial water uses also vary depending on daily, weekly, and seasonal considerations. Both storage and conveyance systems and management institutions must be prepared to satisfy peak loads in high demand periods.

3.2.3 Social Attitudes Toward Water

3.2.3.1 Conflicting Social Cultural Values. Because water is essential to life, and because clean water and sanitation are essential to health, market allocation mechanisms are often rejected in favor of regulatory approaches. The Dublin Conference on Water and Environment in January 1992 asserted as one of its guiding principles for action that "... it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price." The significance of water for life receives further emphasis in arid regions, where crop irrigation is essential to production of the other staff of life, food.

Moreover, many view water as contributing special cultural, religious and social values, and prefer not to have water treated as an economic commodity. Goals other than economic efficiency play an unusually large role in selecting water management institutions. Boulding (1980) has observed that "the sacredness of water as a symbol of ritual purity exempts it somewhat from the dirty rationality of the market." Some cultures or religions (i.e., Islam) proscribe water allocation by market forces.

However, focus on the necessity for life as the basis for design of social institutions tends to obscure the fact that in modern societies only a tiny fraction of water consumption actually is used for drinking and for preservation of human life. Most water is used for convenience, comfort, and aesthetic pleasure. In the arid western United States, residential water withdrawal frequently exceeds 400 liters per capita per day, up to nearly half of which may be applied to irrigate lawns and gardens, with most of the remainder for flushing toilets, bathing, and washing cars (Gleick, 1993).

3.2.4 Legal-Political Considerations

A number of considerations for water policy design fall on the border between economics and political science, or what is sometimes called *political economy*.

3.2.4.1 Transactions Costs Versus the Relative Scarcity of Water. The term *transactions costs* refers to the resources required to establish, operate, and enforce a resource allocation, management, or regulatory system. Transactions costs are also termed ICE costs, because they comprise the costs of obtaining *information* (such as knowledge about the needs and attitudes of other participants), *contracting* costs (resources required to reach agreements), and *enforcement* costs (the expense of enforcing contracts and public laws and regulations). Given the supply and demand characteristics of water noted earlier, transactions costs for water management and allocation tend to be high relative to its value. Where water is plentiful relative to demand, water laws tend to be simple and only casually enforced. Where water is scarce, more elaborate management systems have emerged. In many regions, water supplies are only now becoming scarce enough to require formal management systems. Increased resource scarcity and technological advances, which reduce the transactions cost of monitoring and enforcing regulations, both act to encourage innovations in allocative institutions, so as to economize on the scarce resource.

3.2.4.2 The Cumulative Impact of Many Small Decisions. A related point is that water policy makers must often confront the problem aptly termed the "tyranny of small decisions" by Alfred Kahn (1965). Even though each individual act of water use, taken alone, might have a negligible impact, the sum total can be of major importance. One example is found in the rapid spread of tubewells for irrigation in south Asia. Any one of these small wells would have little effect on the total groundwater supply, but in total, some aquifers are being rapidly depleted. Another case is nonpoint pollution from chemicals carried by runoff from farmers' fields or from forest harvest. Effective public regulation of many small, scattered decision-makers is exceedingly difficult, but increasingly necessary.

3.2.4.3 The "Common Pool" Aspect of Water Resources. *Common pool natural resources* are defined by two characteristics (Gardner, et al., 1990). The first is rivalry, or subtractibility, meaning that a unit of resource withdrawn by one individual is not fully available to other potential users. The second is that the costs to a government entity of excluding potential beneficiaries from exploiting the resource is relatively high. Water and other fugitive or mobile resources, such as petroleum, wildlife, or migratory wildfowl, can be examples of common pool resources.

Common pool problems, or dilemmas, arise when individually rational resource-use decisions bring about a result that is not optimal when considered from the perspective of the exploiters as a group, i.e., of society. The roots of the problems associated with common pools are found in the inadequate economic and institutional framework within which the resource is exploited. Common pool resources have been typically utilized in an open access framework, within which resource ownership is according to a rule of capture. When no one owns the resource, users have no incentive to conserve for the future, or to consider the foregone benefits to others, and the self-interest of individual users leads them to over-rapid and/or excessive exploitation. The characteristics of the economic institutions governing their use is the fundamental issue in managing common pool resources.

Gardner, et al. (1990) specify the following additional conditions as necessary to produce a common pool resource dilemma. First, there are many appropriators, or users, withdrawing the resource. Second, the actions of the individual users, given the particular situation with respect to the resource itself, the characteristics of users, demand for the resource, and extraction technology, bring about suboptimal outcomes from the group's viewpoint. Finally, there must exist institutionally feasible strategies for collective management of the resource that are more efficient than the current situation. (See also Ostrom, et al., 1994.) Both surface and ground water have often been utilized under open access rules, leading to various forms of suboptimality.

To sum up, we see that water is truly an unusual resource, and for numerous physical, social, political, and economic reasons, presents special challenges to getting the incentives right. Before taking up the problems of water policy design, the discussion turns to positive economic analysis applied to water.

3.3 POSITIVE ECONOMICS OF WATER: EMPIRICAL RELATIONSHIPS AND MEASUREMENTS

To perform empirical descriptive measurements of important relationships, to explain and understand the regularities beneath the apparently haphazard occurrences of economic life, and to predict the effects of changes in the society and its policies on water use, are the purposes of positive economic analysis. With regard to the water resource, the regularities that are of primary interest here are: (1) those socioeconomic factors that affect the amount of water consumed, (2) the responsiveness of water use to price and other variables, and (3) the relationship between water supply and regional economic growth. This section will examine empirical evidence on the general patterns of water consumption and on the factors which influence water demand and supply.

Descriptive statistics illuminate broad water use and consumption patterns. In the United States, crop irrigation is the major user of water, accounting for 42 percent of withdrawals and 84 percent of consumption in 1990. The domestic-commercial category represented 11 percent of withdrawals and 7 percent of consumption, while industry took 8 and 5 percent, and thermoelectric power accounted for 39 and 4 percent of the same categories. Water withdrawal and consumption patterns elsewhere in the world reflect climate, degree of economic development, and other factors, but as in the United States, crop irrigation represents the major consumptive use of water in the world. (Space limits preclude the display of the national and worldwide data on water withdrawals and consumption by sector. See Solley, et al., 1993, or Rogers, 1993, for summaries for the United States, and Gleick, 1993, for both a global overview and detailed data on water use.)

3.3.1 Measuring Demand for Water

Human uses of water are conveniently divided into withdrawal (offstream) and in-place (instream) categories. *Withdrawal uses*, those for which water resources are

diverted from their natural bodies of water, include agriculture, industry, commercial, and residential purposes. In-place uses include values for recreation, fish and wildlife habitat, hydroelectric power, waste load assimilation, and the like. A further cross-classification identifies whether the demand is from use and the price of water. Demand is the willingness of users or consumers to pay for goods and services, as that willingness to pay varies (usually inversely) with the amount being purchased. Water demand is very site-specific, varying with a range of natural and socioeconomic factors. The demand relationship is represented graphically by the familiar demand curve, or algebraically as:

$$Q_W = Q_W(P_W, P_a, P, Y, \mathbf{Z}) \tag{3.1}$$

where Q_W refers to the individual's level of consumption of water in a specified time period; P_W refers to the price of water; P_a denotes the price of an alternative water source; P refers to an average price index representing all other goods and services; Y is the consumer's income, and $\mathbf{Z}$ is a vector representing other factors, such as climate and consumer preferences.

Similarly, a model for producers' demands for water can be obtained from the theory of a cost-minimizing producer:

$$Q_W = Q_W(P_W, P_i, P_a, X, \mathbf{S}) \tag{3.2}$$

where, as before, P_W and P_a represent the price of water from the given system and from an alternative source; P_i represents a vector of prices of inputs (capital, labor, and materials); X stands for the quantity of product to be produced; and $\mathbf{S}$ represents a vector of other factors, such as technology and climate. (See Kindler and Russell, 1984; Munasinghe, 1992, Chap. 7; or Spulber and Sabbaghi, 1993, for more complete developments of these models).

In the everyday language of water management, *demand* is often used synonymously with *requirement*. However, these two ideas should be distinguished. If the quantity used is the same no matter what the price, the term *requirement* is appropriate. While the human body requires some minimum daily amount of water for survival, the true requirement for survival is a very small fraction of the amount we normally use—almost all water uses are for production, sanitation, or convenience in daily living. Both consumers and producers can normally change their patterns of water use if price or scarcity makes it in their interest to do so. Households can decrease the frequency or duration of water using activities (i.e., bathing or lawn watering), install water-saving plumbing fixtures or change their outdoor landscaping, while producers might similarly adopt water-efficient technologies or altered production processes.

Forecasting of water use into the distant future is fraught with difficulties. The simplistic extrapolation of trends in per capita "requirements" in water system planning has resulted in many cases in which future water use was greatly overestimated. Rogers (1993, Fig. 6.1) compares actual 1990 withdrawals in the United States with several authoritative forecasts made in the 1970s which foresaw large growth in water use by the 1990s and beyond. In reality, by 1990 the amount of freshwater withdrawal had actually declined from its 1975 level. (See also Solley, et al., 1993.) Some of that decline was doubtless due to increased application of economic rationing mechanisms, such as metering combined with pricing schemes designed to confront customers with more of the costs of their water-use decisions. Bower, et al. (1984) note that similar errors of overestimating water demand were made in Europe, citing the increasing use of volumetric charging mechanisms and the response of industrial water users to water quality regulations, which had the incidental effect of reducing withdrawals because of increased recycling.