Chapter 1

Introduction

1.1 BACKGROUND

Water resources engineering (and management) as defined for the purposes of this book includes engineering for both *water supply management* and *water excess management* (see Figure 1.1.1). This book does not cover the *water quality management (or environmental restoration)* aspect of water resources engineering. The two major processes that are engineered are the *hydrologic processes* and the *hydraulic processes*. The common threads that relate to the explanation of the hydrologic and hydraulic processes are the fundamentals of fluid mechanics. The hydraulic processes include three types of flow: pipe (pressurized) flow, open-channel flow, and groundwater flow.

The broad topic of *water resources* includes areas of study in the biological sciences, engineering, physical sciences, and social sciences, as illustrated in Figure 1.1.1. The areas in biological sciences range from ecology to zoology, those in the physical sciences range from chemistry to meteorology to physics, and those in the social sciences range from economics to sociology. Water resources engineering as used in this book focuses on the engineering aspects of hydrology and hydraulics for water supply management and water excess management.

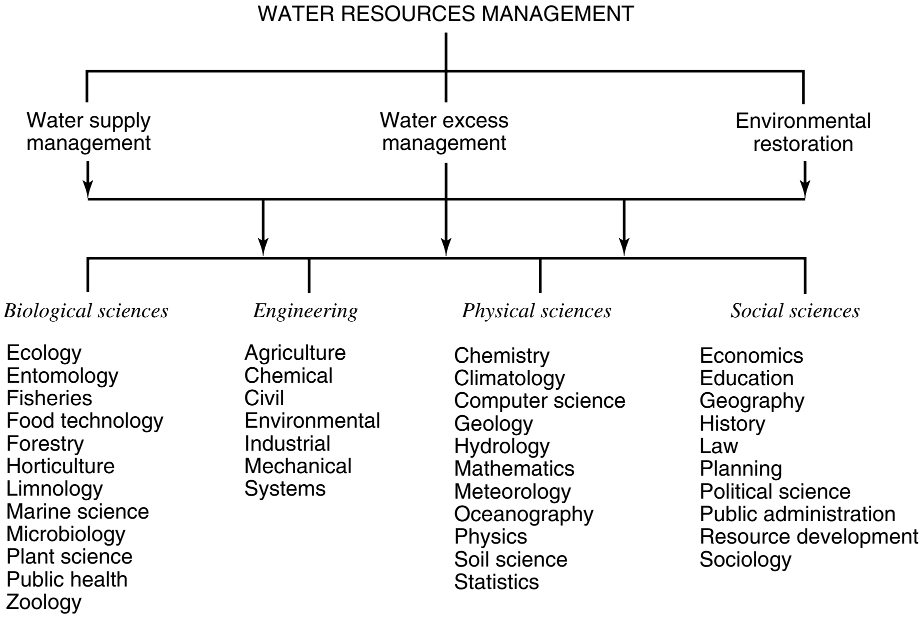

Figure 1.1.1 Ingredients of water resources management (from Mays (1996)).

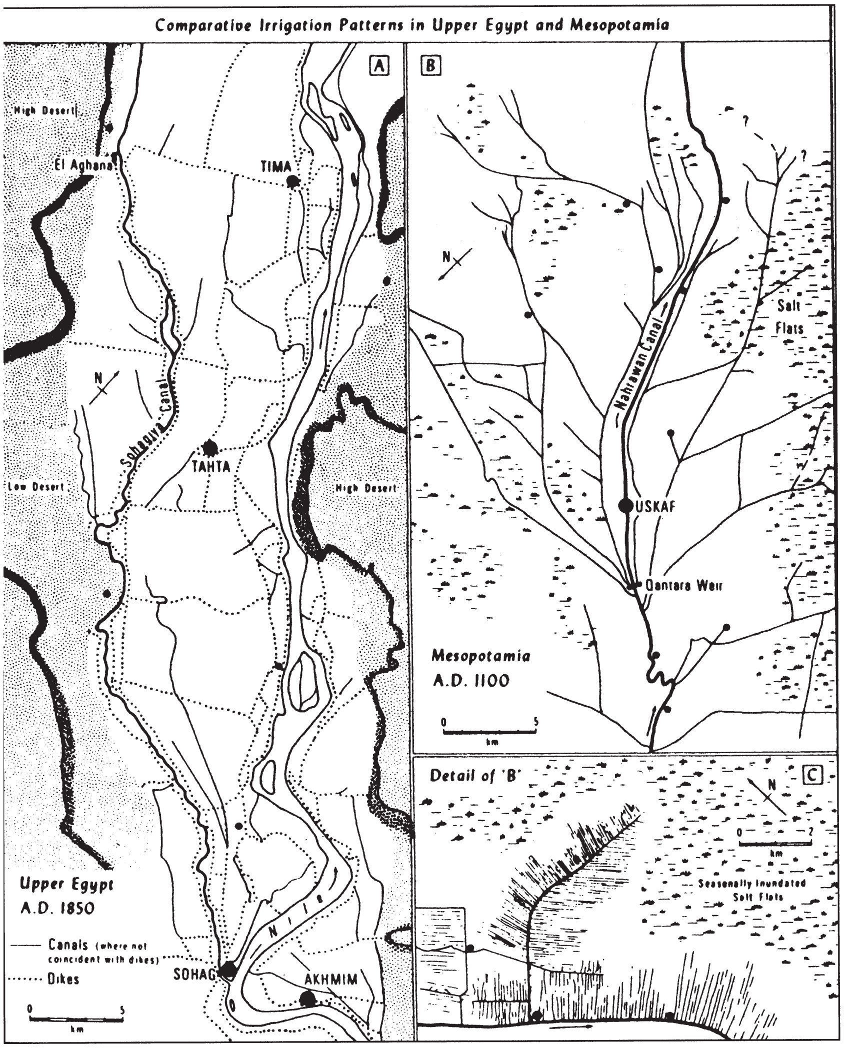

Figure 1.1.2 Comparative irrigation networks in Upper Egypt and Mesopotamia. (*a*) Example of linear, basin irrigation in Sohag province, ca. AD 1850; (*b*) Example of radial canalization system in the lower Nasharawan region southeast of Baghdad, Abbasid (A.D. 883–1150). (Modified from R. M. Adams (1965), Fig. 9. Same scale as Egyptian counterpart). (*c*) Detail of field canal layout in *b*. (Simplified from R. M. Adams (1965), Fig. 10. Figure as presented in Butzer (1976)).

Water resources engineering not only includes the analysis and synthesis of various water problems through the use of the many analytical tools in hydrologic engineering and hydraulic engineering but also extends to the design aspects.

Water resources engineering has evolved over the past 9,000 to 10,000 years as humans have developed the knowledge and techniques for building hydraulic structures to convey and store water. Early examples include irrigation networks built by the Egyptians and Mesopotamians (see Figure 1.1.2) and by the Hohokam in North America (see Figure 1.1.3). The world's oldest large dam was the Sadd-el-kafara dam built in Egypt between 2950 and 2690 B.C. The oldest known pressurized water distribution (approximately 2000 B.C.) was in the ancient city of Knossos on Crete (see Mays, 1999, 2000, for further details). There are many examples of ancient water systems throughout the world.

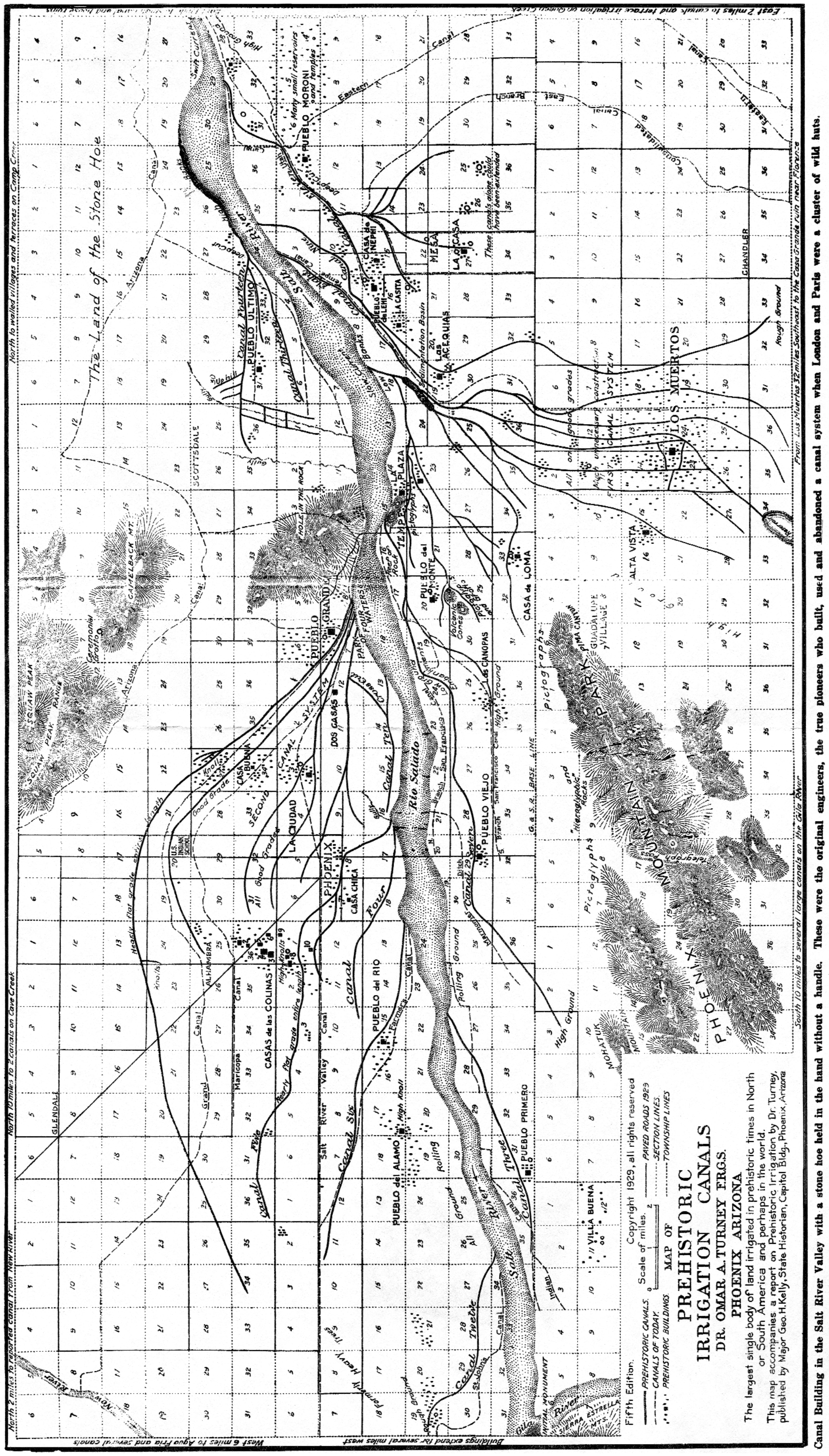

Figure 1.1.3 Canal building in the Salt River Valley with a stone hoe held in the hand without a handle. These were the original engineers, the true pioneers who built, used, and abandoned a canal system when London and Paris were clusters of wild huts (from Turney (1922)). (Courtesy of Salt River Project, Phoenix, Arizona.)

1.2 THE WORLD'S FRESHWATER RESOURCES

Among today's most acute and complex problems are water problems related to the rational use and protection of water resources (see Gleick, 1993). Associated with water problems is the need to supply humankind with adequate clean freshwater. Data collected on global water resources by Soviet scientists are listed in Table 1.2.1. These obviously are only approximations and should not be considered as accurate (Shiklomanov, 1993). Table 1.2.2 presents the dynamics of actual water availability in different regions of the world. Table 1.2.3 presents the dynamics of water use in the world by human activity. Table 1.2.4 presents the annual runoff and water consumption by continents and by physiographic and economic regions of the world.

Table 1.2.1 Water Reserves on the 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 1.2.2 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 per year 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

Table 1.2.2 Dynamics of Actual Water Availability in Different Regions of the World *(continued)*

Continent and region	Area (10^6 km^2)	Actual water availability (10^3 m^3 per year per capita) 1950	1960	1970	1980	2000
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
South-east	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).

Table 1.2.3 Dynamics of Water Use in the World by Human Activity

Water users[a]	1900 (km^3 per year)	1940 (km^3 per year)	1950 (km^3 per year)	1960 (km^3 per year)	1970 (km^3 per year)	1975 (km^3 per year)	1980 (km^3 per year)	1980 (%)	1990[b] (km^3 per year)	1990[b] (%)	2000[b] (km^3 per year)	2000[b] (%)
Agriculture												
Withdrawal	525	893	1,130	1,550	1,850	2,050	2,290	69.0	2,680	64.9	3,250	62.6
Consumption	409	679	859	1,180	1,400	1,570	1,730	88.7	2,050	86.9	2,500	86.2
Industry												
Withdrawal	37.2	124	178	330	540	612	710	21.4	973	23.6	1,280	24.7
Consumption	3.5	9.7	14.5	24.9	38.0	47.2	61.9	3.2	88.5	3.8	117	4.0
Municipal supply												
Withdrawal	16.1	36.3	52.0	82.0	130	161	200	6.0	300	7.3	441	8.5
Consumption	4.0	9.0	14	20.3	29.2	34.3	41.1	2.1	52.4	2.2	64.5	2.2
Reservoirs												
Withdrawal	0.3	3.7	6.5	23.0	66.0	103	120	3.6	170	4.1	220	4.2
Consumption	0.3	3.7	6.5	23.0	66.0	103	120	6.2	170	7.2	220	7.6
Total (rounded off)												
Withdrawal	579	1,060	1,360	1,990	2,590	2,930	3,320	100	4,130	100	5,190	100
Consumption	417	701	894	1,250	1,540	1,760	1,950	100	2,360	100	2,900	100

[a] Total water withdrawal is shown in the first line of each category, consumptive use (irretrievable water loss) is shown in the second line.
[b] Estimated.

Source: Shiklomanov (1993).

Table 1.2.4 Annual Runoff and Water Consumption by Continents and by Physiographic and Economic Regions of the World

	Mean annual runoff		Aridity index	Water consumption (km^3 per year)					
				1980		1990		2000	
Continent and region	(mm)	(km^3 per year)	(R/LP)	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
South-east	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).

1.3 WATER USE IN THE UNITED STATES

Dziegielewski et al. (1996) define *water use* from a hydrologic perspective as all water flows that are a result of human intervention in the hydrologic cycle. The National Water Use Information Program (NWUI Program), conducted by the United States Geological Survey (USGS), used this perspective on water use in establishing a national system of water-use accounting. This accounting system distinguishes the following water-use flows: (1) water withdrawals for off-stream purposes, (2) water deliveries at point of use or quantities released after use, (3) consumptive use, (4) conveyance loss, (5) reclaimed wastewater, (6) return flow, and (7) in-stream flow (Solley et al., 1993). The relationships among these human-made flows at various points of measurement are illustrated in Figure 1.3.1. Figure 1.3.2 illustrates the estimated water use by tracking the sources,

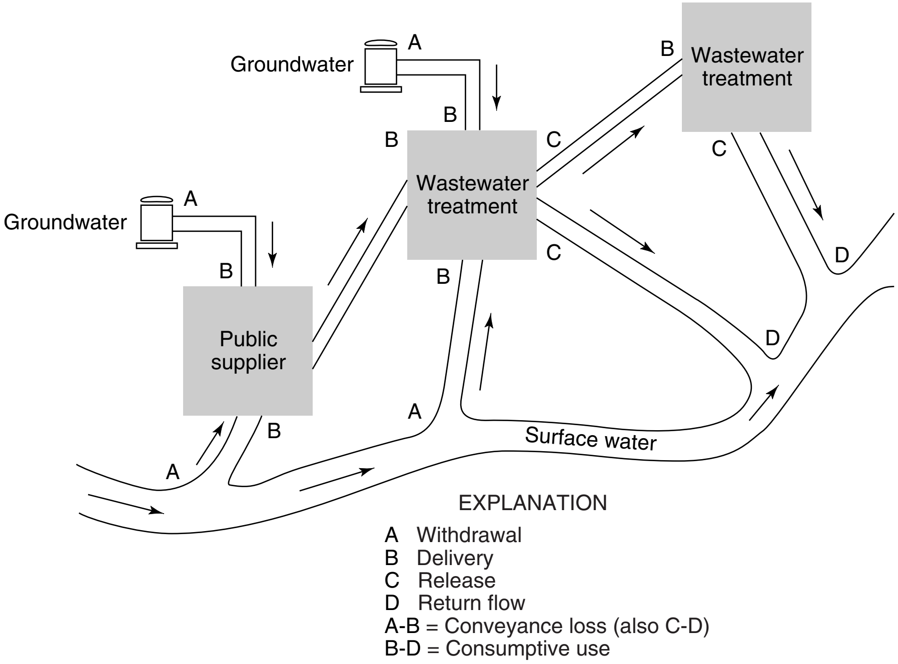

Figure 1.3.1 Definition of water-use flows and losses (from Solley et al. (1993)).

uses, and disposition of freshwater using the hydrologic accounting system given in Figure 1.3.1. Table 1.3.1 defines the major purposes of water use.

Table 1.3.1 Major Purposes of Water Use

Water-use purpose	Definition
Domestic use	Water for household needs such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens (also called residential water use).
Commercial use	Water for motels, hotels, restaurants, office buildings, and other commercial facilities and institutions.
Irrigation use	Artificial application of water on lands to assist in the growing of crops and pastures or to maintain vegetative growth in recreational lands such as parks and golf courses.
Industrial use	Water for industrial purposes such as fabrication, processing, washing, and cooling.
Livestock use	Water for livestock watering, feed lots, dairy operations, fish farming, and other on-farm needs.
Mining use	Water for the extraction of minerals occurring naturally and associated with quarrying, well operations, milling, and other preparations customarily done at the mine site or as part of a mining activity.
Public use	Water supplied from a public water supply and used for such purposes as firefighting, street washing, municipal parks, and swimming pools.
Rural use	Water for suburban or farm areas for domestic and livestock needs, which is generally self-supplied.
Thermoelectric power use	Water for the process of the generation of thermoelectric power.

Source: Solley et al. (1993).

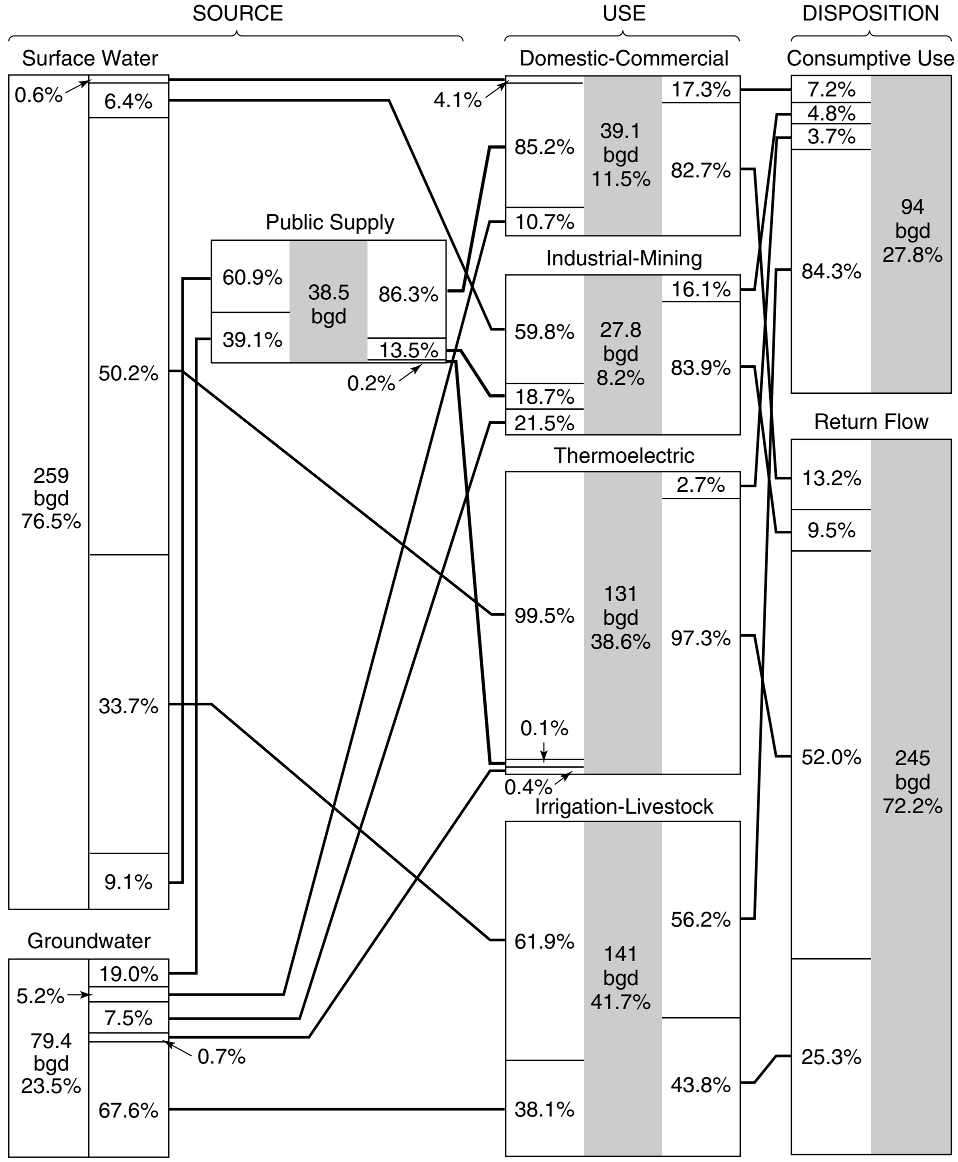

Figure 1.3.2 Estimated water use in the United States, 1990. Freshwater withdrawals and disposition of water in billion gallons per day (bgd). For each water use category, this diagram shows the relative proportion of water source and disposition and the general distribution of water from source to disposition. The lines and arrows indicate the distribution of water from source to disposition for each category; for example, surface water was 76.5 percent of total freshwater withdrawn, and, going from "Source" to "Use" columns, the line from the surface water block to the domestic and commercial block indicates that 0.6 percent of all surface water withdrawn was the source for 4.1 percent of total water (self-supplied withdrawals, public supply deliveries) for domestic and commercial purposes (from Solley, Pierce, and Perlman, (1993)).

1.4 SYSTEMS OF UNITS

The analysis of pressurized (conduit) flow, open-channel flow, and groundwater flows requires an understanding of the elements of fluid mechanics (presented in Chapter 2). A review of the mechanics of materials is a prerequisite to the examination of fluid mechanics principles. Table

1.4.1 lists of the basic mechanical properties of matter with their dimensions and units in the SI system. In the United States much of the technology related to water resources engineering is still based upon the foot-pound-second (FPS) system of units, or what are referred to in this book as U.S. Customary Units. Table 1.4.2 provides a set of correction factors for converting U.S. customary units to SI units.

Table 1.4.1 Definitions, Dimensions, and SI Units for Basic Mechanical Properties

					Dimension of unit	
Property	Symbol	Definition	SI Unit	SI symbol	Derived	Basic
Mass	M		kilogram	kg		kg
Length	l		meter	m		m
Time	t		second	s		s
Area	A	$A = l^2$				m^2
Volume	V	$V = l^3$				m^3
Velocity	v	$v = l/t$				m/s
Acceleration	a	$a = l/t^2$				$\mathrm{m/s^2}$
Force	F	$F = Ma$	newton	N	N	$\mathrm{kg\cdot m/s^2}$
Weight	w	$w = Mg$	newton	N	N	$\mathrm{kg\cdot m/s^2}$
Pressure	p	$p = F/A$	pascal	Pa	$\mathrm{N/m^2}$	$\mathrm{kg/m\cdot s^2}$
Work	W	$W = Fl$	joule	J	N·m	$\mathrm{kg\cdot m^2/s^2}$
Energy		Work done	joule	J	N·m	$\mathrm{kg\cdot m^2/s^2}$
Mass density	p	$p = M/V$				$\mathrm{kg/m^2}$
Weight density	γ	$\gamma = w/V$			$\mathrm{N/m^3}$	$\mathrm{kg/m^2\cdot s^2}$
Stress	σ, τ	Internal response to external p	pascal	Pa	$\mathrm{N/m^2}$	$\mathrm{kg/m\cdot s^2}$
Strain	ϵ	$\epsilon = \Delta V/V$				Dimensionless
Young's modulus	E	Hooke's law			$\mathrm{N/m^2}$	$\mathrm{kg/m\cdot s^2}$

Source: Freeze and Cherry (1979).

Table 1.4.2 Conversion Factors FPS (Foot-Pound-Second) System of Units to SI Units

	Multiply	By	To obtain
Length	ft	3.048×10^{-1}	m
	ft	3.048×10	cm
	ft	3.048×10^{-4}	km
	mile	1.609×103	m
	mile	1.609	km
Area	ft^2	9.290×10^{-2}	m^2
	mi^2	2.590	km^2
	acre	4.047×10^{3}	m^2
	acre	4.047×10^{-3}	km^2
Volume	ft^3	2.832×10^{-2}	m^3
	U.S. gal	3.785×10^{-3}	m^3
	U.K. gal	4.546×10^{-3}	m^3
	ft^3	2.832×10	ℓ
	U.S. gal	3.785	ℓ
	U.K. gal	4.546	ℓ
Velocity	ft/s	3.048×10^{-1}	m/s
	ft/s	3.048×10	cm/s
	mi/h	4.470×10^{-1}	m/s
	mi/h	1.609	km/h
Acceleration	$\mathrm{ft/s^2}$	3.048×10^{-1}	$\mathrm{m/s^2}$

Table 1.4.2 Conversion Factors FPS (Foot-Pound-Second) System of Units to SI Units *(continued)*

	Multiply	By	To obtain
Mass	lb_m*	4.536×10^{-1}	kg
	slug*	1.459×10	kg
	ton	1.016×10^{3}	kg
Force and weight	lb_f*	4.448	N
	poundal	1.383×10^{-1}	N
Pressure and stress	psi	6.895×10^{3}	Pa or N/m^2
	lb_f/ft^2	4.788×10	Pa
	poundal/ft^2	1.488	Pa
	atm	1.013×10^{5}	Pa
	in Hg	3.386×10^{3}	Pa
	mb	1.000×10^{2}	Pa
Work and energy	ft-lbf	1.356	J
	ft-poundal	4.214×10^{-2}	J
	Btu	1.055×10^{-3}	J
	calorie	4.187	J
Mass density	lbm/ft^3	1.602×10	kg/m^3
	slug/ft^3	5.154×10^{2}	kg/m^3
Weight density	lb_f/ft^3	1.571×10^{2}	N/m^3
Discharge	ft^3/s	2.832×10^{-2}	m^3/s
	ft^3/s	2.832×10	ℓ/s
	U.S. gal/min	6.309×10^{-5}	m^3/s
	U.K. gal/min	7.576×10^{-5}	m^3/s
	U.S. gal/min	6.309×10^{-2}	ℓ/s
	U.K. gal/min	7.576×10^{-2}	ℓ/s
Hydraulic conductivity (see also Table 2.3)	ft/s	3.048×10^{-1}	m/s
	U.S. gal/day/ft^2	4.720×10^{-7}	m/s
Transmissivity	ft^2/s	9.290×10^{-2}	m^2/s
	U.S. gal/day/ft	1.438×10^{-7}	m^2/s

*A body whose mass is 1 lb mass (lb_m) has a weight of 1 lb force (lb_f), 1 lb_f is the force required to accelerate a body of 1 lb_m to an acceleration of $g = 32.2\ \text{ft/s}^2$. A slug is the unit of mass which, when acted upon by a force of 1 lb_f, acquires an acceleration of 1 ft/s^2.

Source: Freeze and Cherry (1979).

1.5 WHAT IS WATER?

The water molecule is a unique combination of hydrogen and oxygen atoms, with electrons being shared between them as shown in Figure 1.5.1. 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 Figure 1.5.2 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 Figure 1.5.2, 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 from (or escape) the liquid surface in a process called evaporation, forming

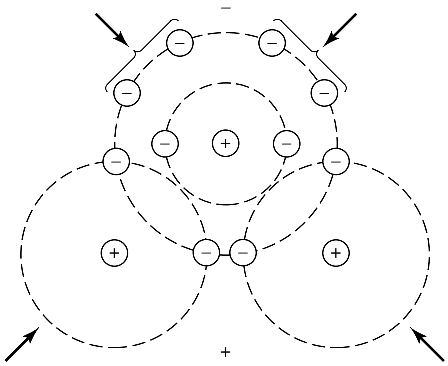

Figure 1.5.1 The water molecule (after Sutcliffe (1968)).

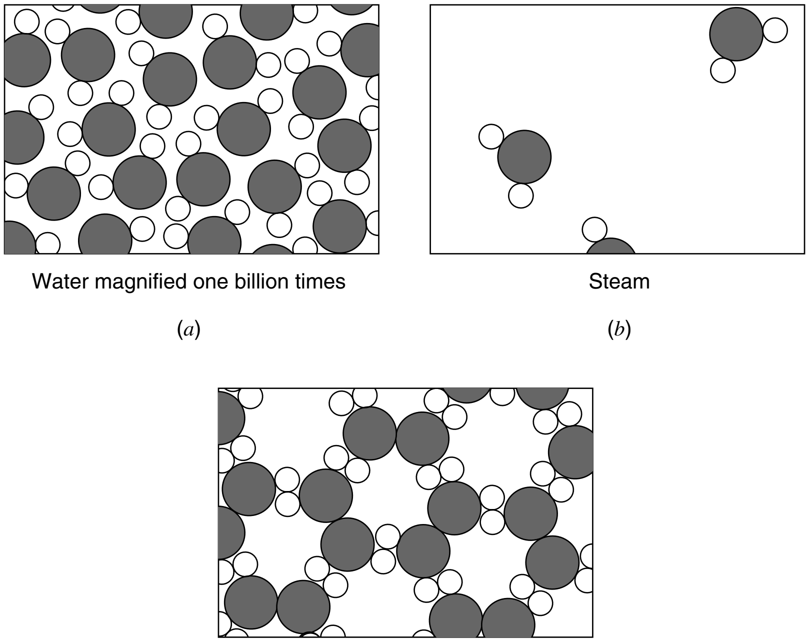

Figure 1.5.2 The three states of water (from Feynman (1963)).

a gaseous or vapor phase. 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, (4) *melting*—solid to liquid, and (5) *freezing*—liquid to solid.

The physical properties of water are unique among 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. Compared to most common liquids, water has a high viscosity and a high surface tension, which are 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. In 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. The latent heat of vaporization is about eight 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).

1.6 THE FUTURE OF 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, of the water 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. The hydrologic cycle must be defined in terms of both water quantity and water quality. Because of the very complex water issues and problems that we face today, many fields of study are involved in their solution. These include the biological sciences, engineering, physical sciences, and social sciences (see Figure 1.1.1), illustrating the wide diversity of disciplines involved in water resources.

As the twenty-first century approaches, 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 ozone layer; destruction of rain forests; threats to wetland, farmland, and other renewable resources; and many others.

These problems are very different from those that humans have faced before. The fact that there are so many things undiscovered by the human race leads me to the statement by Sir Isaac Newton, shortly before his death in 1727:

> *I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, while the great ocean of truth lay all undiscovered before me.*

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