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. Areas in the 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

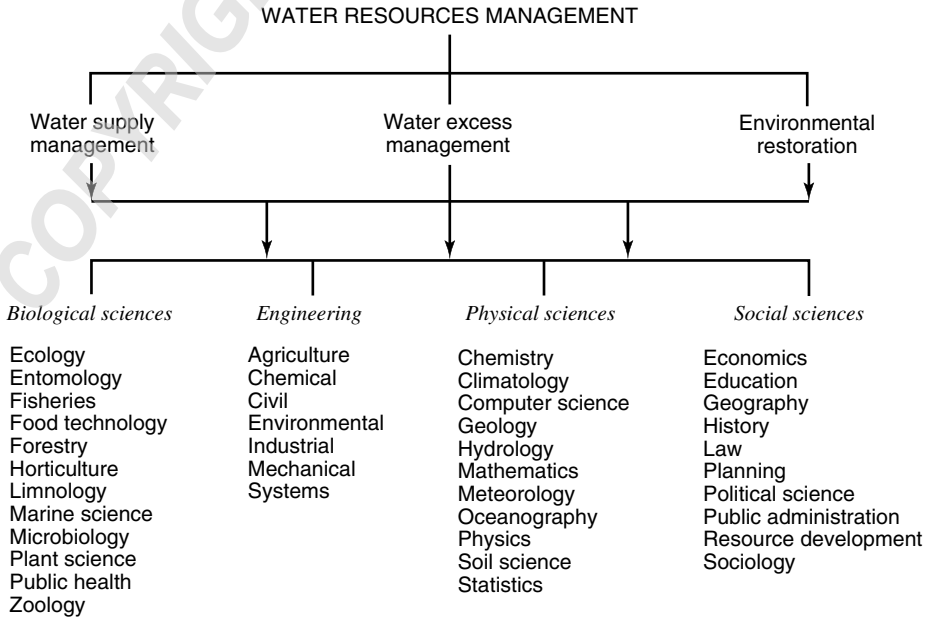


Figure 1.1.1 Ingredients of water resources management (from Mays, 1996).

engineering as used in this book focuses on the engineering aspects of hydrology and hydraulics for water supply management and water excess management.

Humans have spent most of their existence as hunting and food-gathering beings. Only in the last c. 9000–10,000 years, they discovered how to grow agricultural crops and tame animals. Such revolution probably first took place in the hills to the north of Mesopotamia. From there the agricultural revolution spread to the Nile and Indus Valleys. During this agricultural revolution, permanent villages replaced a wandering existence. About 6000–7000 years ago, farming villages of the Near East and Middle East became cities. Hydraulic technology began during antiquity long before the great works of such investigators such as Leonardo da Vinci (1452–1519) and Isaac Newton (1642–1727), and even long before Archimedes (287–212 BC) (Mays, 2008). During the Neolithic Age (c. 5700–3200 BC), the first successful efforts to control the water flow were driven (such as dams and irrigation systems) due to the food needs and were implemented in Mesopotamia and Egypt (Mays et al., 2007). Urban water-supply and sanitation systems are dated later during the Bronze Age (c. 3200–1100 BC).

Today it is well documented that many are not achievements of present day, but date back to 3000–4000 years ago. These achievements include both water and wastewater constructions (such as dams, wells, cisterns, aqueducts, sewerage and drainage systems, toilets, and even recreational structures). These hydraulic works also reflect advanced scientific knowledge, which allowed the construction of tunnels from two openings and the transportation of water both by gravity flow in open channels and by pressurized flow in closed conduits. Certainly, technological developments were driven by the necessities to make efficient use of natural resources, to make civilizations more resistant to destructive natural elements, and to improve the standards of life. With respect to the latter, the Greek (including Minoan) and Roman civilizations developed an advanced, comfortable, and hygienic lifestyle, as manifested from public and private bathrooms and flushing toilets, which can only be compared to the modern one, reestablished in Europe and North America in the beginning of the last century.

1.1.1 Qanats

The Persian qanat technology (dating back over 3000 years) is shown in Figure 1.1.2. Qanat technology has been referred to as the *foggara* in Algeria, as the *khettara* in Morocco, as the *kariz* or *karez* in India and Afghanistan, as the *Ghail* and *Miyan* in Yemen, and as the *Qanat Romani* in Syria. In countries such as Iran, Oman, Afghanistan, Pakistan, China, and Azerbaijan, *qanats* still play a

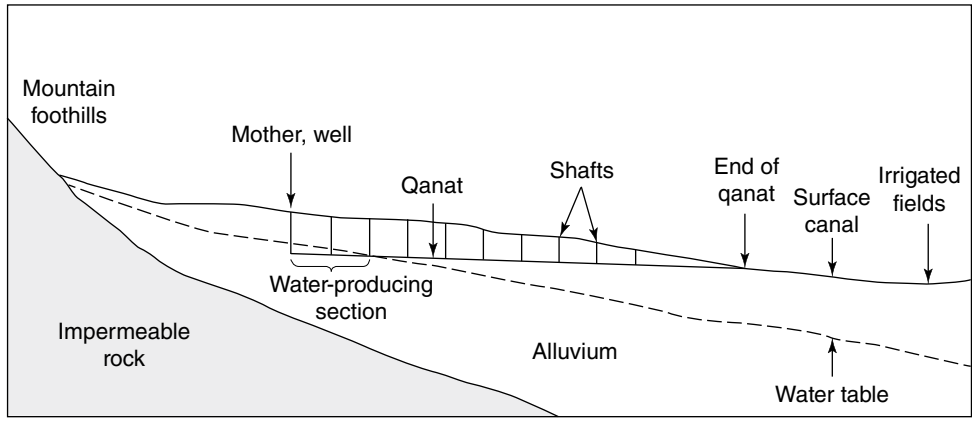


Figure 1.1.2 Components of qanats.

significant role as a sustainable water technology (Hamidian et al., 2015). In fact, the *aflaj* in Oman provides the water supply for one-third of all irrigation (Al-Ghafri, 2008). However, in many regions the qanat technology is in danger of being eliminated due to modern technology such as new canal structures bringing water from mountainous areas and/or groundwater levels being lowered because of extensive pumping.

1.1.2 Cisterns

Cisterns for storing water were used by ancient civilizations and have continued to be used since. Mari in ancient Mesopotamia had a canal connected to the city from both ends and passed through the city. Servant women filled the 25 m^3 cistern of the palace with water supplied by the canal. Later other cisterns were built in Mari and connected to an extended rainfall collection system. The ancient Minoan and Mycenaean settlements used cisterns a 1000 years before the classical and Helenistic-Greek cities. Cisterns were used to supply (store runoff from roof tops and court yards) water for the households through the dry summers of the Mediterranean. Two of the earliest large cisterns of Minoan Crete were built in the first half of the 2nd millennium BC, which was the time of the first Minoan palaces at Myrtos-Pyrgos (see Cadogan, 2006). Figure 1.1.3 (a and b) shows two cisterns on

(*a*)

(*b*)

Figure 1.1.3 Cisterns at (*a*) Myrtos-Pyrgos and (*b*) Kato Zakros. (Photos by L.W. Mays)

(*a*)

Figure 1.1.4 (*a*) Roman cistern below Athens Acropolis. (Photos by L.W. Mays)

(*b*)

Figure 1.1.4 (*b*) Piscina Mirabilis. (Photos by L.W. Mays)

Crete at Myrtos-Pyrgos and at Kato-Zakros. Both cisterns are circular with vertical walls and rounded bottoms. The walls and bottom are coated with white lime plaster 1- to 2-cm thick (Cadogan, 2006).

The Romans also made extensive use of cisterns. Figure 1.1.4a shows the Roman cistern at the base of the Acropolis in Athens, Greece. The Piscina Mirabilis (Figure 1.1.4b) is one of the largest Roman cisterns (capacity of 12,600 m^3 of water). The cistern was supplied with water from the Augustan aqueduct, the Serino aqueduct that was built from Serino to Miseno. The Serino aqueduct, 96-km long with seven branches, supplied many towns including Pompeii, Herculaneum, Acerra, Atella, Nola, and others. The total elevation drop from the source, the Acquaro-Pelosi spring in Serino to the Piscina Mirabilis is 366 m (0.38 percent). This large cistern is 72 m by 27 m in plan and is 15-m deep (according to Hodge, 2002).

(*a*)

Figure 1.1.5 (*a*) Nabataean cistern system at Petra, Jordan. (Photos by L.W. Mays)

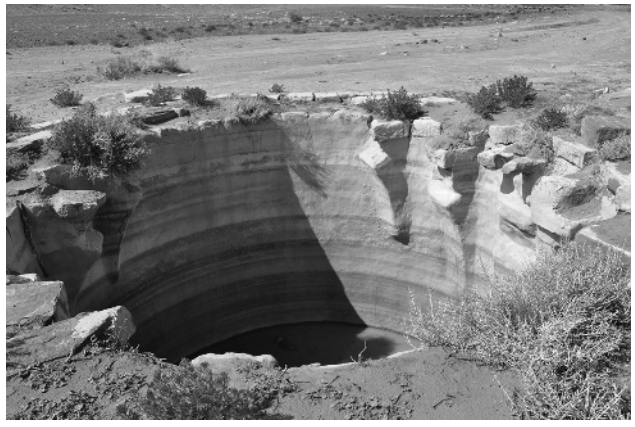
(*b*)

Figure 1.1.5 (*b*) Nabataean cistern near the Garden Tomb at Petra, Jordan. (Photos by L.W. Mays)

Rainwater harvesting was used extensively in Petra by the Nabataeans (300 BC–300 AD). In Petra this meant using the technology on the high places and on bare sandstone walls with many innovations. The Nabataeans used various types of cisterns that they carved out of the rock and waterproofed using plaster as shown in Figure 1.1.5 (a and b). These cisterns ranged from small pools on the highlands to catch runoff to rectangular-shaped cisterns at the bottom of the natural drips. Small pools were carved out of the highland and evolved into bell-shaped cisterns. These large cisterns are similar to large rooms carved out of vertical walls into which complex canals and pipe networks flow (Laureano, 2001). What is so unique is that the Nabataeans used every slope and surface to harvest rainfall and stored every water source from a few drops to the large floods. Figure 1.1.6 (a and b) shows Nabataean cistern at Humeima, Jordan. Note the arches in the photos illustrating the influence of the Romans.

(*a*)

Figure 1.1.6 (*a*) Nabataean cistern at Humeima, Jordan. (Photos by L.W. Mays)



(*b*)

Figure 1.1.6 (*b*) Nabataean cistern at Humeima, Jordan. (Photos by L.W. Mays)

The Byzantine Empire and Eastern Roman Empire are names used to describe the Roman Empire during the Middle Ages, with the capital in Constantinople (Istanbul). During the thousand-year existence of the empire the influence spread widely into North Africa and the near East during the Middle Ages. Figure 1.1.7a shows a Byzantine cistern at the base of the Acropolis in Athens.

During the Byzantine times in Constantinople at least 36 cisterns were constructed (Lerner, 1989). The Basilica Cistern, or in Turkish the 'Yerebatan Sarayi', was the largest (140 m $\times$ 70 m and capable of holding 80,000 m^3) known covered cistern, probably completed in the early 6th century. This cistern, shown in Figure 1.1.7b, is an underground cistern, having 336 marble columns each 9-m high. The columns are arranged in 12 rows each with 38 columns, spaced 4.9 m apart. Figure 1.1.8 shows an Ottoman cistern built for military purposes of the Ottoman Army, located near Bodrum, Turkey.

(*a*)

Figure 1.1.7 (*a*) Byzantine cistern at the base of the Acropolis in Athens. (Photos by L.W. Mays)

(*b*)

Figure 1.1.7 (*b*) Basilica cistern of Constantinople in Istanbul, Turkey. (Photos by L.W. Mays)

Figure 1.1.8 Ottoman cistern built for military purposes of the Ottoman Army, located near Bodrum, Turkey. (Photos by L.W. Mays)

1.1.3 Aqueducts

Figure 1.1.9 illustrates the components of an aqueduct system. The upstream end of the system is the source and the downstream end is the distribution system (*castellum divorsium*), followed by the distribution system. Components include covered channels, storage and settling basins, aqueduct bridges, subterranean conduits, and arcades of elevated tanks. Other aqueducts also include inverted siphons, which also include a header tank, a pressurized conduit, venter bridge, and a receiving tank. The Roman aqueduct bridge in Segovi, Spain is shown in Figure 1.1.10. Aqueducts were also made of terracotta pipe such as the Peisistratean aqueduct built by the ancient Greeks in Athens, shown in Figure 1.1.11 (a and b).

1.1.4 Irrigation Systems

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 9000 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

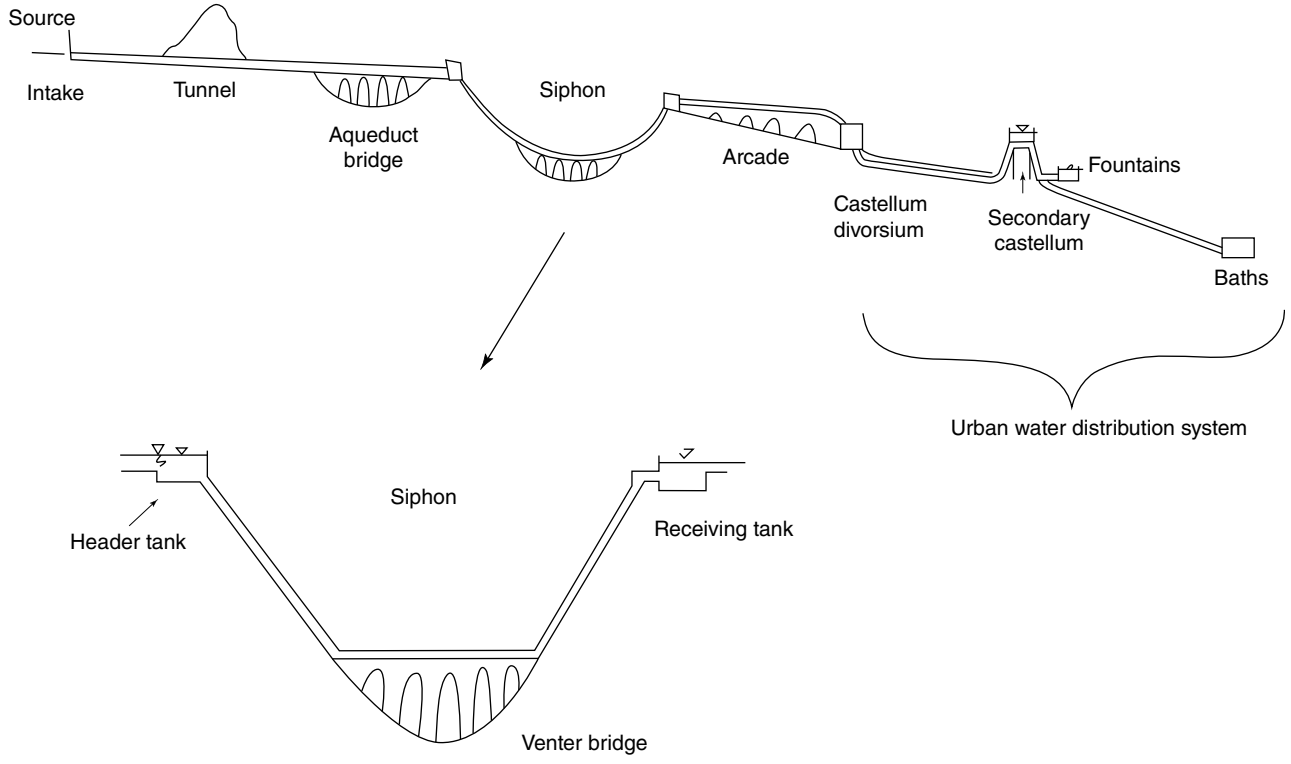
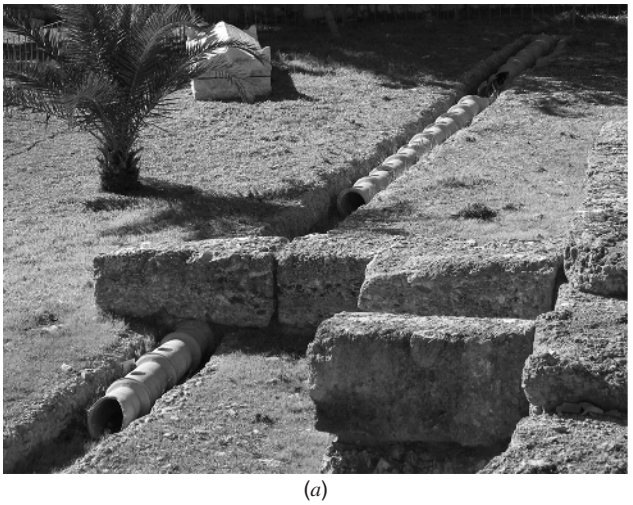


Figure 1.1.9 Components of an aqueduct system.

Figure 1.1.10 Roman aqueduct bridge in Segovia, Spain. (Photos by L.W. Mays)



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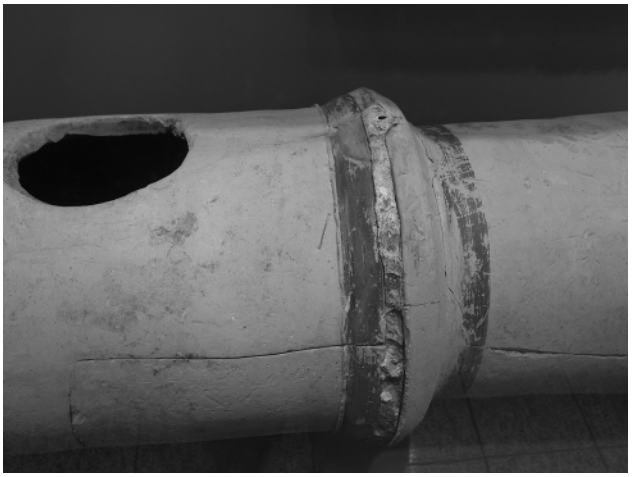

(*b*)

Figure 1.1.11 Peisistratean aqueduct built by the ancient Greeks in Athens ca. 510 BC during the time of the tyrant Peisistratos and his descendants. (*a*) Terracotta pipe segments laid in a channel. (*b*) Pipe segment with lead pipe joint and elliptical pipe opening. (Photos by L.W. Mays)

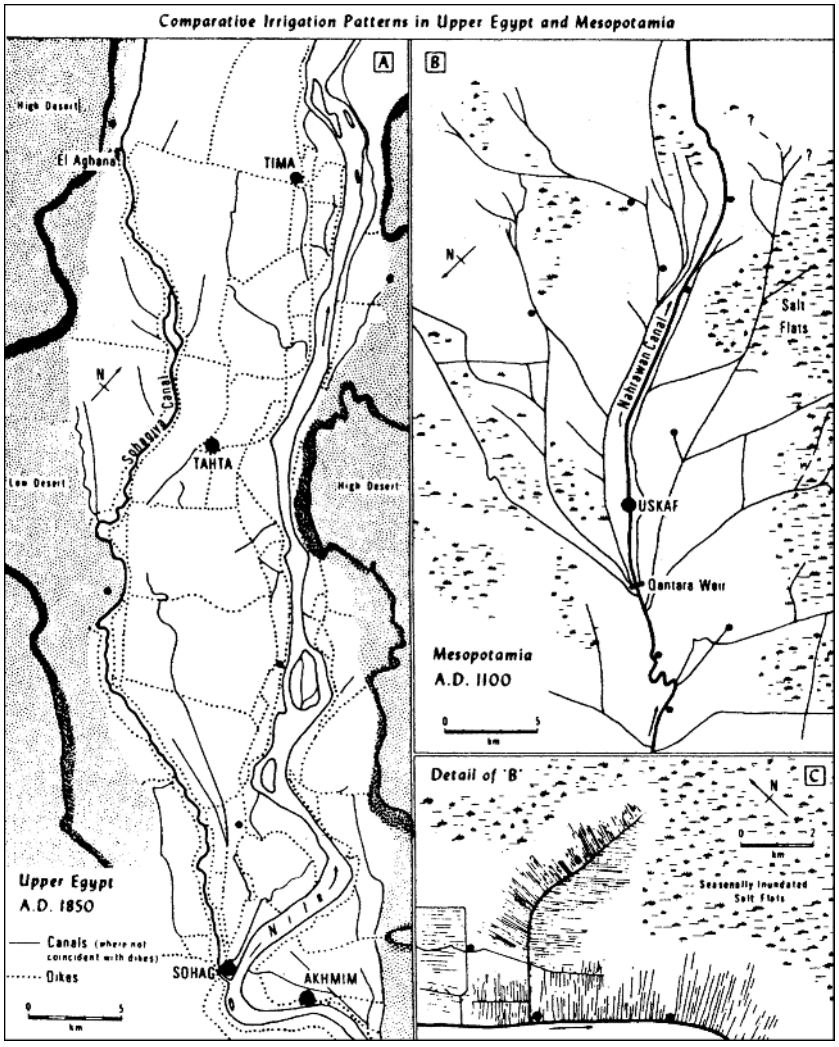

Figure 1.1.12 Comparative irrigation networks in Upper Egypt and Mesopotamia. (*a*) Example of linear, basin irrigation in Sohag province, ca. AD 1850; (*b*) Example of radial canalization system in the lower Nasharawan region southeast of Baghdad, Abbasid (AD (Photo copyright by L.W. Mays) 883–1150) (modified from R. M. Adams. 1965, Fig. 9. Same scale as Egyptian counterpart); (*c*) Detail of field canal layout in (*b*) (simplified from Adams, 1965, Fig. 10. Figure as presented in Butzer, 1976).

Figure 1.1.12) and by the Hobokam in North America (see Figure 1.1.13). The world's oldest large dam was the Sadd-el-kafara dam built in Egypt between 2950 and 2690 BC. The oldest known pressurized water distribution (approximately 2000 BC) 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 (see Mays, 2007, 2008, 2010 and Mays et al., 2007).

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

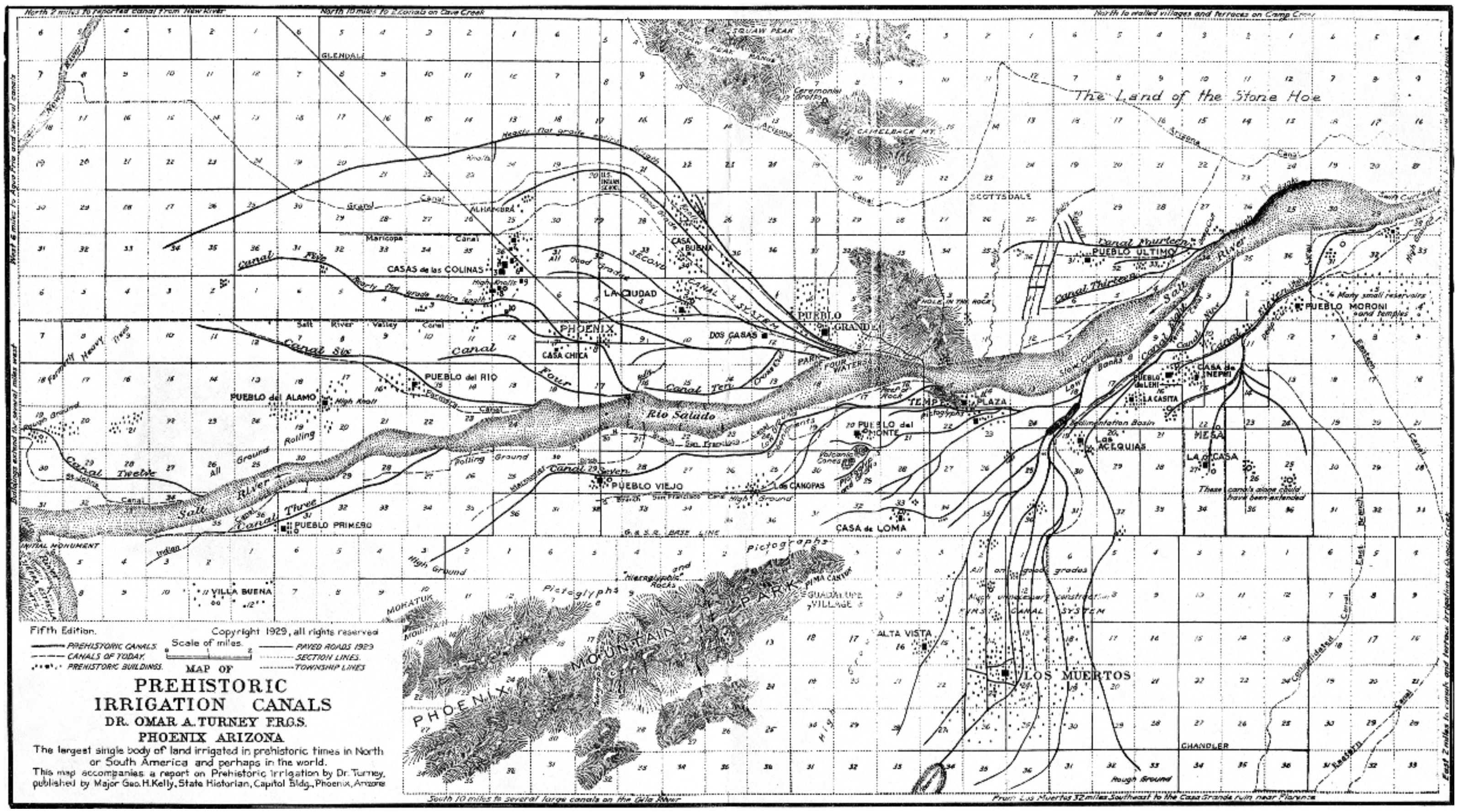

Figure 1.1.13 Canal building in the Salt River Valley with a stone hoe held in the hand without a handle. These were the original engineers, the true pioneers who built, used, and abandoned a canal system when London and Paris were clusters of wild huts (from Turney, 1922). (Courtesy of Salt River Project, Phoenix, Arizona.)

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	Percentage of global reserves: Of freshwater
World ocean	361,300	1,338,000	3700	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	1463	1.74	68.7
Antarctic	13,980	21,600	1546	1.56	61.7
Greenland	1802	2340	1298	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	2058.7	176.4	85.7	0.013	—
Fresh	1236.4	91	73.6	0.007	0.26
Saline	822.3	85.4	103.8	0.006	—
Swamp water	2682.6	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	2718	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	4.0	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	12.0	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	86.0	64.5	50.3	32.2
West	2.33	97.9	77.1	58.6	45.8	25.7
Central	4.46	34.0	27.0	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	23.0	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		1990[b]		2000[b]	
							(km^3 per year)	(%)	(km^3 per year)	(%)	(km^3 per year)	(%)
Agriculture												
Withdrawal	525	893	1130	1550	1850	2050	2290	69.0	2680	64.9	3250	62.6
Consumption	409	679	859	1180	1400	1570	1730	88.7	2050	86.9	2500	86.2
Industry												
Withdrawal	37.2	124	178	330	540	612	710	21.4	973	23.6	1280	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	1060	1360	1990	2590	2930	3320	100	4130	100	5190	100
Consumption	417	701	894	1250	1540	1760	1950	100	2360	100	2900	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

Continent and region	Mean annual runoff (mm)	Mean annual runoff (km^3 per year)	Aridity index (R/LP)	Water consumption (km^3 per year)					
				1980		1990		2000	
				Total	Irretrievable	Total	Irretrievable	Total	Irretrievable
Europe	310	3210	—	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	8200	—	663	224	724	255	796	302
Canada and Alaska	390	5300	0.8	41	8	57	11	97	15
United States	220	1700	1.5	527	155	546	171	531	194
Central America	450	1200	1.2	95	61	120	73	168	93
Africa	150	4570	—	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	1350	2.5	19	14	33	23	51	34
Central	470	1909	0.8	2.8	1.3	4.8	2.1	8.4	3.4
Asia	330	14,410	—	1910	1380	2440	1660	3140	2020
North China and Mongolia	160	1470	2.2	395	270	527	314	677	360
South	490	2200	1.3	668	518	857	638	1200	865
West	72	490	2.7	192	147	220	165	262	190
South-east	1090	6650	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	3350	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	l230	3126	0.6	15	11	23	16	33	20
Brazil	720	6148	0.7	23	10	33	14	48	21
West	740	1714	1.3	40	30	45	32	64	44
Central	170	812	2.0	33	20	48	24	70	31
Australia and Oceania	270	2390		29	15	38	17	47	22
Australia	39	301	4.0	27	13	34	16	42	20
Oceania	1560	2090	0.6	2.4	1.5	3.3	1.8	4.5	2.3
Land area (rounded off)	—	44,500	—	3320	1450	4130	2360	5190	2900

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, 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.

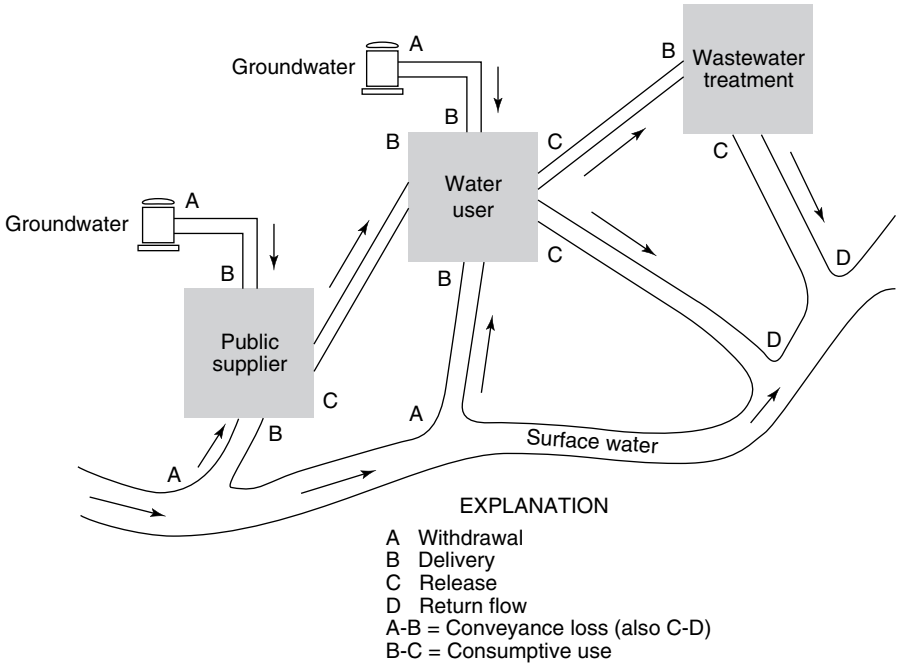

Figure 1.3.1 Definition of water-use flows and losses (from Solley et al., 1993).

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).

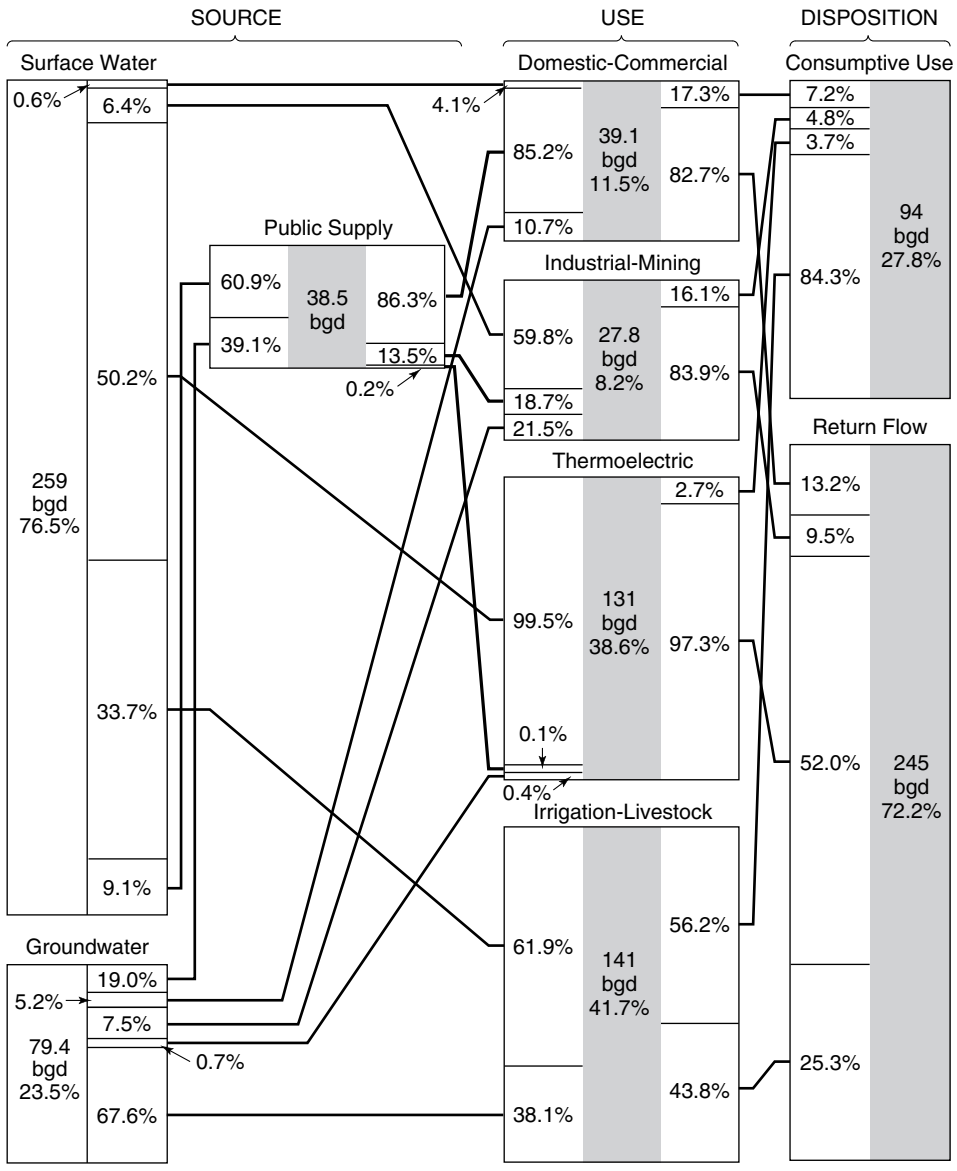

Figure 1.3.2 Estimated water use in the United States, 1990. Freshwater withdrawals and disposition of water in billion gallons per day (bgd). For each water-use category, this diagram shows the relative proportion of water source and disposition and the general distribution of water from source to disposition. 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 et al., 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 3). A review of the mechanics of materials is a prerequisite to the examination of fluid mechanics principles. Table 1.4.1 lists the

Table 1.4.1 Dimensions and SI Units for Basic Mechanical Properties

			Dimension of unit	
Property	SI unit	SI symbol	Derived	Basic
Mass	kilogram	kg		kg
Length	meter	m		m
Time	second	s		s
Area				m^2
Volume				m^3
Velocity				m/s
Acceleration				m/s^2
Force	newton	N		$kg \cdot m/s^2$
Weight	newton	N		$kg \cdot m/s^2$
Pressure	pascal	Pa	N/m^2	$kg/m \cdot s^2$
Work	joule	J	$N \cdot m$	$kg \cdot m^2/s^2$
Energy	joule	J	$N \cdot m$	$kg \cdot m^2/s^2$
Mass density				kg/m^2
Weight density			N/m^3	$kg/m^2 \cdot s^2$
Stress	pascal	Pa	N/m^2	$kg/m \cdot s^2$

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 1.4.2 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	1.609×10^{3}	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	ft/s^2	3.048×10^{-1}	m/s^2

(*Continued*)

Table 1.4.2 (*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	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

1.5 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.

In the 21st 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 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.*

1.6 WATER–ENERGY NEXUS

Historically, the interactions between energy and water have been considered on a regional or technological basis. Water and energy systems have been developed, managed, and regulated independently. Because of the present-day interdependence of water and energy systems the emphasis of the water–energy nexus (see Figure 1.6.1). Water is used in all phases of energy production and electricity generation. Energy is required to pump, convey, and deliver water for

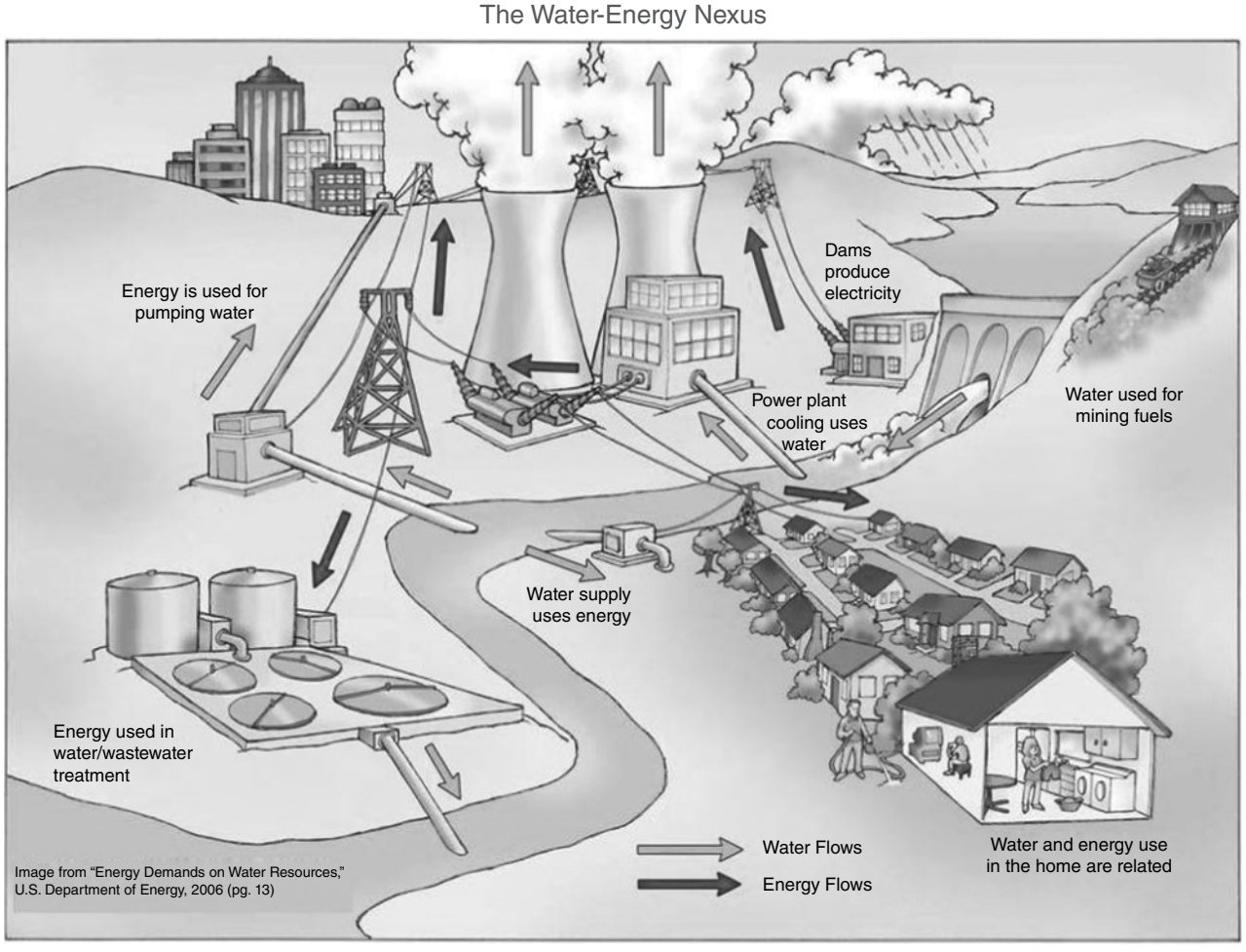

Figure 1.6.1 Water–Energy Nexus. (U.S. Department of Energy, 2006)

diverse human uses, and then treat wastewaters before returning to the environment. Agriculture is the single largest consumer of water and competes directly with energy sector for water.

Importance has been placed on the interdependencies of water and energy infrastructure because of natural hazards (droughts, hurricanes, and floods), climate change, changing demographics, and technological changes. Severe droughts affected more than a third of the United States in 2012 with limited water availability that constrained the operation of some power plants and other energy-production activities. Hurricane Sandy, Harvey, Maria, and others have demonstrated that vital water infrastructure can be impaired when it loses power and/or water infrastructure is destroyed.

Hydraulic fracturing and horizontal drilling have added complexity to the relationship between energy and water resources. Climate change is already affecting precipitation and temperature patterns around the world. Population growth and regional migration trends will result in new challenges for the water–energy nexus. One example is the population increase in arid areas such as the Southwest United States and other arid regions around the world further impacting the management energy and water systems. New technologies in the energy and water sectors could shift water and energy demands.

Flows of energy and water are interconnected intrinsically. This is due mostly to the characteristics and properties of water that make it so useful for producing energy and the energy requirements to treat and distribute water for human use. Figure 1.6.2 is a Sankey diagram illustrating the interconnectivity of water and energy flow and captures the magnitude flows for the United States. Note the breakdown of useful and waste energy in each sector (dark vs. light gray) due to the nature of heat engines, which cannot convert all thermal energy into useful work and consequently lose a portion of their heat to the environment.

Thermoelectric power generation withdraws large quantities of water for cooling and dissipates tremendous quantities of primary energy due to inefficiencies in converting thermal energy to electricity. The intensity of required water and dissipated energy varies with generation and cooling technology. Figure 1.6.3 further illustrates the water use for thermoelectric generation and other sectors.

The connection of water and energy to land, including connection to regional and global climate change variability are also very important. Figure 1.6.4 shows the connection of energy and water to land (EWL) and the global and regional climate change variability. Figure 1.6.5 is an illustration of the climate–EWL nexus showing linkages and interactions among the three resource sectors energy, water, and land with climate variability and change. Other references on the energy–water–land systems include: Dale (2011), EPRI (2011), Mozer (2011), Mozer (2012), and U.S. Department of Energy (2013a and 2013b).

1.6.1 Human Systems and Earth Natural Systems

The U.S. Department of Energy has taken the lead in the development of integrated assessment models (IAMs), which take a comprehensive approach to representing complex interactions among human activities and Earth systems at the global scale. Figure 1.6.6 illustrates the comprehensive treatment of human and Earth systems, including the EWL components.

Water follows a series of stages in urban water supply systems starting with the sources of water, followed by drinking water treatment processes, followed by water distribution to customers, followed by customer use, and finally the wastewater treatment stage. The drinking water processes include all such activities involved in conversion of raw-water to water safe for human consumption including extraction of raw-water, water treatment, and distribution of treated water to consumers. The customer-use stage of water life cycle includes use by residential/commercial and industrial customers. The last stage in the water life cycle consists of various processes such as wastewater treatment, effluent discharge and reuse, and so on. Every stage involved in urban water life cycle is

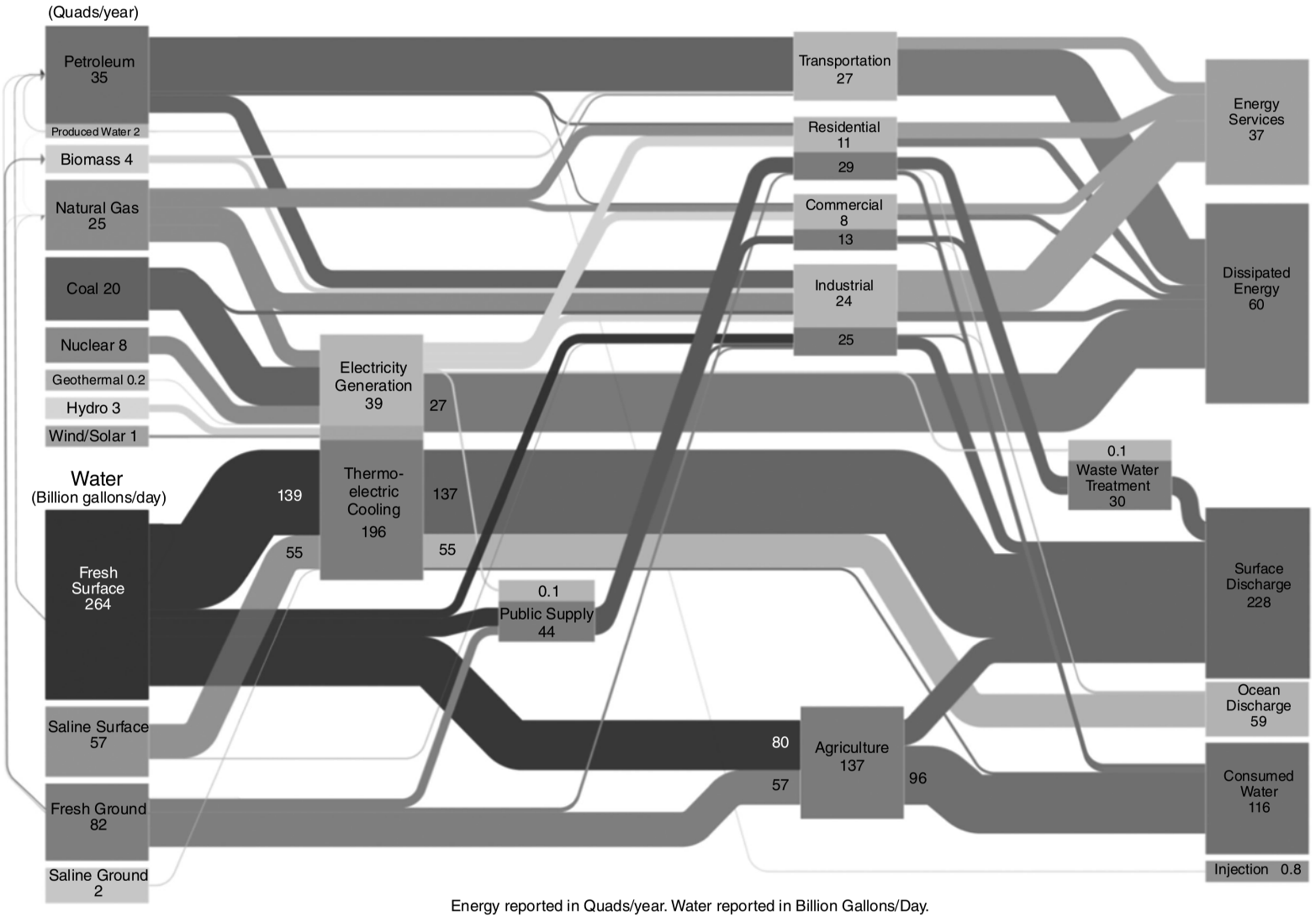

Figure 1.6.2 Hybrid Sankey diagram of 2011 U.S. interconnected water and energy flows. A Sankey diagram is a flow diagram in which the width of the arrows is shown proportionally to the flow quantity. A quad is 10^{15}Btu, or 1.055×10^{18} joules. Note the breakdown of useful and waste energy in each sector (dark vs. light gray) due to the nature of heat engines, which cannot convert all thermal energy into useful work and consequently lose a portion of their heat to the environment, U.S. Department of Energy (2014).

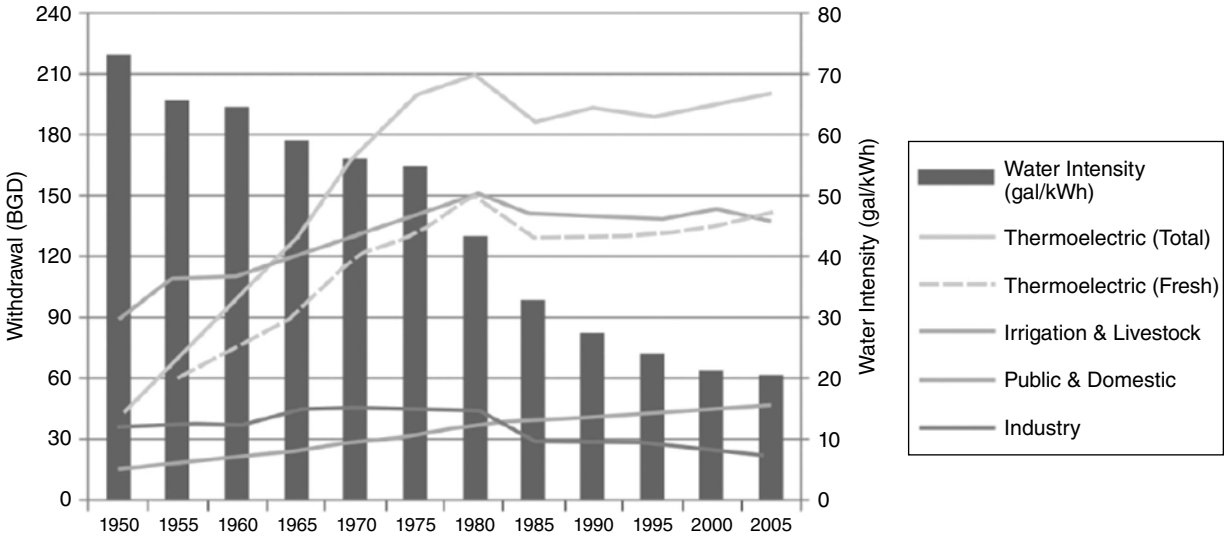

Figure 1.6.3 Water use for thermoelectric generation and other sectors. (U.S. Department of Energy, 2014)

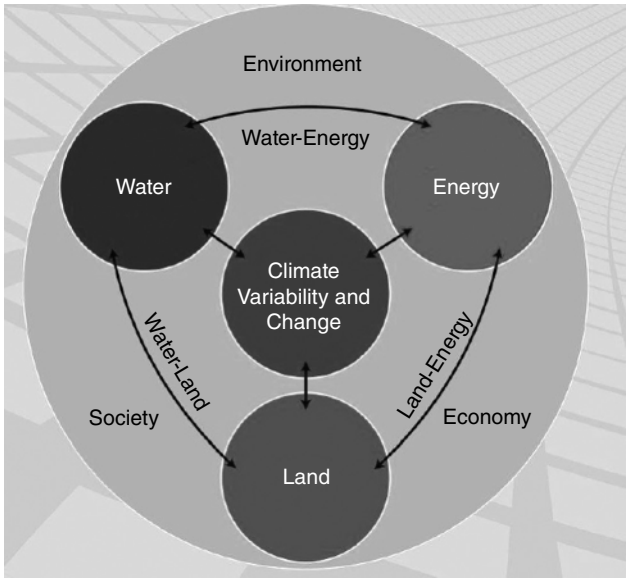

Figure 1.6.4 The climate–energy–water–land (EWL) Nexus. (Skaggs et al., 2012)

very energy dependent and involves a high level of electrical power usage. The interdependencies of a water distribution infrastructure over the electric grid depend on several factors regarding the layout and components of the system. Major energy consumption for pumping is required for the conveyance (pumping) of water from the source to treatment facility and finally to the customer.

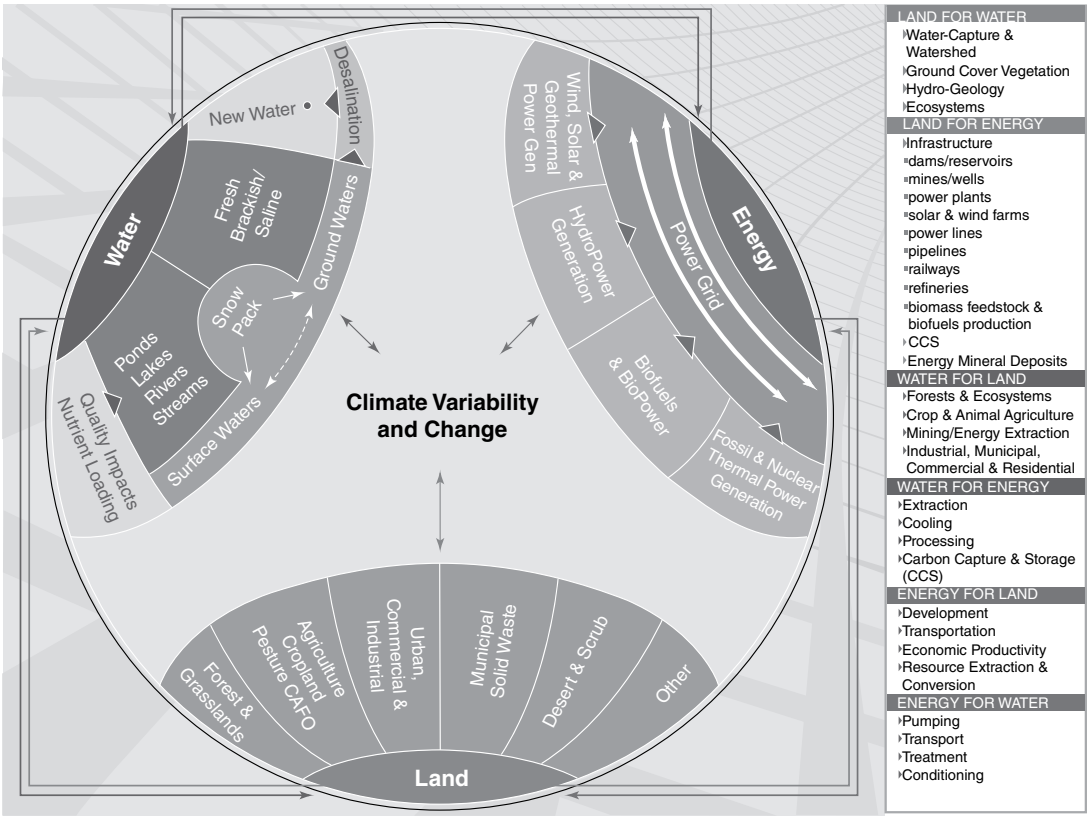

Figure 1.6.5 Illustration of the climate–EWL nexus showing linkages and interactions among the three resource sectors with climate variability and change (Skaggs et al., 2012).

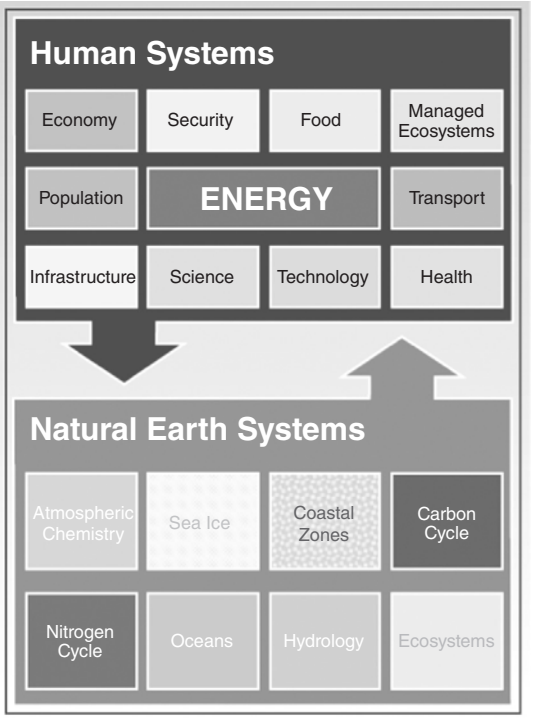

Figure 1.6.6 Interactions of human systems and natural earth systems. (U.S. Department of Energy, 2009)

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