Contents

3 Groundwater Movement 86

4 Groundwater and Well Hydraulics 146

5 Water Wells 206

13 Artificial Recharge of Groundwater 547

Chapter 1

Introduction

Groundwater hydrology may be defined as the science of the occurrence, distribution, and movement of water below the surface of the earth. *Geohydrology* has an identical connotation, and *hydrogeology* differs only by its greater emphasis on geology. Utilization of groundwater dates from ancient times, although an understanding of the occurrence and movement of subsurface water as part of the hydrologic cycle is recent.

The U.S. National Research Council (1991) presented the following definition of hydrology:

> Hydrology is the science that treats the waters of the Earth, their occurrence, circulation, and distribution, their chemical and physical properties, and their reaction with the environment, including the relation to living things. The domain of hydrology embraces the full life history of water on Earth.

Section 1.5 describes in further detail the concepts of the hydrologic cycle.

The importance of groundwater (hydrology) in the hydrologic cycle has been the subject of extensive technical research and publishing by many investigators over the past decades. Many of these publications are introduced in this book. Also, many books written on the subject of the fate of water have caught the attention of the general public, especially those interested in saving our resources. These include books by Carson[18] and de Villiers,[28] among others.

1.1 SCOPE

Groundwater (referred to without further specification) is commonly understood to mean water occupying all the voids within a geologic stratum. This *saturated zone* is to be distinguished from an *unsaturated,* or *aeration, zone* where voids are filled with water and air. Water contained in saturated zones is important for engineering works, geologic studies, and water supply developments; consequently, the occurrence of water in these zones will be emphasized here. Unsaturated zones are usually found above saturated zones and extend upward to the ground surface; because water here includes soil moisture within the root zone, it is a major concern of agriculture, botany, and soil science. No rigid demarcation of waters between the two zones is possible, for they possess an interdependent boundary, and water can move from zone to zone in either direction. The interrelationships are described more fully in Chapter 2.

Groundwater plays an important part in petroleum engineering. Two-fluid systems, involving oil and water, and three-fluid systems, involving gas, oil, and water, occur frequently in development of petroleum. Although the same hydrodynamic laws govern flows of these systems and groundwater, the distinctive nature of water in petroleum reservoirs sets it apart from other groundwater. Major differences exist in water quality, depth of occurrence, and methods of development and utilization, all of which contribute to a separation of interests and applications. Therefore, groundwater in petroleum reservoirs will not be treated specifically in this book. It should be noted, however, that groundwater hydrology has gained immeasurably from research conducted by the petroleum industry.

1.2 HISTORICAL BACKGROUND

1.2.1 *Qanats*

Groundwater development dates from ancient times.[15, 47*] The Old Testament contains numerous references to groundwater, springs, and wells. Other than dug wells, groundwater in ancient times was supplied from horizontal wells known as *qanats.*[†] These persist to the present day and can be found in a band across the arid regions of Southwestern Asia and North Africa extending from Afghanistan to Morocco. A cross section along a qanat is shown in Figure 1.2.1. Typically, a gently sloping tunnel dug through alluvial material leads water by gravity flow from beneath the water table at its upper end to a ground surface outlet and irrigation canal at its lower end.[13] Vertical shafts dug at closely spaced intervals provide access to the tunnel.[81] Qanats are laboriously hand constructed by skilled workers employing techniques that date back 3,000 years.[‡]

Iran possesses the greatest concentration of qanats; here some 22,000 qanats supply 75 percent of all water used in the country. Lengths of qanats extend up to 30 km, but most are less than 5 km.[13] The depth of the qanat mother well (see Figure 1.2.1) is normally less than 50 m, but instances of depths exceeding 250 m have been reported. Discharges of qanats vary seasonally with water table fluctuations and seldom exceed 100 m^3/hr. Indicative of the density of qanats is the map in Figure 1.2.2. Based on aerial photographs of the Varamin Plain, located 40 km southeast of Tehran, this identifies 266 qanats within an area of 1,300 km^2.

1.2.2 Groundwater Theories

Utilization of groundwater greatly preceded understanding of its origin, occurrence, and movement. The writings of Greek and Roman philosophers to explain origins of springs and ground-

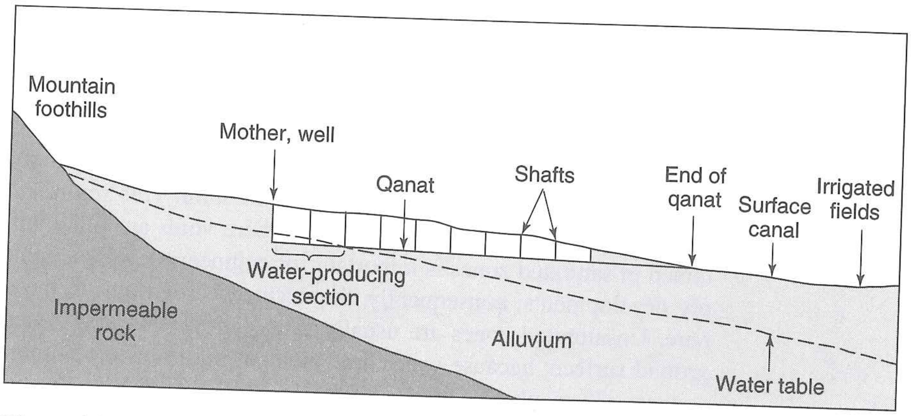

Figure 1.2.1. Vertical cross section along a qanat (after Beaumont[12]).

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[*] Superscript numbers refer to references at the end of the chapter.

[†] *Qanat* comes from a Semitic word meaning "to dig." There are several variants of the name, including *karez, foggara,* and *falaj,* depending on location; in addition, there are numerous differences in spelling.[26]

[‡] Illustrative of the tremendous human effort expended to construct a qanat is a calculation by Beaumont.[13] The longest qanat near Zarand, Iran, is 29 km long with a mother well depth of 96 m and with 966 shafts along its length; the total volume of material excavated is estimated at 75,400 m^3.

water contain theories ranging from fantasy to nearly correct accounts.[1, 6] As late as the seventeenth century it was generally assumed that water emerging from springs could not be derived from rainfall, for it was believed that the quantity was inadequate and the earth too impervious to permit penetration of rainwater far below the surface. Thus, early Greek philosophers such as Homer, Thales, and Plato hypothesized that springs were formed by seawater conducted through subterranean channels below the mountains, then purified and raised to the surface. Aristotle suggested that air enters cold dark caverns under the mountains where it condenses into water and contributes to springs.

The Roman philosophers, including Seneca and Pliny, followed the Greek ideas and contributed little to the subject. An important step forward, however, was made by the Roman architect Vitruvius. He explained the now-accepted infiltration theory that the mountains receive large amounts of rain that percolate through the rock strata and emerge at their base to form streams.

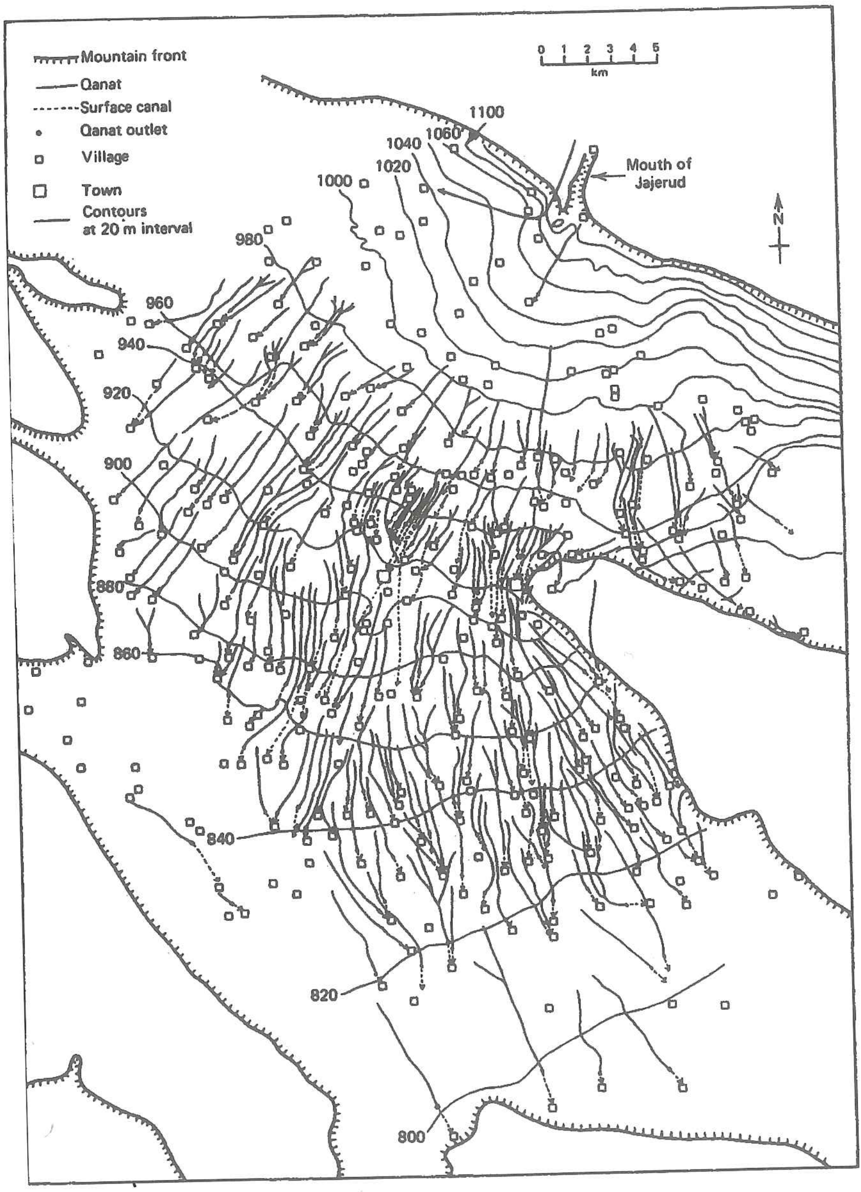

Figure 1.2.2. Map of qanats on the Varamin Plain, Iran (after Beaumont[9]).

The Greek theories persisted through the Middle Ages with no advances until the end of the Renaissance. The French potter and philosopher Bernard Palissy (c. 1510–1589) reiterated the infiltration theory in 1580, but his teachings were generally ignored. The German astronomer Johannes Kepler (1571–1630) was a man of strong imagination who likened the earth to a huge animal that takes in water of the ocean, digests and assimilates it, and discharges the end products of these physiological processes as groundwater and springs. The seawater theory of the Greeks, supplemented by the ideas of vaporization and condensation processes within the earth, was restated by the French philosopher René Descartes (1596–1650).

A clear understanding of the hydrologic cycle was achieved by the latter part of the seventeenth century. For the first time, theories were based on observations and quantitative data. Three Europeans made notable contributions, although others contributed to and supported these advances. Pierre Perrault[*] (1611–1680) measured rainfall during three years and estimated runoff of the upper Seine River drainage basin. He reported in 1674 that precipitation on the basin was about six times the river discharge, thereby demonstrating as false the early assumption of inadequate rainfall.[57] The French physicist Edme Mariotte (c. 1620–1684) made measurements of the Seine at Paris and confirmed Perrault's work. His publications appeared in 1686, after his death, and contained factual data strongly supporting the infiltration theory. Meinzer[54] once stated, "Mariotte . . . probably deserves more than any other man the distinction of being regarded as the founder of groundwater hydrology, perhaps I should say of the entire science of hydrology." The third contribution came from the English astronomer Edmund Halley (1656–1742), who reported in 1693 on measurements of evaporation, demonstrating that sea evaporation was sufficient to account for all springs and stream flow.

1.2.3 Recent Centuries

During the eighteenth century, fundamentals in geology were established that provided a basis for understanding the occurrence and movement of groundwater. During the first half of the nineteenth century many artesian wells were drilled in France, stimulating interest in groundwater. The French hydraulic engineer Henry Darcy (1803–1858) studied the movement of water through sand. His treatise of 1856 defined the relation, now known as Darcy's law, governing groundwater flow in most alluvial and sedimentary formations. Later European contributions of the nineteenth century emphasized the hydraulics of groundwater development. Significant contributions were made by J. Boussinesq, G. A. Daubrée, J. Dupuit, P. Forchheimer, and A. Thiem. In the twentieth century, increased activity in all phases of groundwater hydrology occurred. Many Europeans have participated with publications of either specialized or comprehensive works. There are too many people to mention them all, but R. Dachler, E. Imbeaux, K. Keilhack, W. Koehne, J. Kozeny, E. Prinz, H. Schoeller, and G. Thiem are best known in the United States.

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[*] Pierre Perrault was a lawyer by profession and held administrative and financial positions in the French government; hence he is not well known in scientific circles. His interest in groundwater, leading to publication of *De l'Origine des Fontaines* in 1674, can be traced to the stimulus of the Dutch mathematician, astronomer, and physicist, Christiaan Huygens, who was then living in Paris and to whom the book is dedicated. Also, Pierre Perrault is often overshadowed by his four distinguished brothers: Jean (c. 1610–1669), a lawyer; Nicolas (1624–1662), a noted theologian; Claude (1613–1688), a physician, architect, and scientist, who is regarded as one of the most eminent French scholars of his time; and Charles (1628–1703), author and critic, who is best known for his Mother Goose fairy tales.

American contributions to groundwater hydrology date from near the end of the nineteenth century. In the past 110 years, tremendous advances have been made. Important early theoretical contributions were made by A. Hazen, F. H. King, and C. S. Slichter, while detailed field investigations were begun by men such as T. C. Chamberlin, N. H. Darton, W. T. Lee, and W. C. Mendenhall. O. E. Meinzer, through his consuming interest in groundwater and his dynamic leadership of groundwater activities of the U.S. Geological Survey, stimulated many individuals in the quest for groundwater knowledge. In recent decades the publications of M. S. Hantush, C. E. Jacob, G. B. Maxey, C. L. McGuinness, and R. W. Stallman are noteworthy. Within the last 40 years the surge in university research on groundwater problems, the establishment of professional consulting firms specializing in groundwater, the advent of the digital computer, and the extensive development of computer software have jointly produced a competence for development and management of groundwater resources.

1.3 TRENDS IN WATER WITHDRAWALS AND USE

The U.S. Geological Survey[65] estimated the total fresh and saline withdrawals in the United States during 1995 to have been 402,000 million gallons per day (Mgal/d) for all off-stream water-use categories (public supply, domestic, commercial, irrigation, livestock, industrial, mining, thermoelectric power). This estimate is nearly two percent less than the withdrawal estimate for 1990. Table 1.3.1 and Figure 1.3.1 provide a comparison of total water withdrawals by water-resources region. This comparison indicates that the California, South Atlantic–Gulf, and Mid-Atlantic regions account for one-third of the total water withdrawn in the United States.

National water-use compilations began in 1950 and are conducted at five-year intervals.[65] Estimates in Table 1.3.2 and Figure 1.3.2 summarize the water use—withdrawals, source of water, reclaimed wastewater, consumptive use, and in-stream use (hydroelectric power)—at five-year intervals. Figure 1.3.3 illustrates the trends in water withdrawals by water-use category and total withdrawals for 1960–1995. Table 1.3.2 also illustrates the percentage change in the 1990 and 1995 summary estimates. Estimates indicate that the general increase in water use from 1950 to 1980 and the decrease from 1980 to 1995 can be attributed in part to the following major factors:[65]

- Most of the increases in water use from 1950 to 1980 were the result of expansion of irrigation systems and increases in energy development.
- The development of center-pivot irrigation systems and the availability of plentiful and inexpensive groundwater resources supported the expansion of irrigation systems.
- Higher energy prices in the 1970s, and large drawdown in groundwater levels in some areas increased the cost of irrigation water. In the 1980s, improved application techniques, increased competition for water, and a downturn in farm economy reduced demands for irrigation water.
- The transition from water-supply management to water-demand management encouraged more efficient use of water.
- New technologies in the industrial sector that require less water, improved plant efficiencies, increased water recycling, higher energy prices, and changes in laws and regulations to reduce the discharge of pollutants resulted in decreased water use and less water being returned to natural systems after use.
- The enhanced awareness by the general public of water resources and the active conservation programs in many states have contributed to reduced water demands.

Table 1.3.1 Total Offstream Water Use by Water-Resources Region, 1995

Region	Population (thousands)	Per capita use, freshwater (gal/d)	Withdrawals (Mgal/d) (includes irrigation conveyance losses)									Reclaimed wastewater (Mgal/d)	Conveyance losses (Mgal/d)	Consumptive use, freshwater (Mgal/d)
			By source and type						Total					
			Groundwater			Surface water								
			Fresh	Saline	Total	Fresh	Saline	Total	Fresh	Saline	Total			
New England	12,849	289	725	0	726	2,980	8,800	11,800	3,710	8,800	12,600	0	0	388
Mid-Atlantic	42,412	509	2,690	1	2,690	18,900	20,300	39,200	21,600	20,300	41,900	72	1.9	1,170
South Atlantic –Gulf	37,845	848	7,110	16	7,120	25,000	12,700	37,700	32,100	12,700	44,800	237	33	5,570
Great Lakes	21,836	1,500	1,510	4.6	1,520	31,100	6.5	31,100	32,700	11	32,700	0	.1	1,580
Ohio	22,631	1,330	1,980	22	2,000	28,100	.6	28,100	30,100	23	30,100	1.1	.7	1,870
Tennessee	4,198	2,140	258	0	258	8,730	0	8,730	8,980	0	8,980	.3	0	289
Upper Mississippi	22,268	1,050	2,570	4.2	2,570	20,700	0	20,700	23,300	4.2	23,300	11	0	1,660
Lower Mississippi	7,324	2,720	9,180	0	9,180	10,800	0	10,800	20,000	0	20,000	.7	553	7,740
Souris–Red –Rainy	693	364	115	0	115	138	0	138	253	0	253	0	1.8	122
Missouri Basin	10,664	3,380	9,320	38	9,360	26,700	0	26,700	36,000	38	36,100	22	7,840	14,200
Arkansas–White –Red	8,931	1,800	7,490	284	7,780	8,590	0	8,590	16,100	284	16,400	37	944	8,190
Texas-Gulf	16,755	1,050	5,960	324	6,280	11,700	4,860	16,600	17,700	5,190	22,900	71	390	7,340
Rio Grande	2,566	2,600	1,930	61	1,990	4,740	0	4,740	6,670	61	6,730	7.2	1,360	2,960
Upper Colorado	714	10,400	116	14	130	7,310	0	7,310	7,420	14	7,440	1.7	1,940	2,520
Lower Colorado	5,318	1,500	3,000	12	3,010	4,970	2.3	4,970	7,960	14	7,980	187	1,090	4,520
Great Basin	2,405	2,510	1,610	56	1,660	4,420	143	4,560	6,030	199	6,230	33	1,140	3,260
Pacific Northwest	9,948	3,220	5,500	0	5,500	26,500	38	26,500	32,000	38	32,000	.1	8,050	10,600
California	32,060	1,140	14,600	185	14,800	21,900	9,450	31,300	36,500	9,640	46,100	330	1,860	25,300
Alaska	604	350	58	75	132	154	43	196	211	117	329	0	.1	25
Hawaii	1,187	853	515	16	531	497	906	1,400	1,010	922	1,930	6.2	98	542
Caribbean	3,858	152	156	.2	156	433	2,450	2,880	588	2,450	3,040	0	15	189
Total	267,068	1,280	76,400	1,110	77,500	264,000	59,700	324,000	341,000	60,800	402,000	1,020	25,300	100,000

Source: Solley[65]

Figures may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day

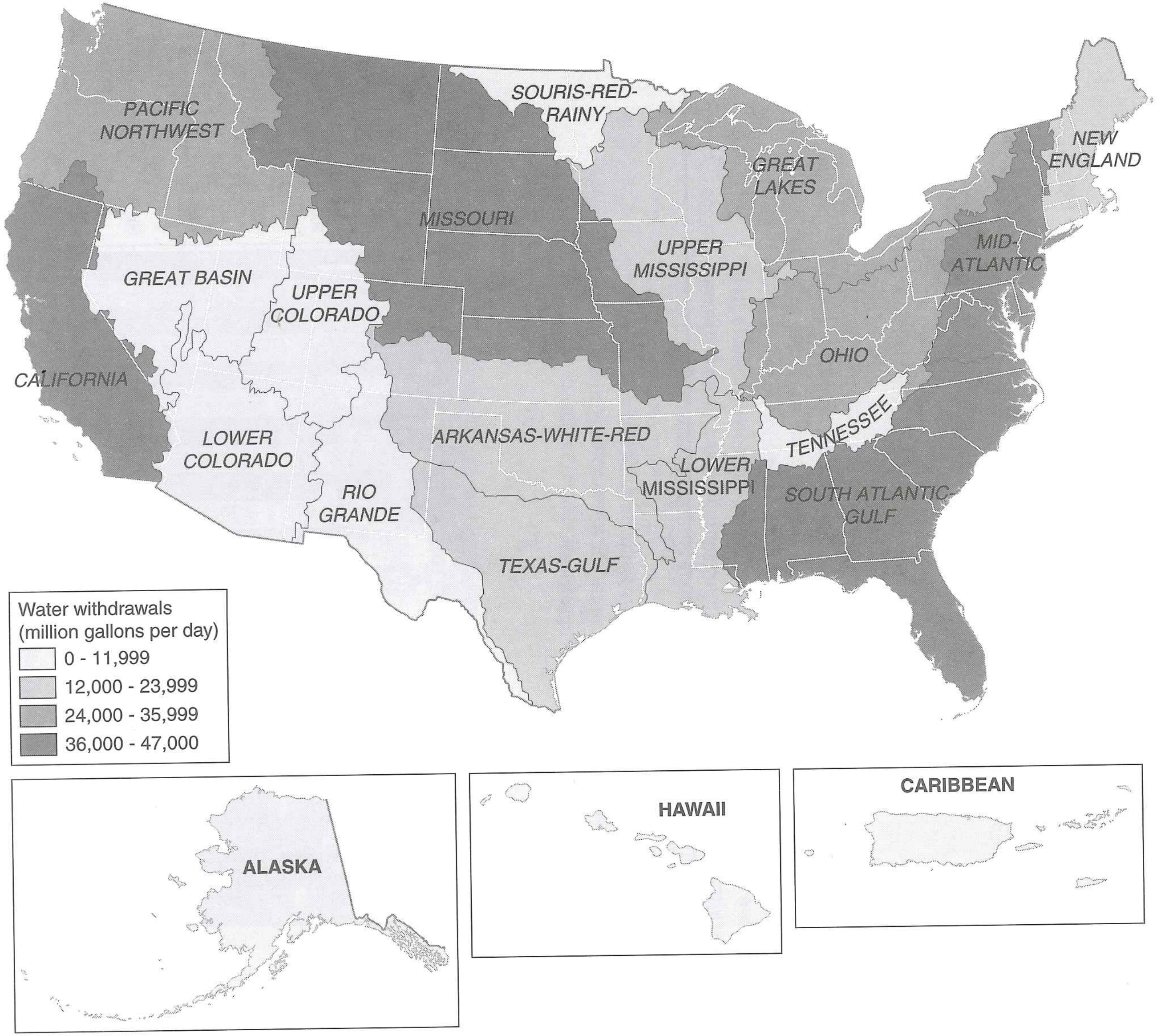


Figure 1.3.1. Total water withdrawals by water-resources region, 1995.[65]

Table 1.3.2 Trends of Estimated Water Use in the United States, 1950–95

	Year										Percentage change
	1950[1]	1955[1]	1960[2]	1965[2]	1970[3]	1975[4]	1980[4]	1985[4]	1990[4]	1995[4]	1990–95
Population (millions)	150.7	164.0	179.3	193.8	205.9	216.4	229.6	242.4	252.3	267.1	+6
Offstream use											
Total withdrawals	180	240	270	310	370	420	440[5]	399	408	402	–2
Public supply	14	17	21	24	27	29	34	36.5	38.5	40.2	+4
Rural domestic and livestock	3.6	3.6	3.6	4.0	4.5	4.9	5.6	7.79	7.89	8.89	+13
Irrigation	89	110	110	120	130	140	150	137	137	134	–2
Industrial											
Thermoelectric power use	40	72	100	130	170	200	210	187	195	190	–3
Other industrial use	37	39	38	46	47	45	45	30.5	29.9	29.1	–3
Source of water											
Ground											
Fresh	34	47	50	60	68	82	83[5]	73.2	79.4	76.4	–4
Saline	(6)	.6	.4	.5	1	1	.9	.652	1.22	1.11	–9
Surface											
Fresh	140	180	190	210	250	260	290	265	259	264	+2
Saline	10	18	31	43	53	69	71	59.6	68.2	59.7	–12
Reclaimed wastewater	(6)	.2	.6	.7	.5	.5	.5	.579	.750	1.02	+36
Consumptive use	(6)	(6)	61	77	87[7]	96[7]	100[7]	92.3[7]	94[7]	100[7]	+6
Instream use											
Hydroelectric power	1,100	1,500	2,000	2,300	2,800	3,300	3,300	3,050	3,290	3,160	–4

[1] 48 States and District of Columbia

[2] 50 States and District of Columbia

[3] 50 States and District of Columbia, and Puerto Rico

[4] 50 States and District of Columbia, Puerto Rico, and Virgin Islands

[5] Revised

[6] Data not available.

[7] Freshwater only

Source: Solley[65]

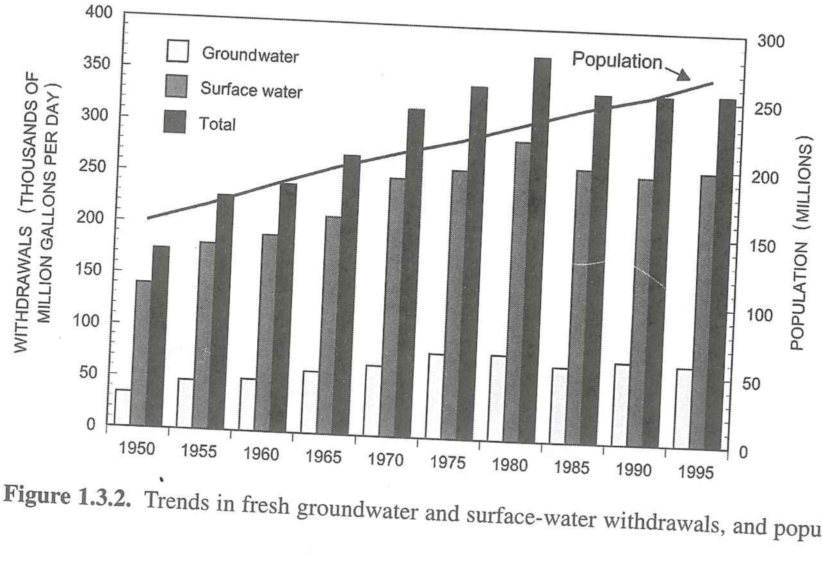


Figure 1.3.2. Trends in fresh groundwater and surface-water withdrawals, and population, 1950–95.[65]

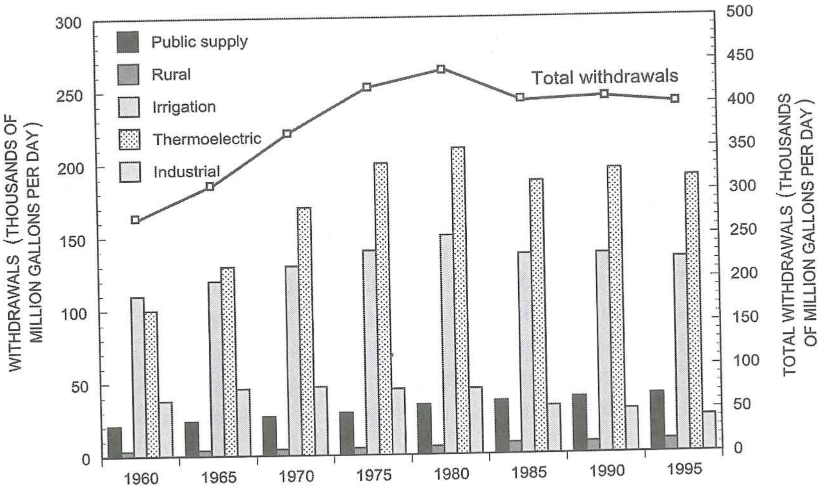


Figure 1.3.3. Trends in water withdrawals (fresh and saline) by water-use category and total (fresh and saline) withdrawals, 1960–95.[65]

1.4 UTILIZATION OF GROUNDWATER

Groundwater is an important source of water supply throughout the world. Its use in irrigation, industries, municipalities, and rural homes continues to increase. Figure 1.4.1 strikingly illustrates the dependence of an Indian village on its only water source—groundwater from a single dug well. Cooling and air conditioning have made heavy demands on groundwater because of its characteristic uniformity in temperature. Shortages of groundwater in areas where excessive withdrawals have occurred emphasize the need for accurate estimates of the available subsurface resources and the importance of proper planning to ensure the continued availability of water supplies.

There is a tendency to think of groundwater as being the primary water source in arid regions and of surface water in humid regions. But a study of groundwater use in the United States, for example, reveals that groundwater serves as an important resource in all climatic

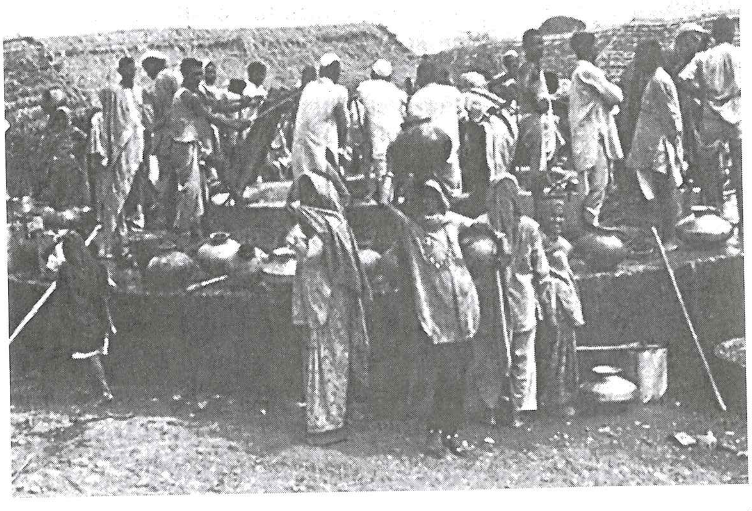


Figure 1.4.1. Villagers laboriously lifting and carrying water from a deep dug well in northern India (photo by David K. Todd).

zones.[55] Reasons for this include its convenient availability near the point of use, its excellent quality (which typically requires little treatment), and its relatively low cost of development. Furthermore, in humid locales such as Barbados, Jamaica, and Hawaii, groundwater predominates as the water source because the high infiltration capacity of the soils sharply reduces surface runoff.

Figure 1.4.2 illustrates the relative proportion of water source and disposition and the general distribution of water from source to disposition for 1995. Table 1.4.1 lists the total off-stream water use by state for 1995—breaking down the withdrawals into groundwater and surface water and subdividing these into fresh and saline water. The total groundwater withdrawal was 77,500 Mgal/d and the total surface-water withdrawal was 324,000 Mgal/d. Table 1.4.2 lists the groundwater withdrawals by water-use category and water-resources region for 1995. The significant proportion of groundwater used for irrigation purposes is clearly indicated by the fact that 49,000 Mgal/d of the total 77,500 Mgal/d is used for irrigation.

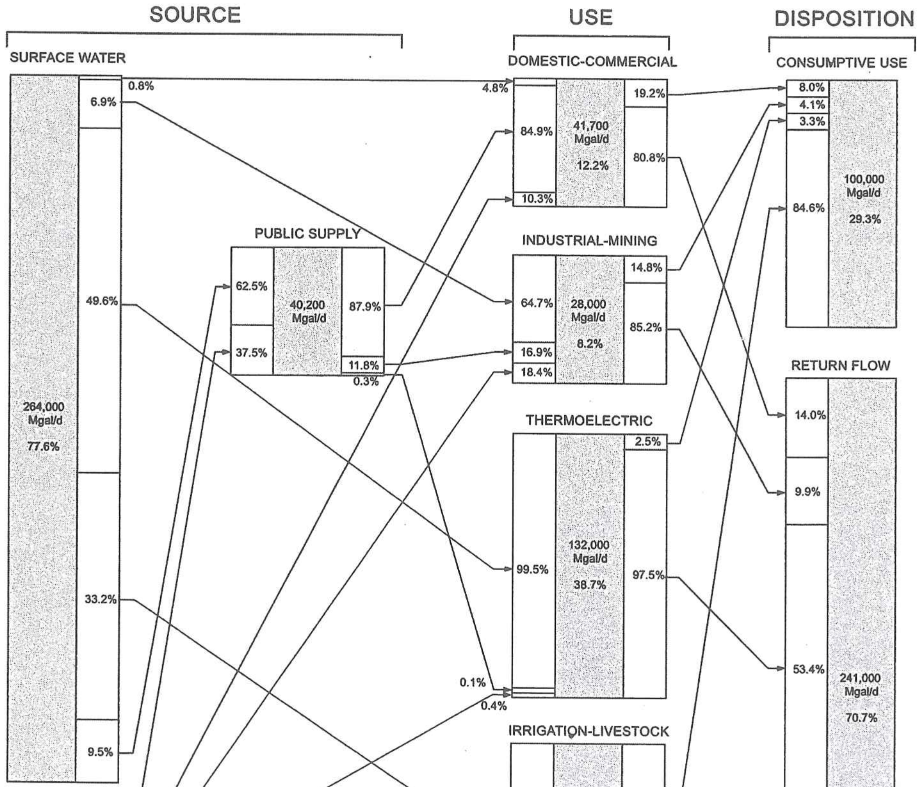


Figure 1.4.2. Source, use, and disposition of freshwater in the United States, 1995. For each water-use category, this diagram shows the relative proportion of water source and disposition and the general distribution of water from source to disposition. The lines and arrows indicate the distribution of water from source to disposition for each category; for example, surface water was 77.6 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 0.8 percent of all surface water withdrawn was the source for 4.8 percent of total water (self-supplied withdrawals, public-supply deliveries) for domestic and commercial purposes. In addition, going from the "Use" to "Disposition" columns, the line from the domestic and commercial block to the consumptive use block indicates that 19.2 percent of the water for domestic and commercial purposes was consumptive use; this represents 8.0 percent of total consumptive use by all water-use categories.[65]

Table 1.4.1 Total Offstream Water Use by State, 1995

Region	Population (thousands)	Per capita use freshwater (gal/d)	Withdrawals (Mgal/d) (includes irrigation conveyance losses)									Reclaimed wastewater (Mgal/d)	Conveyance losses (Mgal/d)	Consumptive use, freshwater (Mgal/d)
			By source and type						Total					
			Groundwater			Surface water								
			Fresh	Saline	Total	Fresh	Saline	Total	Fresh	Saline	Total			
Alabama	4,253	1,670	436	9.1	445	6,650	0	6,650	7,090	9.1	7,100	0.1	0	532
Alaska	604	350	58	75	132	154	43	196	211	117	329	0	.1	25
Arizona	4,218	1,620	2,830	12	2,840	3,980	2.3	3,990	6,820	14	6,830	180	1,030	3,830
Arkansas	2,484	3,530	5,460	0	6,460	3,310	0	3,310	8,770	0	8,770	0	416	4,760
California	32,063	1,130	14,500	185	14,700	21,800	9,450	31,300	36,300	9,640	45,900	334	1,670	25,500
Colorado	3,747	3,690	2,260	17	2,270	11,600	0	11,600	13,800	17	13,800	11	3,770	5,230
Connecticut	3,275	389	166	0	166	1,110	3,180	4,290	1,280	3,180	4,450	0	0	97
Delaware	717	1,050	110	0	110	642	743	1,390	752	743	1,500	0	0	71
D.C.	554	18	.5	0	.6	9.7	0	9.7	10	0	10	0	0	15
Florida	14,166	509	4,340	4.6	4,340	2,880	11,000	13,800	7,210	11,000	18,200	236	32	2,780
Georgia	7,201	799	1,190	0	1,190	4,560	64	4,630	5,750	64	5,820	.6	0	1,170
Hawaii	1,187	853	515	16	531	497	906	1,400	1,010	922	1,930	6.2	98	542
Idaho	1,163	13,000	2,830	0	2,830	12,300	0	12,300	15,100	0	15,100	0	5,480	4,340
Illinois	11,830	1,680	928	25	953	19,000	0	19,000	19,900	25	19,900	2.0	0	857
Indiana	5,803	1,570	709	0	709	8,430	0	8,430	9,140	0	9,140	0	0	505
Iowa	2,842	1,070	528	0	528	2,510	0	2,510	3,030	0	3,030	0	0	290
Kansas	2,565	2,040	3,510	0	3,510	1,720	0	1,720	5,240	0	5,240	6.8	143	3,620
Kentucky	3,860	1,150	226	0	226	4,190	0	4,190	4,420	0	4,420	0	.5	318
Louisiana	4,342	2,270	1,350	0	1,350	8,500	0	8,500	9,850	0	9,850	0	166	1,930
Maine	1,241	178	80	0	80	141	105	248	221	105	326	0	0	48
Maryland	5,042	289	246	0	246	1,210	6,270	7,480	1,460	6,270	7,730	70	0	150
Massachusetts	6,074	189	351	0	351	795	4,370	5,160	1,150	4,370	5,510	0	0	180
Michigan	9,549	1,260	858	4.4	862	11,200	0	11,200	12,100	4.4	12,100	0	0	667
Minnesota	4,610	736	714	0	714	2,680	0	2,680	3,390	0	3,390	0	0	417
Mississippi	2,697	1,140	2,590	0	2,590	502	112	614	3,090	112	3,200	0	17	1,570
Missouri	5,324	1,320	891	0	891	6,140	0	6,140	7,030	0	7,030	11	0	692
Montana	870	10,200	204	13	217	8,640	0	8,640	8,850	13	8,860	0	4,410	1,960
Nebraska	1,637	6,440	6,200	4.7	6,200	4,350	0	4,350	10,500	4.7	10,500	2.0	906	7,020
Nevada	1,530	1,480	855	42	896	1,400	0	1,400	2,260	42	2,300	24	473	1,340
New Hampshire	1,148	388	81	0	81	364	877	1,240	446	877	1,320	0	0	35

(continues)

Table 1.4.1 (continued) Total Offstream Water Use by State, 1995

Region	Population (thousands)	Per capita use freshwater (gal/d)	Withdrawals (Mgal/d) (includes irrigation conveyance losses)									Reclaimed wastewater (Mgal/d)	Conveyance losses (Mgal/d)	Consumptive use, freshwater (Mgal/d)
			By source and type											
			Groundwater			Surface water			Total					
			Fresh	Saline	Total	Fresh	Saline	Total	Fresh	Saline	Total			
New Jersey	7,945	269	580	0	580	1,560	3,980	5,530	2,140	3,980	6,110	1.1	0	210
New Mexico	1,686	2,080	1,700	0	1,700	1,800	0	1,800	3,510	0	3,510	0	628	1,980
New York	18,136	567	1,010	1.5	1,010	9,270	6,500	15,800	10,300	6,500	16,800	0	0	469
North Carolina	7,195	1,070	535	2.1	535	7,200	1,550	8,750	7,730	1,560	9,290	1.0	0	713
North Dakota	641	1,750	122	0	122	1,000	0	1,000	1,120	0	1,120	0	5.1	181
Ohio	11,151	944	905	0	905	9,620	0	9,620	10,500	0	10,500	0	.2	791
Oklahoma	3,278	543	959	259	1,220	822	0	822	1,780	259	2,040	0	4.9	716
Oregon	3,140	2,520	1,050	0	1,050	6,860	0	6,860	7,910	0	7,910	0	1,300	3,210
Pennsylvania	12,072	802	860	0	860	8,820	0	8,820	9,680	0	9,680	1.1	0	565
Rhode Island	990	138	27	0	27	109	275	383	136	275	411	0	0	19
South Carolina	3,673	1,690	322	0	322	5,880	0	5,880	6,200	0	6,200	0	0	321
South Dakota	729	631	187	0	187	273	0	273	460	0	460	0	54	249
Tennessee	5,256	1,920	435	0	435	9,640	0	9,640	10,100	0	10,100	.5	0	233
Texas	18,724	1,300	8,370	411	8,780	16,000	4,860	20,800	24,300	5,280	29,600	109	540	10,500
Utah	1,951	2,200	776	14	790	3,530	143	3,670	4,300	157	4,460	14	612	2,200
Vermont	585	967	50	0	50	515	0	515	565	0	565	0	0	24
Virginia	6,618	826	358	0	358	5,110	2,800	7,900	5,470	2,800	8,260	0	2.9	218
Washington	5,431	1,620	1,760	0	1,760	7,060	38	7,100	8,820	38	8,860	0	1,090	3,080
West Virginia	1,828	2,530	146	.5	146	4,470	0	4,470	4,620	.5	4,620	0	0	352
Wisconsin	5,102	1,420	759	0	759	6,490	0	6,490	7,250	0	7,250	0	0	443
Wyoming	480	14,700	317	18	335	6,720	0	6,720	7,040	18	7,060	9.1	2,470	2,800
Puerto Rico	3,755	154	155	0	155	422	2,260	2,680	576	2,260	2,840	0	15	187
Virgin Islands	103	113	.5	.2	.7	11	190	201	12	190	202	0	0	1.9
Total	267,068	1,280	76,400	1,110	77,500	264,000	59,700	324,000	341,000	60,800	402,000	1,020	25,300	100,000

Figures may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day

Source: Solley[65]

Table 1.4.2 Groundwater Withdrawals by Water-Use Category and Water-Resources Region, 1995

Region	Public supply	Domestic	Commer-cial	Irrigation	Live-stock	Industrial		Mining		Thermo-electric	Total	
	Fresh	Fresh	Fresh	Fresh	Fresh	Fresh	Saline	Fresh	Saline	Fresh	Fresh	Saline
New England	335	168	64	47	6.4	53	0	2.9	0	48	725	0
Mid-Atlantic	1,270	485	217	128	79	344	0	159	1.0	11	2,690	1.0
South Atlantic–Gulf	2,760	719	114	2,280	188	787	0	177	9.1	79	7,110	16
Great Lakes	585	354	44	170	50	270	3.6	34	1.0	7.6	1,510	4.6
Ohio	880	323	91	61	60	379	0	115	22	70	1,980	22
Tennessee	125	64	3.6	8.7	19	35	0	3.7	0	0	258	0
Upper Mississippi	1,150	311	94	430	216	328	0	22	4.2	24	2,570	4.2
Lower Mississippi	741	73	15	6,930	740	611	0	3.1	0	69	9,180	0
Souris–Red–Rainy	34	17	.2	45	17	1.7	0	.4	0	0	115	0
Missouri Basin	643	137	19	8,030	253	102	0	104	38	30	9,320	38
Arkansas–White–Red	378	105	16	6,660	190	78	0	30	284	37	7,490	284
Texas–Gulf	978	115	34	4,370	82	214	.5	118	324	50	5,960	324
Rio Grande	356	25	17	1,420	27	10	0	53	60	16	1,930	61
Upper Colorado	35	11	5.6	38	4.2	2.4	0	20	14	0	116	14
Lower Colorado	476	44	22	2,210	33	42	0	126	12	45	3,000	12
Great Basin	350	13	10	1,090	9.2	60	.1	71	19	2.6	1,610	56
Pacific Northwest	917	253	37	4,030	44	215	0	6.5	0	.5	5,500	0
California	2,730	112	77	10,900	231	522	10	16	151	3.6	14,600	185
Alaska	30	8.3	11	.1	.1	3.8	0	0	75	4.2	58	75
Hawaii	200	2.4	45	173	7.5	19	.9	.5	0	67	515	16
Caribbean	95	6.4	1.3	33	4.5	10	.2	3.4	0	2.2	156	.2
Total	15,100	3,350	939	49,000	2,260	4,090	15	1,070	1,010	565	76,400	1,110

Figures may not add to totals because of independent rounding. All values in million gallons per day

Source: Solley[65]

The largest single demand for groundwater is irrigation, amounting to 67.3% percent of all groundwater used in 1995. More than 90 percent of this water is pumped in the western states, where arid and semiarid conditions have fostered extensive irrigation development.

1.5 GROUNDWATER IN THE HYDROLOGIC CYCLE

1.5.1 Hydrologic Cycle

The central focus of hydrology is the *hydrologic cycle* consisting of the continuous processes shown in Figure 1.5.1. Water evaporates from the oceans and land surfaces to become water vapor that is carried over the earth by atmospheric circulation. The *water vapor* condenses and *precipitates* on the land and oceans. The 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,* or discharge as *surface runoff.* Evaporation from the land surface comprises evaporation directly from soil and vegetation surfaces, and *transpiration* through plant leaves. Collectively these processes are called *evapotranspiration.* Infiltrated water may percolate deeper to recharge groundwater and later become *springflow* or *seepage into streams to also become streamflow.*

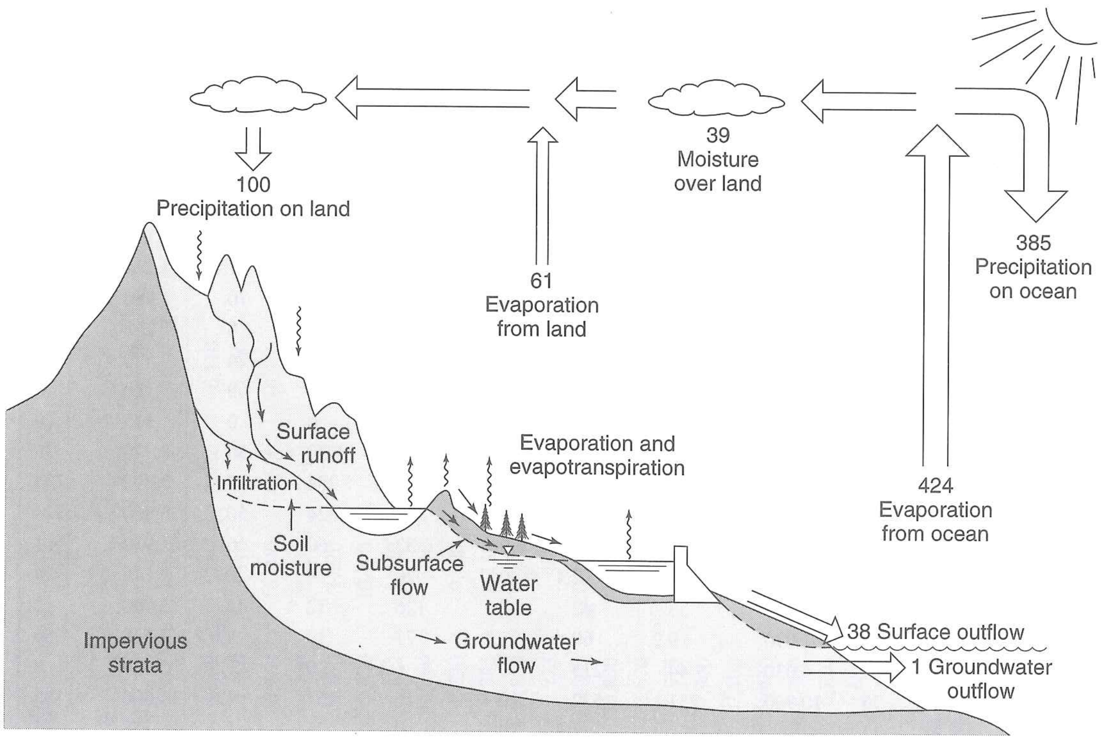


Figure 1.5.1. Hydrologic cycle with global annual average water balance given in units relative to a value of 100 for the rate of precipitation on land.[22]

A *hydrologic system* is defined as a structure or volume in space, surrounded by a boundary, that accepts water and other inputs, operates on them internally, and produces them as outputs.[21, 22] The structure (for surface or subsurface flow) or volume in space (for atmospheric moisture flow) is the totality of the flow paths through which the water may pass as throughput from the point it enters the system to the point it leaves. The boundary is a continuous surface defined in three dimensions enclosing the volume or structure. A *working medium* enters the system as input, interacts with the structure and other media, and leaves as output. Physical, chemical, and biological processes operate on the working media within the system; the most common working media involved in hydrologic analysis are water, air, and heat energy.

The *global hydrologic cycle* can be represented as a system containing three subsystems: the *atmospheric water system*, the *surface water system*, and the *subsurface water system* as shown in Figure 1.5.2. Another example is the storm–rainfall–runoff process on a watershed, which can be represented as a hydrologic system. The input is rainfall distributed in time and space over the watershed and the output is streamflow at the watershed outlet. The boundary is defined by the watershed divide and extends vertically upward and downward to horizontal planes.

Drainage basins, catchments, and *watersheds* are three synonymous terms that refer to the topographic area that collects and discharges surface streamflow through one outlet or mouth. Catchments are typically referred to as small drainage basins but no specific area limits have been established. The drainage basin divide, watershed divide, or catchment divide is the line dividing land whose drainage flows toward the given stream from land whose drainage flows away from that stream. Think of drainage basin sizes ranging from the Mississippi River drainage basin to a small urban drainage basin in your local community or some small valley in the countryside near you.

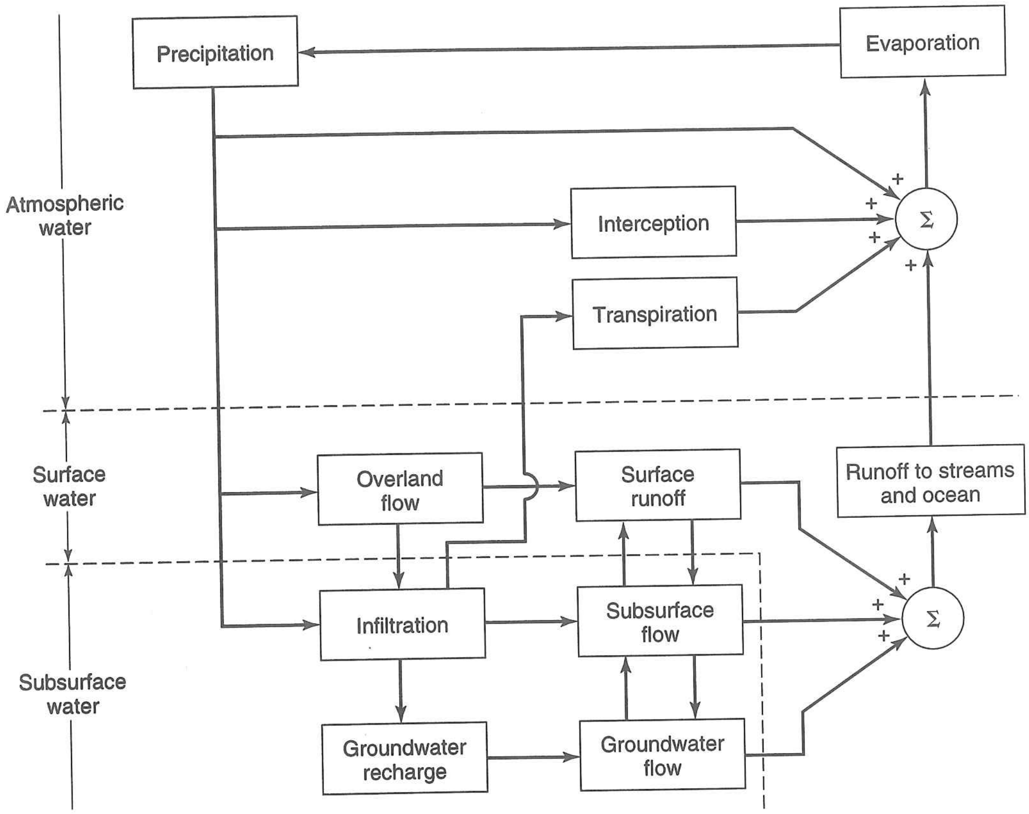


Figure 1.5.2. Block-diagram representation of the global hydrologic system.[22]

1.5.2 The Groundwater System in the Hydrologic Cycle

Groundwater constitutes one portion of the earth's water circulatory system known as the hydrologic cycle. Figure 1.5.1 illustrates some of the many facets involved in this cycle. Water-bearing formations of the earth's crust act as conduits for transmission and as reservoirs for storage of water. Water enters these formations from the ground surface or from bodies of surface water, after which it travels slowly for varying distances until it returns to the surface by action of natural flow, plants, or humans. The storage capacity of groundwater reservoirs combined with small flow rates provide large, extensively distributed sources of water supply. Groundwater emerging into surface stream channels aids in sustaining streamflow when surface runoff is low or nonexistent. Similarly, water pumped from wells represents the sole water source in many regions during much of every year.

Practically all groundwater originates as surface water. Principal sources of natural recharge include precipitation, streamflow, lakes, and reservoirs. Other contributions, known as artificial recharge, occur from excess irrigation, seepage from canals, and water purposely applied to augment groundwater supplies. Even seawater can enter underground along coasts where hydraulic gradients slope downward in an inland direction. Water within the ground moves downward through the unsaturated zone under the action of gravity, whereas in the saturated zone it moves in a direction determined by the surrounding hydraulic situation.

Discharge of groundwater occurs when water emerges from underground. Most natural discharge occurs as flow into surface water bodies, such as streams, lakes, and oceans; flow to the surface appears as a spring. Groundwater near the surface may return directly to the atmosphere by evaporation from within the soil and by transpiration from vegetation. Pumpage from wells constitutes the major artificial discharge of groundwater.

In this section we will discuss in general some of the aspects of the movement of groundwater in the hydrologic cycle. *The groundwater flow system* comprises the subsurface water, the geologic (porous) media containing the water, the flow boundaries, the sources (outcrop areas, streams for recharge to the aquifer), and the sinks (springs, interaquifer flow, and wells for flow from the aquifer). Water flows through and is stored within the groundwater system. Under natural conditions, the *travel time* of groundwater can range from less than a day to more than a million years. The *age* of the water can range from recent precipitation to water trapped in sediments that were deposited in geologic time. Chapter 3, Groundwater Movement, discusses the mechanics of groundwater movement.

The water that is withdrawn from a groundwater system initially comes from storage. The effects of the withdrawal from storage are propagated through the system, over time, as *water heads* (the *water table*) decrease at greater distances from the point of withdrawal. Ultimately, the effect of the withdrawal reaches a boundary such as a stream. At the stream, either increased *recharge* (*water added*) to the groundwater system occurs or increased discharge from the system occurs. Figure 1.5.3 shows the sources of water supplying pumpage from ten major regional aquifer systems in the United States. The figure illustrates the variability of aquifer response to long-term pumping and the extent to which changes in recharge and discharge can exceed changes in storage. It is important to quantify recharge, despite the difficulty of that undertaking.

Typically, most water from precipitation that infiltrates does not become recharge, but instead is stored in the soil zone and is eventually returned to the atmosphere by evaporation and plant transpiration.[2] The percentage of precipitation that becomes diffuse recharge is highly variable and depends upon many factors, such as depths to the water table, properties of surface soils, aquifer properties, and many other factors.

Interactions of surface-water systems with groundwater systems depend upon many factors, including positions of the surface-water systems relative to the groundwater systems; characteristics of the surface-water systems and their underlying materials; and the climate setting.[2, 80] Figure 1.5.4 illustrates the effect of *transient recharge* from precipitation on the configuration of a water table and the associated groundwater flow. The exchange of water across the interface between surface water and groundwater can result from downstream movement of water in and out of streambeds and banks, as illustrated in Figure 1.5.5. Other exchanges result from tides, wave action, filling or draining of reservoirs, and transpiration from vegetation at the edges of wetlands and other surface water sources. Most studies of exchanges have focused on streams.

Flows within groundwater systems can be on a local, intermediate, and regional basis, as illustrated in Figure 1.5.6. The recharge and discharge areas in a *local system of groundwater flow* are adjacent to each other. The recharge and discharge in an *intermediate groundwater flow system* are separated by one or more topographic high and low. In *regional groundwater flow* systems, recharge areas are along groundwater divides and discharge areas are located at the bottom of major drainage divides. Not every aquifer has each of these types of flow systems.[33, 71] In an aquifer system, the largest amount of groundwater flow is commonly in the local flow systems which are mostly affected by seasonal variations in recharge. Recharge areas of these local systems make up the largest part of the surface of a drainage basin, are relatively shallow, and have transient conditions. Regional groundwater flow systems are less transient than local and intermediate flow systems.

A *conceptual model of an aquifer system,* as illustrated in Figure 1.5.6 for the Midwestern Basins and Arches aquifer system (see Figure 1.5.7 for location), is a simplified qualitative

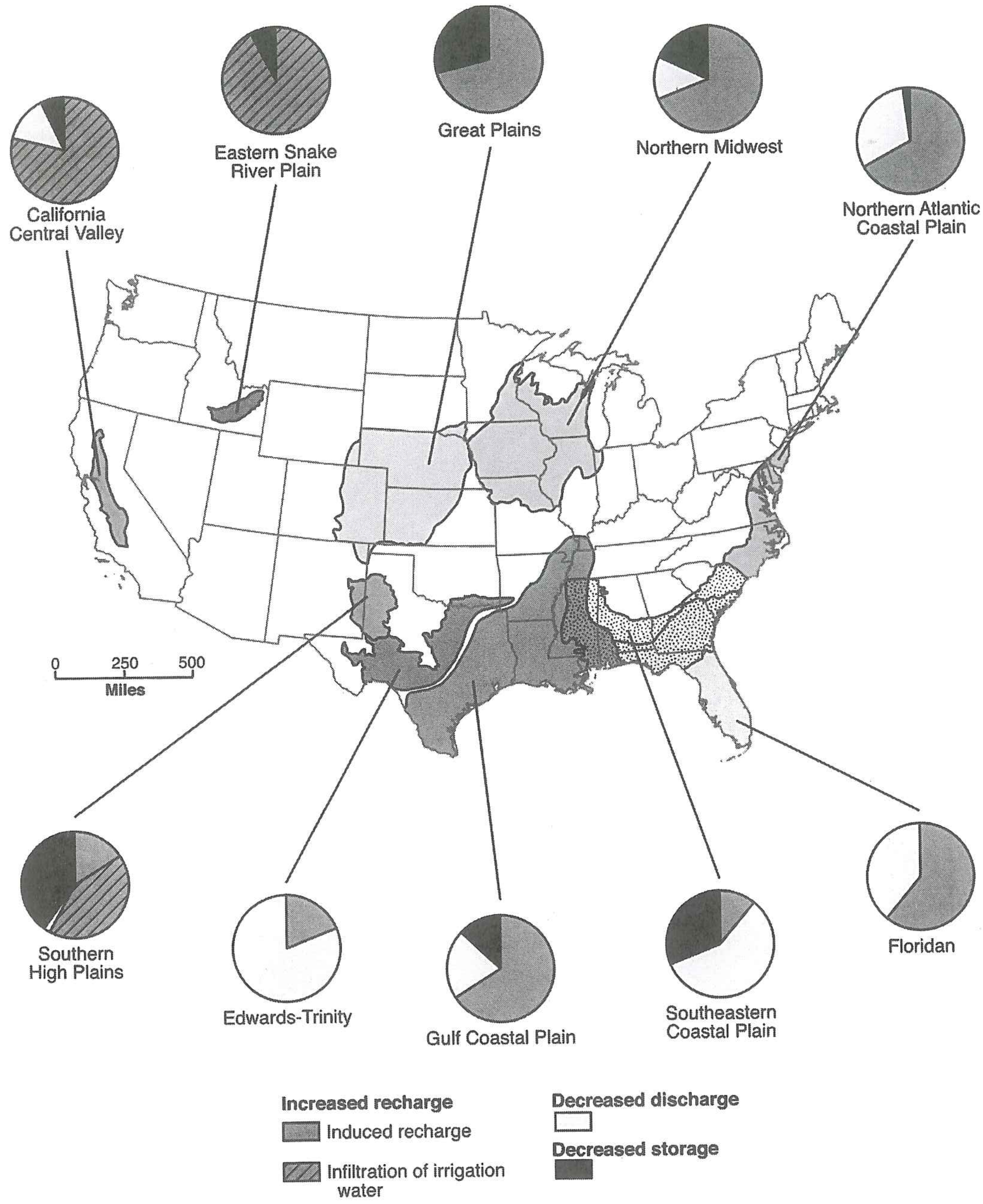
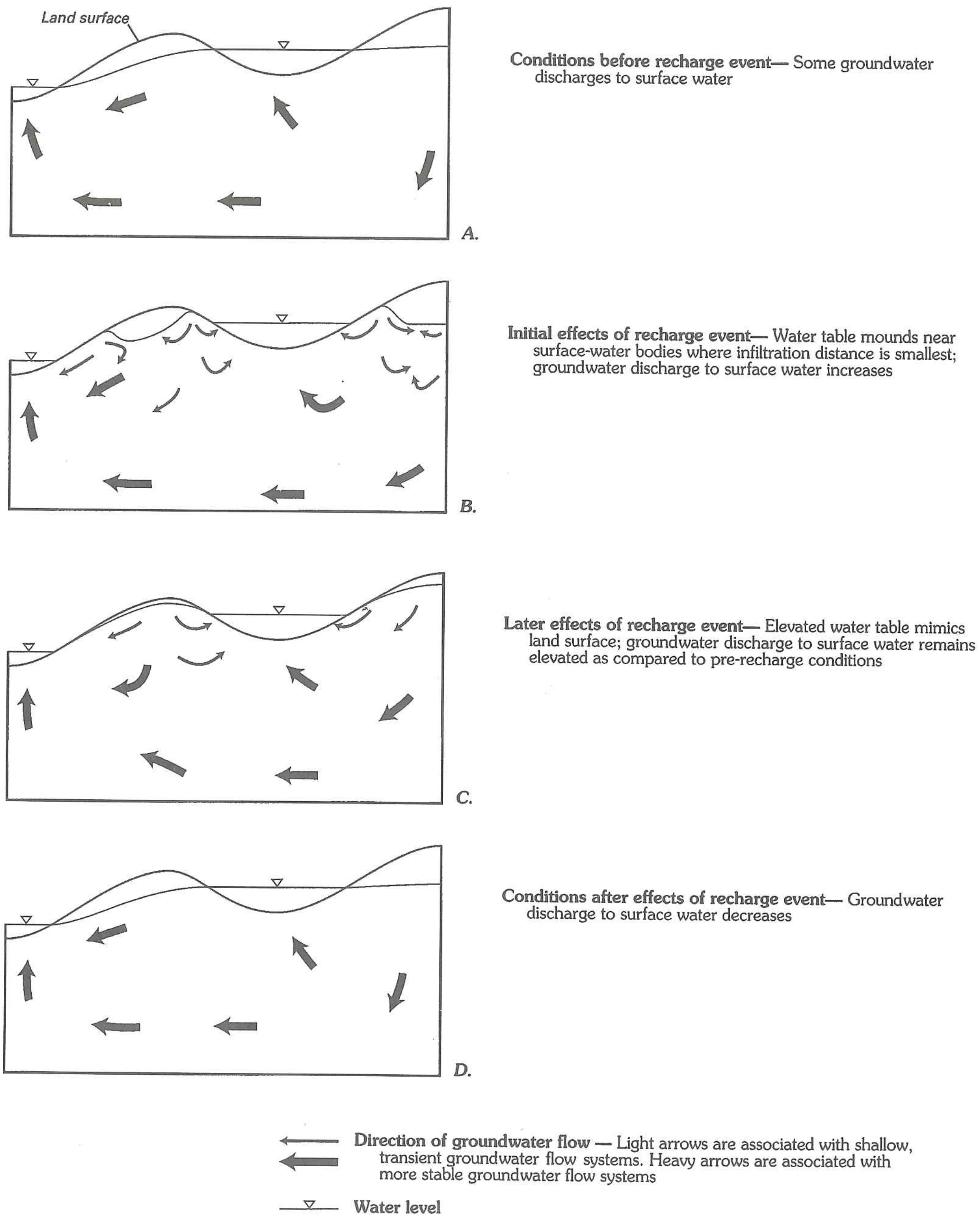


Figure 1.5.3. Sources of water that supply withdrawals from major aquifer systems in the United States are highly variable, as shown by these results from model simulations for various periods (Johnston, 1997). The Floridan and Edwards–Trinity aquifer systems, which equilibrate rapidly after pumping, were simulated as steady-state with no long-term change in storage. In contrast, the Southern High Plains (with most natural discharge occurring far from pumping wells) and the deeply buried Great Plains aquifer system have had substantial changes in groundwater storage. The distinction between changes in recharge and changes in discharge is a function of how the system was defined (i.e., a gain to one system may result in a loss from an adjoining system). For example, groundwater withdrawals from confined aquifers (Northern Atlantic Coastal Plain, Gulf Coastal Plain) can cause flow to be diverted (recharged) into the deeper regional flow regime that would otherwise discharge to streams in the outcrop areas or cause vertical leakage across confining units. Groundwater recharge in a region can be increased as a result of human modifications, such as return flow of excess irrigation water (California Central Valley). Note that the areal extent of the Southeastern Coastal Plain aquifer system overlaps the areal extents of the Floridan and Gulf Coastal Plain aquifer systems.[2]

description of the physical system.[33] Conceptual models may include a description of the aquifers and confining units that make up the aquifer system, the boundary conditions, flow regimes, sources and sinks of water, and general directions of the groundwater flow.



Conditions before recharge event— Some groundwater discharges to surface water

Initial effects of recharge event— Water table mounds near surface-water bodies where infiltration distance is smallest; groundwater discharge to surface water increases

Later effects of recharge event— Elevated water table mimics land surface; groundwater discharge to surface water remains elevated as compared to pre-recharge conditions

Conditions after effects of recharge event— Groundwater discharge to surface water decreases

Direction of groundwater flow — Light arrows are associated with shallow, transient groundwater flow systems. Heavy arrows are associated with more stable groundwater flow systems

Water level

Figure 1.5.4. Diagrams showing the effect of transient recharge from precipitation on the configuration of a water table and associated groundwater flow.[33]

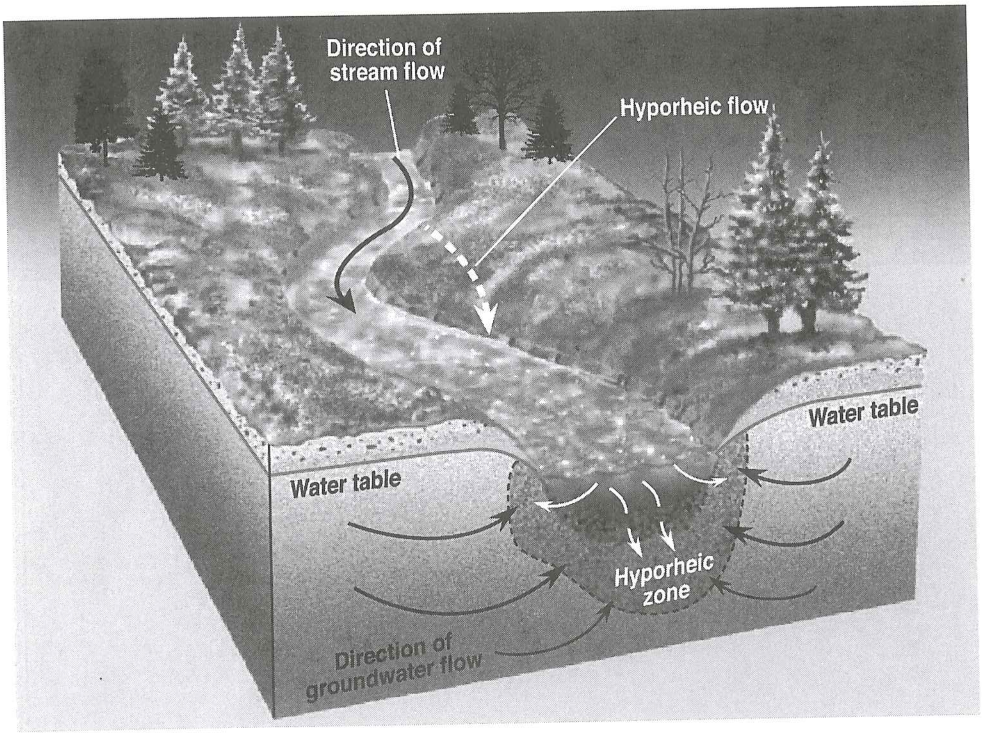


Figure 1.5.5. Local geomorphic features such as streambed topography, streambed roughness, meandering, and heterogeneities in sediment hydraulic conductivities can give rise to localized flow systems within streambeds and banks. The near-stream subsurface environment with active exchange between surface water and groundwater is commonly referred to as the *hyporheic zone*, although the transition between groundwater and surface water represents a hydrologic continuum, preventing a precise separation.[2]

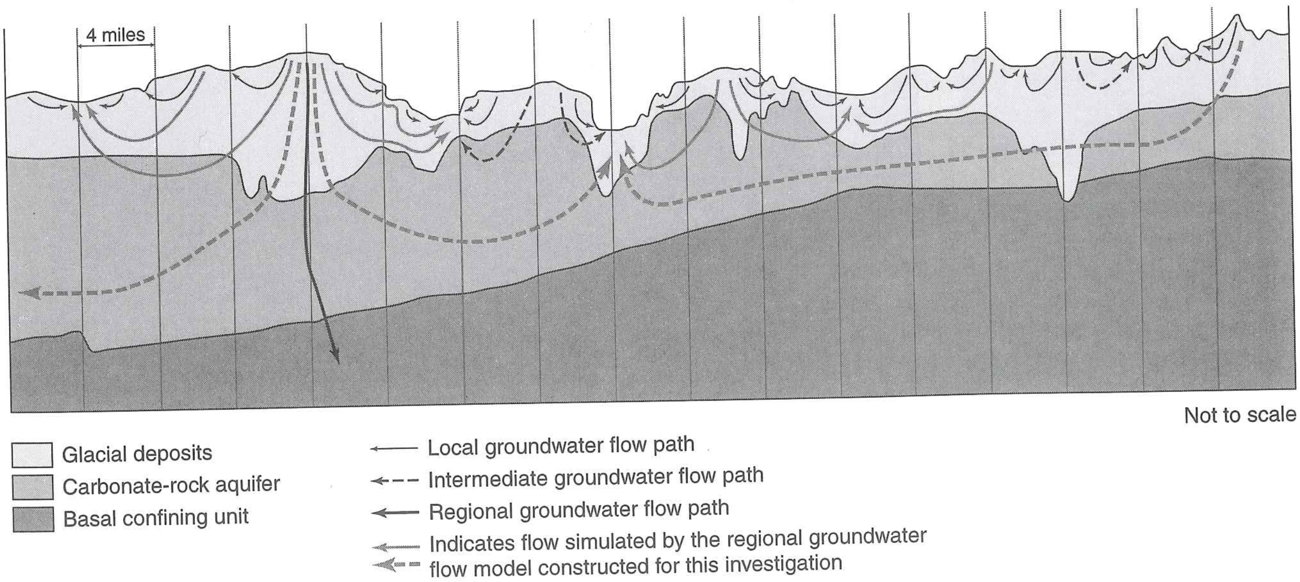


Figure 1.5.6. Diagrammatic conceptual model of the Midwestern Basins and Arches aquifer system showing flow paths associated with local, intermediate, and regional flow systems[71] and flow systems simulated by the regional groundwater flow model.[33]

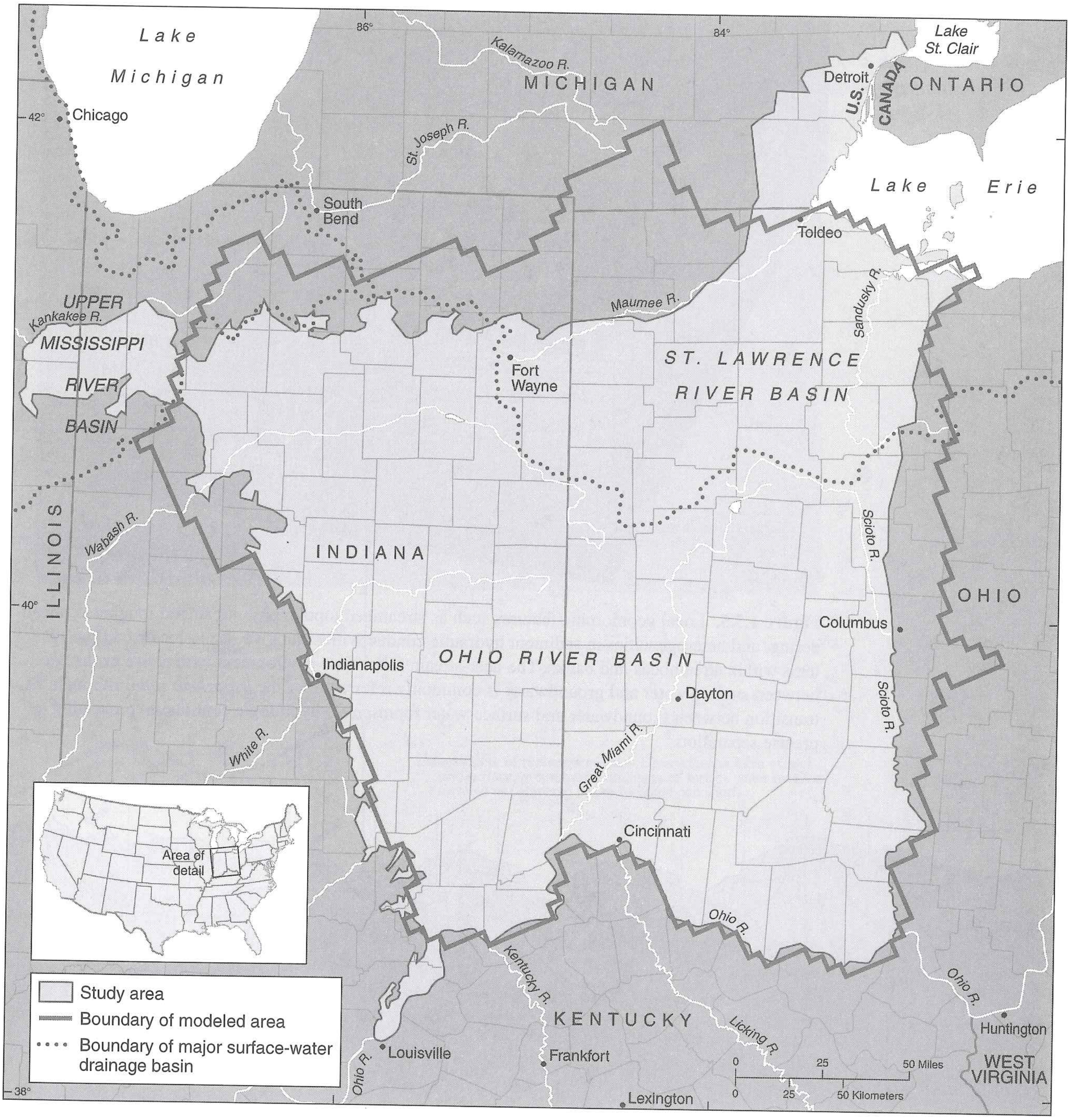


Figure 1.5.7. Midwestern Basin and Arches aquifer system in Parts of Indiana, Ohio, Michigan, and Illinois.[33]

1.6 HYDROLOGIC BUDGET

A *hydrologic budget, water budget,* or *water balance* is a measurement of continuity of the flow of water, which holds true for any time interval and applies to any size area ranging from local-scale areas to regional-scale areas or from any drainage area to the earth as a whole. The hydrologists usually must consider an open system, for which the quantification of the hydro-

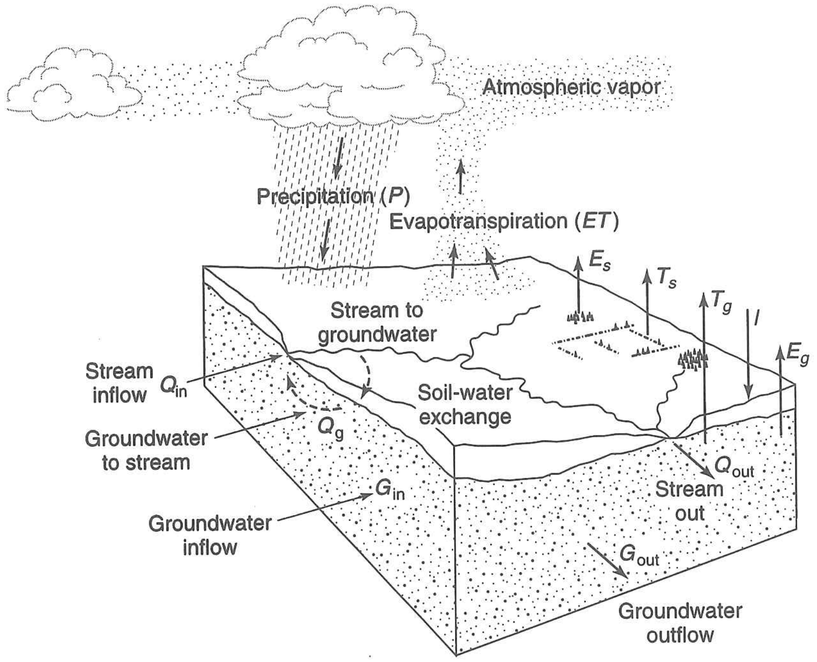


Figure 1.6.1. Components of hydrologic cycle in an open system: the major inflows and outflows of water from a parcel of land. *Source:* W.M. Marsh and J. Dozier, *Landscape: An Introduction to Physical Geography.* Copyright © 1986 by Wiley. Reprinted by permission of John Wiley & Sons, Inc.

logic cycle for that system becomes a mass balance equation in which the change of storage of water (dS/dt) with respect to time within that system is equal to the inputs (I) to the system minus the outputs (O) from the system.

Considering the open system in Figure 1.6.1, the water balance equation can be expressed for the surface water system and the groundwater system in units of volume per unit time separately, or for a given time period and area, in depth.

Surface Water System Hydrologic Budget

$$P + Q_{\text{in}} - Q_{\text{out}} + Q_g - E_s - T_s - \mathrm{I} = \Delta S_s, \tag{1.6.1}$$

where P is the precipitation, Q_{in} is the surface water flow into the system, Q_{out} is the surface water flow out of the system, Q_g is the groundwater flow into the stream, E_s is the surface evaporation, T_s is the transpiration, I is the infiltration, and ΔS_s is the change in water storage of the surface water system.

Groundwater System Hydrologic Budget

$$I + G_{\text{in}} - G_{\text{out}} - Q_g - E_g - T_g = \Delta S_g, \tag{1.6.2}$$

where G_{in} is the groundwater flow into the system, G_{out} is the groundwater flow out of the system, and ΔS_g is the change in groundwater storage. The evaporation, E_g, and the transpiration, T_g, can be significant if the water table is near the ground surface.

System Hydrologic Budget

The system hydrologic budget is developed by adding the above two budgets together:

$$P - (Q_{\text{out}} - Q_{\text{in}}) - (E_s + E_g) - (T_s + T_g) - (G_{\text{out}} - G_{\text{in}}) = \Delta(S_s + S_g) \tag{1.6.3}$$

Using net mass exchanges, the above system hydrologic budget can be expressed as

$$P - Q - G - E - T = \Delta S \tag{1.6.4}$$

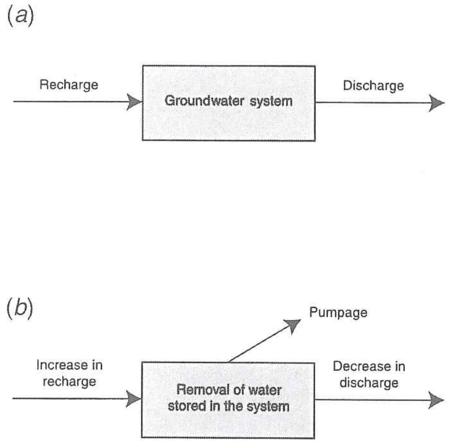


Figure 1.6.2. Diagrams illustrating water budgets for a groundwater system for predevelopment and development conditions.[3] (*a*) Predevelopment water-budget diagram illustrating that inflow equals outflow. (*b*) Water-budget diagram showing changes in flow for a groundwater system being pumped. The sources of water for the pumpage are changes in recharge, discharge, and the amount of water stored. The initial predevelopment values do not directly enter the budget calculation.

Hydrologic budgets can be used for numerous studies related to groundwater including

- Estimating groundwater exchange with lakes.[32, 39, 46, 60, 63, 64, 72]
- Estimating surface water and groundwater interaction.[38, 42, 62]
- Computing recharge from a well-hydrograph data.[39]

A diagram illustrating water budgets for a groundwater system for predevelopment and development conditions is presented in Figure 1.6.2. A groundwater budget for part of Nassau and Suffolk Counties, Long Island, New York, is shown in Figure 1.6.3. Both of these water budgets assume equilibrium conditions with little or no change in storage.

EXAMPLE 1.6.1

During 1996, the water budget terms for Lake Annie in Florida[60] included precipitation (P) of 43 inch/yr, evaporation (E) of 53 inch/yr, surface water inflow (Q_{in}) of 1 inch/yr, surface outflow (Q_{out}) of 173 inch/yr, and change in lake volume (ΔS) of –2 inch/yr. Determine the net groundwater flow (the groundwater inflow minus the groundwater outflow).

SOLUTION

Assuming $T_g = 0$, the water budget equation (1.6.4) to define the net groundwater flow for the lake is

$$G = \Delta S - P + E - Q_{\text{in}} + Q_{\text{out}}$$

$$= -2 - 43 + 53 - 1 + 173$$

$$= 180 \text{ inch/yr}$$

■

EXAMPLE 1.6.2

During January 1996, the water-budget terms for Lake Annie in Florida[60] included precipitation (P) of 1.9 inch, evaporation (E) of 1.5 inch, surface water inflow (Q_{in}) of 0 inch, surface outflow (Q_{out}) of 17.4 inch, and change in lake volume (ΔS) of 0 inch. Determine the net groundwater flow for January 1996 (the groundwater inflow minus the groundwater outflow).

SOLUTION

The water budget equation to define the net groundwater flow for the lake is

$$G = \Delta S - P + E - Q_{\text{in}} + Q_{\text{out}} = 0 - 1.9 + 1.5 - 0 + 17.4 = 17 \text{ inch for January 1996}$$

■

OVERALL PREDEVELOPMENT WATER-BUDGET ANALYSIS

INFLOW TO LONG ISLAND HYDROLOGIC SYSTEM	CUBIC FEET PER SECOND
1. Precipitation	2,475
OUTFLOW FROM LONG ISLAND HYDROLOGIC SYSTEM	
2. Evapotranspiration of precipitation	1,175
3. Ground-water discharge to sea	725
4. Streamflow discharge to sea	525
5. Evapotranspiration of ground water	25
6. Spring flow	25
Total outflow	2,475

GROUND-WATER PREDEVELOPMENT WATER-BUDGET ANALYSIS

INFLOW TO LONG ISLAND GROUND-WATER SYSTEM	CUBIC FEET PER SECOND
7. Ground-water recharge	1,275
OUTFLOW FROM LONG ISLAND GROUND-WATER SYSTEM	
8. Ground-water discharge to streams	500
9. Ground-water discharge to sea	725
10. Evapotranspiration of ground water	25
11. Spring flow	25
Total outflow	1,275

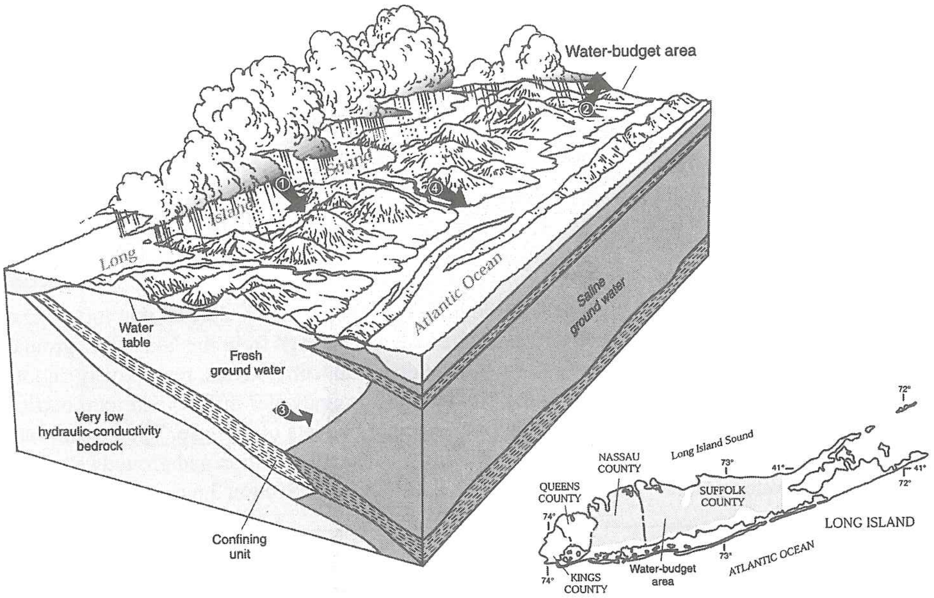


Figure 1.6.3. Groundwater budget for part of Nassau and Suffolk Counties, Long Island, New York.[3] Block diagram of Long Island, New York, and tables listing the overall water budget and groundwater budget under predevelopment conditions. Both water budgets assume equilibrium conditions with little or no change in storage.

The components of hydrologic budgets are either measured, calculated, or estimated. Evaporation, for example, may be obtained from measured pan evaporation data or calculated from the energy balance method, the aerodynamic method (such as the Thornthwaite–Holzman equation), or a combination of these methods (such as the Priestley–Taylor evaporation method). Detailed discussions of these methods are presented in References 22, 49, and 52. Precipitation data are measured or is obtained from recorded data, and in some cases are estimated based upon recorded data for other time periods of interest. Depending upon the time period of the budget, average monthly values could also be used. In the case when the hydrologic budgets are of lakes, lake volume changes are needed and they can be computed using actual lake-stage measurements and relationships between lake stage and lake volume. Using estimates of lake volume changes, evaporation, and precipitation, estimates of net groundwater flow to a lake can be made. The individual components of net groundwater flow are the groundwater inflow to the lake and the leakage from the lake, which can be determined through groundwater simulation models. Groundwater simulation models (Chapter 9), however, need to be calibrated, which requires the monitoring of groundwater levels (hydraulic heads, Chapter 2), lithographic data (Chapter 12), results (hydraulic conductivities) from pump tests (Chapter 4), or slug tests (Chapter 5). With a calibrated groundwater flow model, the groundwater flow into a lake and the leakage from a lake can be determined using simulated groundwater flow fields.

CASE STUDY *Lake Five-O, Florida*

Grubbs[39] described the hydrologic budgetary analysis that was performed for Lake Five-O (a seepage lake), located in Bay County in northwestern Florida (see Figures 1.6.4 and 1.6.5). This hydrologic budget (Table 1.6.1 and Figure 1.6.6) was determined using both collected data and model simulation results (see Chapter 9). Lake Five-O is located in an area characterized by coastal terrace deposits that have been modified by extensive karst development. Soils in the area are deep, excessively drained, and consist of very permeable, Lakeland series sands. Maximum lake depth ranged from 13.5 m to 15.4 m. Surface area ranged from 10.4 to 11.3 hectares, and the lake volume ranged from 9.09×10^5 to 1.11×10^6 m^3.

The net groundwater flow (groundwater inflow minus leakage) was determined by the water balance approach utilizing measurements of precipitation, lake evaporation was determined using the energy budget method, and lake volume changes were estimated from lake-stage measurements and a relationship between lake stage and lake volume. The analysis was utilized to make qualitative assessments of the significance of lake–groundwater exchanges during the study period. A groundwater simulation model was used to determine the groundwater inflows and seepage from the lake. The simulation model was developed using lithographic data to define the three geohydrologic units, a network of monitoring wells to define the hydraulic heads over the time of the hydrologic budget, previously published data, and limited slug tests to help determine hydraulic conductivities. The analysis made it possible to develop quantitative estimates of minimum groundwater inflow and leakage rates not only during the study period, but also for long-term average conditions.

The hydrologic budget for Lake Five-O is expressed as

$$\Delta S = P - E + Q_{\text{in}} - Q_{\text{out}}$$

The hydrologic budget by Grubbs[39] showed that the groundwater inflow to the lake and leakage from the lake to the groundwater system are the dominant components, respectively, in total inflow (precipitation plus groundwater inflow) and total outflow (evaporation plus leakage) budgets of the lake. The groundwater movement, including the head distribution and groundwater flow near Lake Five-O, is discussed in Section 3.6.6.

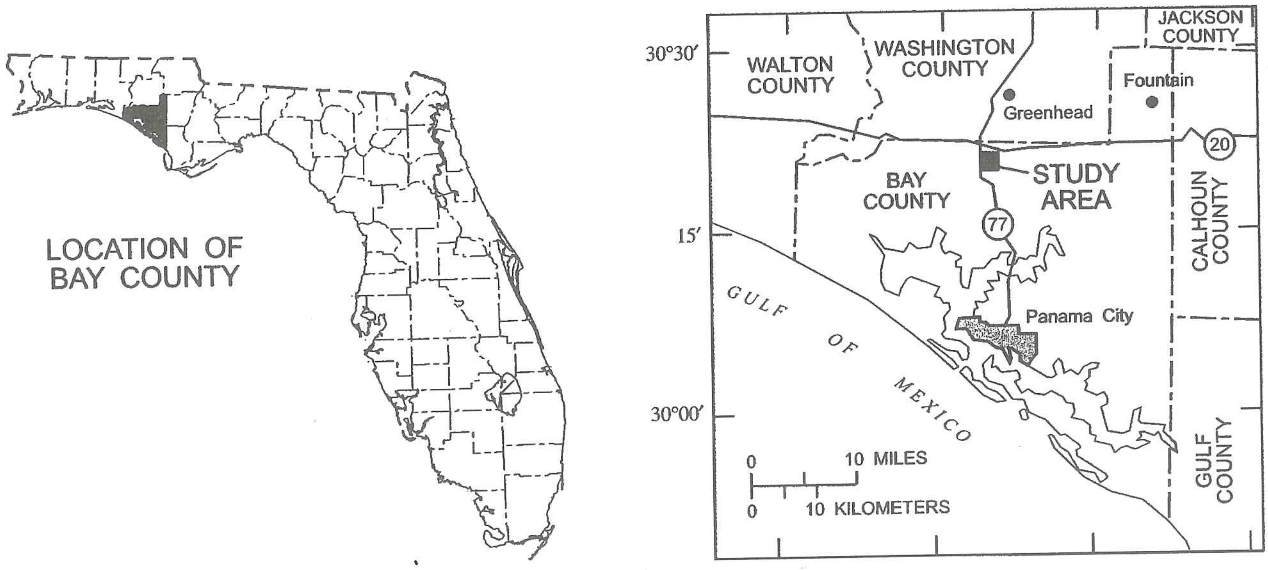


Figure 1.6.4. Location of Lake Five-O study area.[39]

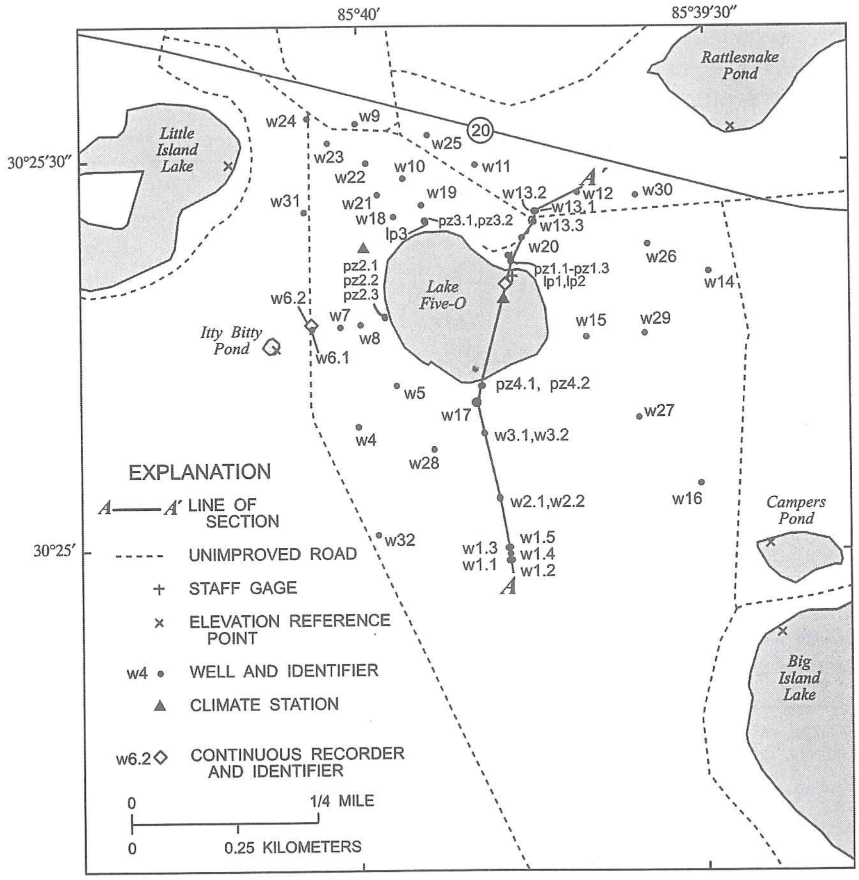


Figure 1.6.5. Location of data-collection sites in the Lake Five-O study area.[39]

Table 1.6.1 Monthly Net Groundwater Flow to Lake Five-O, 1989–90[39]

Month	Average lake volume	Change in lake volume	Precipitation	Evaporation	Net ground-water flow	Standard deviation	Standard deviation (percent of net ground-water flow)
				1989			
Jan.	989,700	–26,100	3,800	3,200	–26,700	2,300	9
Feb.	964,000	–21,900	6,900	4,100	–24,700	2,600	10
Mar.	943,300	–13,900	17,700	7,900	–23,700	3,300	14
Apr.	935,200	–8,700	10,600	11,000	–8,300	2,800	34
May	922,500	–14,700	8,900	13,800	–9,900	2,900	29
June	945,600	69,100	56,800	12,000	24,400	9,300	38
July	1,024,800	66,700	26,300	13,300	53,700	5,400	10
Aug.	1,068,400	26,200	20,900	12,300	17,600	3,700	21
Sept.	1,091,800	22,300	21,500	16,800	17,700	3,700	21
Oct.	1,103,400	3,100	15,100	13,000	1,000	2,700	270
Nov.	1,108,200	4,100	13,800	9,400	–300	2,300	770
Dec.	1,102,700	1,000	13,500	7,900	–4,600	2,300	50

(*continues*)

Table 1.6.1 (*continued*) Monthly Net Groundwater Flow to Lake Five-O, 1989–90

Month	Average lake volume	Change in lake volume	Precipitation	Evaporation	Net ground-water flow	Standard deviation	Standard deviation (percent of net ground-water flow)
				1990			
Jan.	1,107,000	–3,100	3,800	3,300	–3,500	1,500	43
Feb.	1,103,000	–4,800	5,700	4,800	–5,800	1,300	22
Mar.	1,092,000	–15,500	9,600	8,600	–16,500	2,000	12
Apr.	1,076,100	–17,800	12,000	11,100	–18,700	2,400	13
May	1,058,600	–22,000	9,400	15,100	–16,300	2,400	15
June	1,041,300	–9,100	23,700	14,300	–18,500	4,200	23
July	1,046,400	17,900	31,300	15,000	1,600	5,300	330
Aug.	1,055,600	–2,400	16,000	15,600	–2,800	3,600	130
Sept.	1,033,300	–35,600	3,900	17,900	–21,600	2,900	13
Oct.	998,600	–35,100	5,500	15,400	–25,200	2,800	11
Nov.	963,200	–35,600	800	11,300	–25,100	2,600	10
Dec.	932,000	–28,900	7,000	7,400	–28,500	2,600	9

All units are in cubic meters, unless otherwise noted. Standard deviation is the error component of the net groundwater flow estimate. Negative values of net groundwater flow indicate that leakage exceeded groundwater inflow.

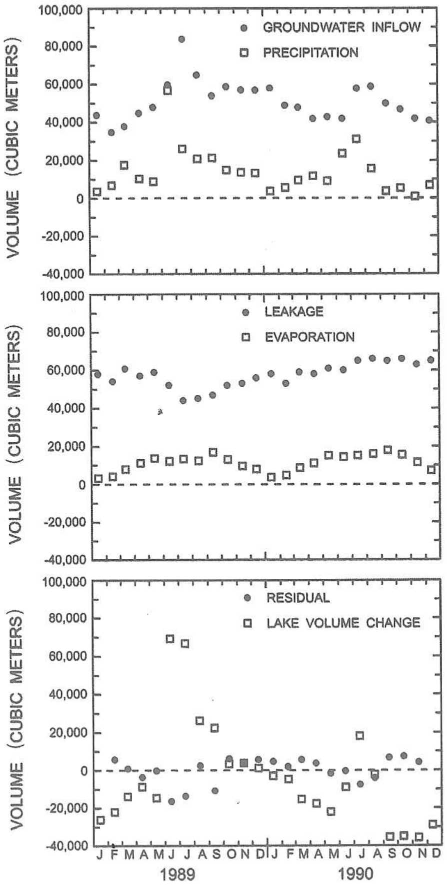


Figure 1.6.6. Monthly hydrologic budget components for Lake Five-O, 1989–90.[39]

The components of a hydrologic budget, whether they are measured or calculated, have associated errors. These errors are based on the degree of uncertainty of the measurements, limitations of methods, and the assumptions made to calculate the values. In many situations information on the rainfall, surface outflow, and withdrawal for supply may be the most reliable. Calculated values of lake evaporation and lake storage may be less reliable because offsite pan evaporation and estimated pan coefficients are used. Lake stage data may be less reliable because of the uncertainty in assessing the surface area of the lake. Groundwater flow is typically the least reliable. When the measured or calculated components are used in the budget calculations, imbalances between the inflow and outflow components, called *residuals*, occur. The residual term in a hydrologic budget is an accumulation of all the errors in the components of the budget. The previous hydrologic budget equations do not reflect residual terms; however, the analysis by Grubbs[39] describes the residuals in detail.

1.7 PUBLICATION SOURCES

1.7.1 Internet Resources

The Internet has changed the availability of sources of information on groundwater hydrology. Now we can access many types of data and publications very rapidly through the use of a computer. Appendix A provides a list of U.S. government and nongovernmental organizations' Web sites.

Much of this book has been developed to serve as a portal to the vast resources on groundwater hydrology that now exist on the Internet. Hopefully this book will help guide the student, the professional, and the researcher to the general documents, program plans, field project details, software, and other information found on the Internet. Many of the new figures and tables in this edition have been taken from various Web sites, in particular the U.S. Geological Survey site. These items not only provide specific information but also serve as samples of graphics and tabulations available on the Internet, making the style of this book more variable than that of most textbooks. The majority of Web sites referenced in this book are maintained by government agencies and established organizations, and therefore should be accessible for many years to come. Several end-of-chapter problems throughout the book are based upon Internet exercises.

1.7.2 U.S. Geological Survey Publications

In the United States, a majority of the field measurements and investigations of groundwater have been conducted by the U.S. Geological Survey (USGS). Most work has been on a cooperative basis with individual states. Results are published by the Survey as *circulars,* digital data series, fact sheets, hydrologic atlases, open-file reports, techniques of water-resources, water data reports, water-resources investigation reports, *professional papers,* and *water-supply papers.* Table 1.7.1 describes the various types of U.S. Geological Survey reports, and Table 1.7.2 describes how to find and reference on-line USGS water resources reports. Since 1935 records of groundwater measurements in key observation wells have been published in *water-supply papers* under the title *Groundwater Levels in the United States.* The U.S. Geological Survey publishes at irregular intervals other papers on the geology and groundwater resources of local areas. Invariably, these intensive investigations concern areas containing important groundwater problems and are carried out in cooperation with local agencies.

Table 1.7.1 Types of U.S. Geological Survey Reports

Circulars—Purpose: To present to general or scientific audiences short summaries or articles of short-term, popular, or local interest.

Digital Data Series—The Digital Data Series encompasses a broad range of digital data, including computer programs, interpreted results of investigations, comprehensive reviewed databases, spatial data sets, digital images and animation, and multimedia presentations that are not intended for printed release. Scientific reports in this series cover a wide variety of subjects and facets of U.S. Geological Survey investigations and research that are of lasting scientific interest and value. Releases in the Digital Data Series offer access to scientific information that is available in digital form; the information is primarily for viewing, processing, and (or) analyzing by computer.

Fact Sheets—Purpose: To describe Water Resources Division (WRD) programs, projects, products, and water-resources topics to either a general or professional audience. Water Fact Sheets are concise and timely publications that increase the understanding and visibility of WRD activities and accomplishments.

Hydrologic Atlases—Purpose: To present reports on hydrology or geohydrology in map format to a wide range of hydrologically oriented audiences.

Open-File Reports—Purpose: To make available (1) data reports, (2) reports preliminary findings that would be of interest to few persons other than the cooperating agency, (3) reports and maps pending publication elsewhere but requiring immediate release, and (4) timely information describing programs, projects, products, and water-resources topics.

Professional Papers—Purpose: To present comprehensive or topical reports on any field in the earth sciences. This series is commonly used for summaries of wide popular, scientific, or geographic interest, and for significant scientific contributions—generally on topics other than hydrology.

Techniques of Water-Resources—Purpose: To present to technically oriented audiences reports on methods and techniques used in collecting, analyzing, and processing hydrologic data.

Water Data Reports—A series of annual reports that document hydrologic data gathered from the U.S. Geological Survey's and cooperating agencies' surface and groundwater data-collection networks in each state, Puerto Rico, and Trust Territories. These records of streamflow, groundwater levels, and water quality provide the hydrologic information needed by state, local, and federal agencies, and the private sector for developing and managing our Nation's land and water resources.

Water-Resources Investigations Reports—Purpose: To (a) present to interdisciplinary audiences comprehensive or topical interpretive reports and maps that are mainly of local or short-term interest; (b) provide a medium of release for reports and maps that would not be feasible in any other series or journal or that would be published quickly.

Water-Supply Papers—Purpose: To present significant interpretive results of hydrologic investigations of broader than local interests.

Water Errata Sheets—Changes made to reports after publication.

Source: http://water.usgs.gov/pub.html

Table 1.7.2 How to Find and Reference Online USGS Water Resources Reports

Many USGS reports on water resources topics are now being served online. You can access them by their series and number. For example, to see Circular 1123, you should enter CIR 1123 in the search box at the following URL: http://water.usgs.gov/pubs.

Constructing a reference

Use one of these prefixes for the report series, followed by the report number. Dashes and underlines are permitted (and ignored), but blanks are not allowed. Case is insensitive.

Report Series	Preferred Prefix	Alternate Prefix(es) Allowed
Fact Sheet	FAC	FS FACT FS_
Open-File Report	OFR	OF
Water-Resources Investigation	WRI	WR WRIR
Professional Paper	PRO	PROF PP
Water-Data Report	WDR	WD DATA
Circular	CIR	CIRC C
Water-Supply Paper	WSP	WS
Bulletin	BUL	BULL
Techniques of Water-Resources Investigations	TWRI	TWRI

Table 1.7.2 (continued) How to Find and Reference Online USGS Water Resources Reports

Referencing parts of a document
Using only the series and number will reference the home page (index.html) of the document. You also can reference a specific part of a document in html format, even if it's not on the home page. For example, to find the section named *HRD4* in a file of Circular 1123 called *overview.html*, use this URL: http://pubs.water.usgs.gov/cir1123/overview.html#HDR4. This technique will work for any sub-page or figure of the html document.
The "pubs.water.usgs.gov" reference is persistent!
The USGS is committed to supporting this referencing system for the indefinite future. This means you can safely incorporate a "pubs.water.usgs.gov" reference in your Web pages and even in your printed documents and it will still work many years later. When viewing a document, your browser's location may show you another URL that corresponds to the current physical location of the document. Do not use this physical location as a "persistent" reference! As our system grows, these locations will change but the "pubs.water.usgs.gov" reference will not.

Source: http://water.usgs.gov/pubs/referencing.html

1.7.3 Publications

The following journals provide articles on various topics of groundwater:

Environmental Science and Technology, American Chemical Society
Ground Water, National Ground Water Association
Groundwater Management, Water Well Journal Publishing Co.
Ground Water Monitoring and Remediation, Groundwater Publishing Company
Hydrological Science and Technology, American Institute of Hydrology
Journal of the American Water Resources Association, American Water Resources Association
Journal of Contaminant Hydrology, Elsevier Scientific Publishers
Journal of Hydraulics, American Society of Civil Engineers
Journal of Hydrology, Elsevier Scientific Publishers
Journal of Water Resources Planning and Management, American Society of Civil Engineers

There have been many books published on the subject of groundwater. Earlier books include References 4, 5, 7, 17, 19, 23, 26, 29–31, 40, 41, 43, 56, 58, 59, 61, 67, 70, 73, and 74.

Over the past three decades there are several previous books that have been published on groundwater including *Applied Hydrogeology*[35]; *Aquifer Hydraulics*[8]; *Contaminant Hydrogeology*[34]; *Groundwater*[36]; *Ground Water Contamination: Transport and Remediation*[14]; *Groundwater Engineering*[45]; *Groundwater Hydrology*[16]; *Groundwater Hydrology*[69]; *Groundwater Hydraulics and Pollutant Transport*[20]; *Groundwater Mechanics*[66]; *Groundwater Science*[36]; *Groundwater Systems Planning and Management*[77]; *The Handbook of Groundwater Engineering*[27]; *Hydraulics of Groundwater*[10]; *Manual of Applied Field Hydrogeology*[76]; *Modeling Groundwater Flow and Pollution*[11]; *Principles of Groundwater Engineering*[75]; and *Quantitative Hydrogeology.*[51]

1.8 DATA SOURCES

Table 1.8.1 lists the principal types of data and data compilations that are required for the analysis of groundwater systems. The lists are for the physical framework, hydrologic budgets and stresses, and the chemical framework. One of the sources of data used frequently by groundwater hydrologists is the U.S. Geological Survey NWIS system.

Table 1.8.1 Principal Types of Data and Data Compilations Required for Analysis of Groundwater Systems

Physical framework
Topographic maps showing the stream drainage network, surface-water bodies, landforms, cultural features, and locations of structures and activities related to water
Geologic maps of surficial deposits and bedrock
Hydrogeologic maps showing extent and boundaries of aquifers and confining units
Maps of tops and bottoms of aquifers and confining units
Saturated-thickness maps of unconfined (water-table) and confined aquifers
Average hydraulic conductivity maps for aquifers and confining units and transmissivity maps for aquifers
Maps showing variations in storage coefficient for aquifers
Estimates of age of groundwater at selected locations in aquifers
Hydrologic budgets and stresses
Precipitation data
Evaporation data
Streamflow data, including measurements of gain and loss of streamflow between gaging stations
Maps of the stream drainage network showing extent of normally perennial flow, normally dry channels, and normally seasonal flow
Estimates of total groundwater discharge to streams
Measurements of spring discharge
Measurements of surface-water diversions and return flows
Quantities and locations of interbasin diversions
History and spatial distribution of pumping rates in aquifers
Amount of groundwater consumed for each type of use and spatial distribution of return flows
Well hydrographs and historical head (water-level) maps for aquifers
Location of recharge areas (areal recharge from precipitation, losing streams, irrigated areas, recharge basins and recharge wells), and estimates of recharge
Chemical framework
Geochemical characteristics of earth materials and naturally occurring groundwater in aquifers and confining units
Spatial distribution of water quality in aquifers, both areally and with depth
Temporal changes in water quality, particularly for contaminated or potentially vulnerable unconfined aquifers
Sources and types of potential contaminants
Chemical characteristics of artificially introduced waters or waste liquids
Maps of land cover/land use at different scales, depending on study needs
Streamflow quality (water-quality sampling in space and time), particularly during periods of low flow

Source: Alley et al.[3]

1.8.1 NWISWeb Data for the Nation

The U.S. Geological Survey is the principal federal water data agency in the United States. The USGS collects and disseminates about 70 percent of the water data currently being used by numerous state, local, private, and other federal agencies to develop and manage water resources. The National WATer Data STOrage and REtrieval System (WATSTORE) was established in 1972 to provide an effective and efficient means for the processing and maintenance of water data collected through the USGS and to facilitate release of the data to the public. In 1976, the USGS opened WATSTORE to the public for direct access.

The U.S.G.S. National Water Information System (NWIS) has replaced WATSTORE and is referred to as NWISWeb (http://waterdata.usgs.gov/nwis). NWIS is a very large collection of data and information on the water resources of the United States. This database contains current and historical water data from more than 1.5 million locations across the nation. The data categories are real-time data, site information, surface water data, groundwater data, and water quality. Real-time data includes data transmitted from selected groundwater sites. Site information includes descriptive site information, including latitude, longitude, well depth, aquifer, and site use. The groundwater database includes groundwater site inventory, groundwater level data, and water-quality data. The groundwater site inventory consists of more than 850,000 records of wells, springs, test holes, tunnels, drains, and excavations in the United States. The groundwater data can be obtained at http://waterdata.usgs.gov/nwis/gw.

1.8.2 Real-Time Data

Real-time groundwater data include data that are automatically collected, transmitted, and made available to the public at least once a day according to the U.S.G.S. (Fact Sheet 090–01, December 2001). These data can be transmitted by land-lined telephone, cellular telephone, land-based *radio frequency* (RF) technology, satellite telemetry, or a combination of these technologies. Within the U.S.G.S., satellite telemetry is the most common method for real-time data transmission. Water levels are the most common data transmitted in real time by the USGS. Figure 1.8.1 illustrates a real-time data collection and transmission system. With this method, water-level data are recorded by a *data-collection platform* (DCP) (see Figure 1.8.2) and transmitted, often on a four-hour schedule, by satellite telemetry to a U.S.G.S. ground station. The data are then displayed at http://water.usgs.gov/nwis/gw.

Real-time data have many inherent advantages over data collected and distributed by traditional means, including timeliness, data quality, data availability, and cost. Additional information on real-time groundwater data can be obtained at http://water.usgs.gov/nwis/gw or from the following address: Office of Groundwater, U.S. Geological Survey, 411 National Center, 12201 Sunrise Valley Drive, Reston, Virginia 20192, 703–648–5001.

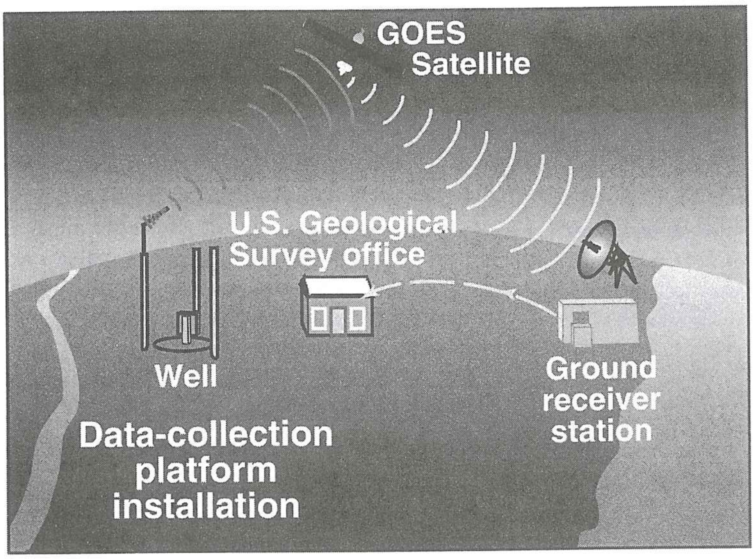


Figure 1.8.1. Real-time data collection and transmission system.[25]

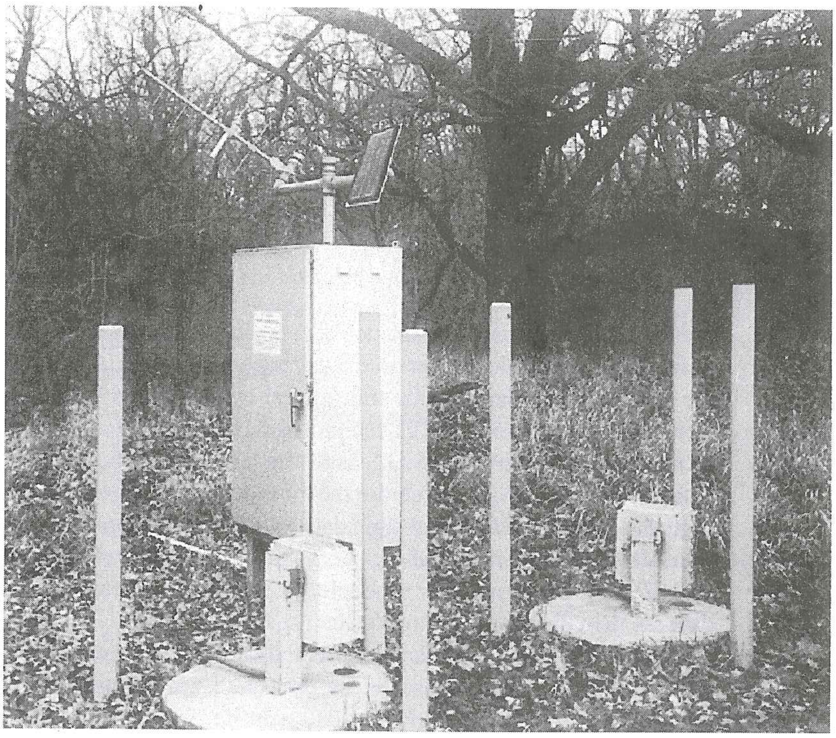


Figure 1.8.2. Multiple sensor data-collection platform (DCP) installation in Kansas.[25]

PROBLEMS

1.6.1 Using the data for Lake Five-O in Table 1.6.1, show that the net groundwater flow for December 1989 is –4,600 cubic meters.

1.6.2 Using the data for Lake Five-O in Table 1.6.1, show that the net groundwater flow for December 1990 is –28,500 cubic meters.

1.6.3 Determine cumulative net groundwater flow for Lake Five-O during 1989.

1.6.4 Determine cumulative net groundwater flow for Lake Five-O during 1990.

1.7.1 Perform a search of the U.S. Geological Survey online publications (including circulars, fact sheets, open-file reports, professional papers, water-resources investigation reports, and water supply papers) to determine what studies, if any, have been performed on the regional aquifer system closest to where you live.

1.7.2 Develop an inventory of wells in the county where you live using the USGS data sources for your state. Select a well that has a time history of water levels and print the hydrograph.

1.7.3 Perform a search of U.S.G.S. publications for the topic "hydrologic budget and water budget." To perform the search, go to http://usgs-georef.cos.com. How many publications are listed?

1.7.4 Perform a search of U.S.G.S. publications for the High Plains Aquifer. To perform the search, go to http://usgs-georef.cos.com. How many publications are listed?

1.7.5 Perform a search of U.S.G.S. publications for the Edwards Aquifer. To perform the search, go to http://usgs-georef.cos.com. How many publications are listed?

1.7.6 Perform a search of U.S.G.S. publications for the topic of karst terrains. To perform the search go to http://usgs-georef.cos.com. How many publications are listed?

1.7.7 Go to the site http://water.usgs.gov/software and obtain a list of the groundwater software that the U.S.G.S. has available.

1.7.8 Write a description of the U.S.G.S. Ground-Water Resources Program. Use the site http://water.usgs.gov/ogw/GWRP.html.

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