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Appendix 9. Historical Ground-Water-Flow Conditions

Figures

Table

Appendix 9. Historical Ground-Water-Flow Conditions

The nature of a regional ground-water-flow system at a specific time is determined by the hydraulic characteristics, previous conditions, and stresses of the system. The source and residence time of ground water at a location depend on hydrologic and anthropogenic factors such as location in the ground-water-flow field, hydraulic conductivity and anisotropy, and ground-water withdrawals and returns. For example, a regional investigation in Pennsylvania (Burton and others, 2002) found bedrock-fracture anisotropy to influence ground-water residence times significantly. Ground-water residence times represent a mixture of travel times and are affected by changes in regional withdrawals over time (Zinn and Konikow, 2007). The regional ground-water-flow system in the Seacoast model area was evaluated with respect to climate conditions and historical water uses over recent decades.

Historical hydrologic observations in the study area are at most 10 years old; some monitoring-well data were collected over a 10-year period, whereas the only continuous streamflow data were those data collected for this study. A multidecade simulation was developed to examine the Seacoast ground-water-flow system in relation to environmental tracers used in determining residence time of ground-water samples collected in this study (chlorofluorocarbons). Chlorofluorocarbons (CFCs) have previously been used to determine the residence time, commonly referred to as "age dating," of ground water in New Hampshire (Ayotte and others, 2003; Busenberg and Plummer, 1993; Flanagan and others, 1999). The residence time of ground water in selected bedrock aquifers in New England ranged from approximately 50 years to very short for recently recharged water, with a median of about 25 years (Ayotte and others, 2003). Ground-water residence times, including those listed in table 9–1, are commonly analyzed by assuming a piston-flow model for ground-water flow (Busenberg and Plummer, 1993). The piston-flow model is based on the assumption that the water sampled is of one age, not a mixture of waters with different ages. A piston-flow analysis may be more applicable for wells with little or no water use, such as a monitoring well or domestic well with little use, and may not be suitable for wells in which the water is highly mixed (Hunt and others, 2005). An uncertainty in the residence-time calculation, particularly for water that is actually younger than 1990, is that atmospheric CFC concentrations peaked between 1990 and 2000; the result is that two ages, one before and the other after the peak, correspond to the CFC concentration in water.

Fifteen bedrock wells (fig. 9–1) were sampled and analyzed for CFC-11, CFC-12, and CFC-113 at the USGS Reston Chlorofluorocarbon Laboratory (L.N. Plummer and E. Busenberg, U.S. Geological Survey, written commun., 2005). Table 9–1 provides a summary of well conditions, water use, and analysis of ground-water age. Detailed results are provided in appendix 10 (table 10–1). The wells sampled were subject to withdrawal conditions (table 9–1) that ranged from unused monitoring wells (not used for supply), seasonally or intermittently used supply wells, domestic-supply wells with a low rate of household use (estimated to be about 200 gal/d), and supply wells that were pumped nearly continuously at high rates of withdrawal (400,000 gal/d or greater). The variety of wells provided ground water with a range of use types and locations in the ground-water-flow system. Uncertainties in the CFC analysis are indicated by the different ages calculated with different CFCs for specific wells (table 9–1). Additional isotopic or dissolved gas analyses can be used to further refine residence-time analyses, but such data were not available for this analysis.

To illustrate the effect of changing recharge and water use on the Seacoast hydrologic system, long-term ground-water flow was simulated with time-varying recharge and water-use rates. Figure 9–2 illustrates the effect of changing recharge and water use on simulated average base flows over time. The 55-year simulation was discretized into six steady-state stress periods approximating recharge and water-use conditions over the five 10-year periods between 1950 and 2000 and the 5-year period between 2000 and 2004. Hydraulic conductivities were based on the transient model analysis (appendix 7). On the basis of the recharge analysis and the results of monthly transient simulations (appendix 7), recharge rates for these periods were assumed to be 54 percent of the Portsmouth-Greenland average annual precipitation for each period (fig. 9–3). The recharge rates used for the six stress periods differed slightly and, from 1950 on, were 24, 22, 26, 25, 27, and 25 in/yr. Rates of water use, however, have increased considerably in recent decades (Marilee A. Horn, U.S. Geological Survey, written commun., 2007). Changing water use was approximated over the 55-year period by reducing the total current (2003–04) water use by the approximate percentage of past total water use based on population changes. Withdrawals and returns for the five decades were reduced to 30 percent (1950), 35 percent (1960), 46 percent (1970), 57 percent (1980), and 79 percent (1990) of current uses. Water-use rates during the 5-year period (2000) were set equal to the present (2003–04) estimated water-use rates. Figure 9–2 illustrates the effects of low periods of recharge, in the 1950s and 1960s, and increasing water use in later decades (post 1990).

The simulation used approximate decadal-average recharges and stresses sufficient for the simulation of historical flow conditions; the use of current water-use rates or seasonal low-recharge rates in a long-term (multidecade) simulation would have resulted in greater stresses on the ground-water-flow system than historically were present. Ground-water residence times are

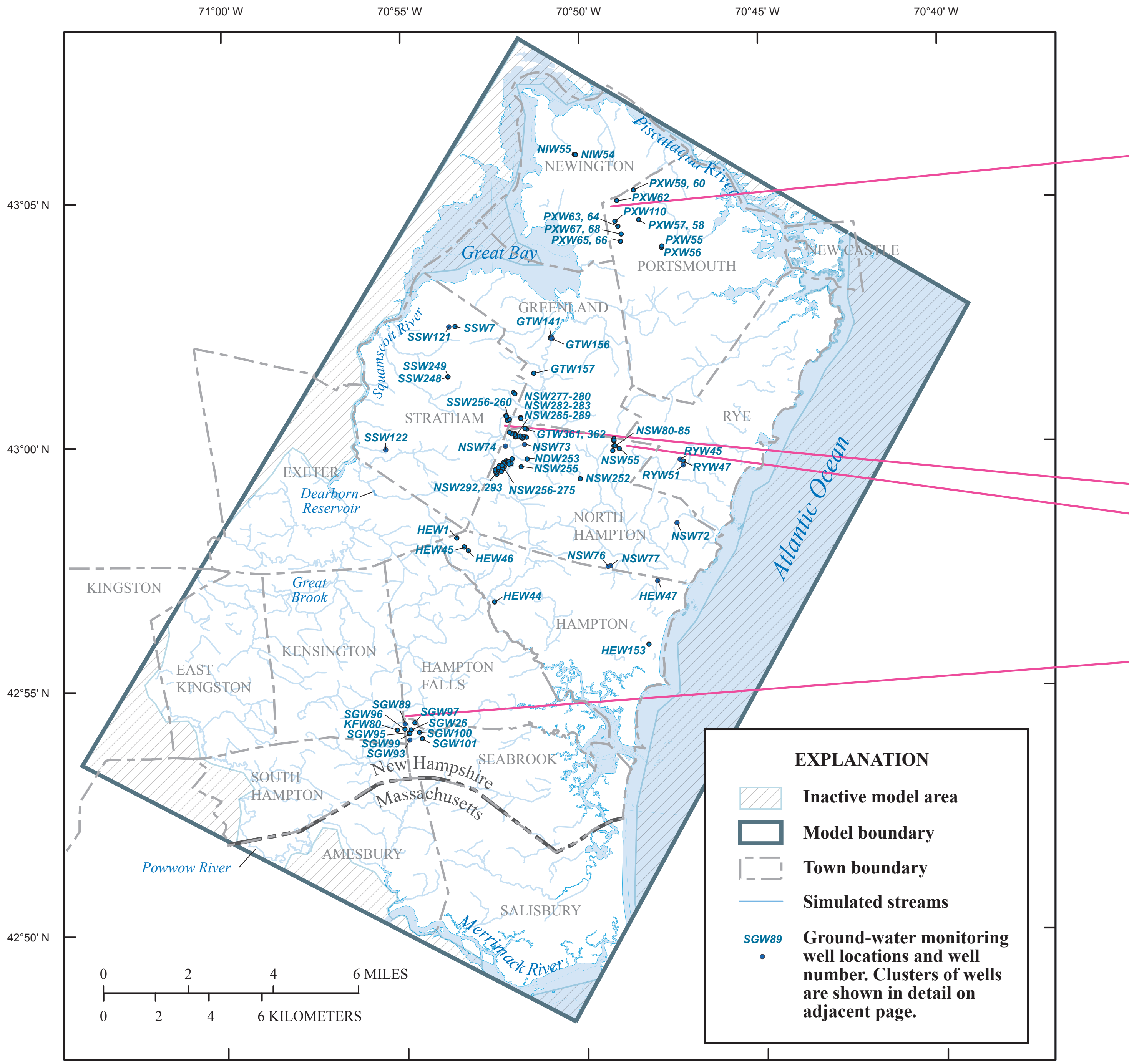
Table 9–1. Summary information and residence time of ground-water samples, determined by chlorofluorocarbon analysis, for selected wells in the Seacoast model area, southeastern New Hampshire.

[Multiple samples were analyzed from each well; ft, feet; gal/min, gallons per minute; yrs, years; —, not available or not calculated]

Sample number	Site name	Well depth (ft)	Use code[1]	Withdrawal or sampling rate (gal/min)	Sampling date	CFC-11 (yrs)	CFC-12 (yrs)	CFC-113 (yrs)	Age calculated from CFC113/CFC12 ratio[2] (yrs)	Percentage of young water in mixture from CFC113	Recommended age basis	Comments regarding sample analysis or age estimation
1	GTW-141	405	U	3	2/1/2005	31	56	48	18	2	CFC-12, 113	Early 1950s or older.
2						31	53	49	25	4		
3	HEW-46	170	D	3	10/13/2004	45	24	29	N	—	CFC-12	Early 1980s.
4						43	24	28	N	—		
5						46	23	33	N	—		CFC-11 possibly degraded.
6	HEW-47	480	D	3	10/13/2004	C	18	19	N	—	CFC-12, 113	Middle 1980s with late peaks.
7						C	18	19	N	—		High CFC-11 contamination.
8	NHW-44	500	U	3	2/2/2005	17	29	40	N	—	CFC-12	Middle 1970s.
9						18	30	42	N	—		
10	NSW-72	320	D	3	10/7/2004	39	30	29	27	87	CFC-12, 113	Middle 1970s.
11						40	30	30	N	—		
12						41	31	32	N	—		
13	NSW-73	500	P	93	10/8/2004	C	C	28	N	—	CFC-113	Middle 1970s.
14						C	C	29	N	—		High CFC-11 and CFC-12 contamination.
15	NSW-74	500	P	300	10/8/2004	48	M	36	N	—	CFC-113	Late 1960s to early 1970s.
16						48	M	35	N	—		
17	NSW-76	600	P	250	10/8/2004	50	19	34	N	—	CFC-113	Early 1970s.
18						50	20	33	N	—		CFC-11 degraded.
19	NSW-77	600	P	250	10/8/2004	51	C	42	N	—	CFC-113	Early to middle 1960s.
20						52	C	42	N	—		CFC-11 degraded.
21	RYW-45	551	P	100	10/7/2004	52	C	41	N	—	CFC-113	Middle 1960s.
22						52	C	40	N	—		High CFC-12 contamination. CFC-11 degraded.
23	RYW-51	437	P	100	10/7/2004	51	C	43	N	—	CFC-113	Early 1960s.
24						53	C	41	N	—		High CFC-12 contamination. CFC-11 degraded.
25	SGW-89	500	P	200	10/13/2004	40	C	24	N	—	CFC-113	Early 1980s.
26						40	C	24	N	—		CFC-11 degraded.
27	SGW-93	492	P	300	10/8/2004	55	22	48	N	—	CFC-12 or 113	Early 1980s if CFC-12 is not contaminated, otherwise use CFC-113 apparent age.
28						54	23	48	N	—		
29	SSW-121	300	S	3	10/8/2004	49	23	41	N	—	CFC-12 or 113	Early 1980s if CFC-12 is not contaminated, otherwise use CFC-113 apparent age.
30						49	23	41	N	—		
31	SSW-122	500	I	10	10/29/2004	32	C	21	N	—	CFC-113	Early to middle 1980s.
32						33	C	21	N	—		

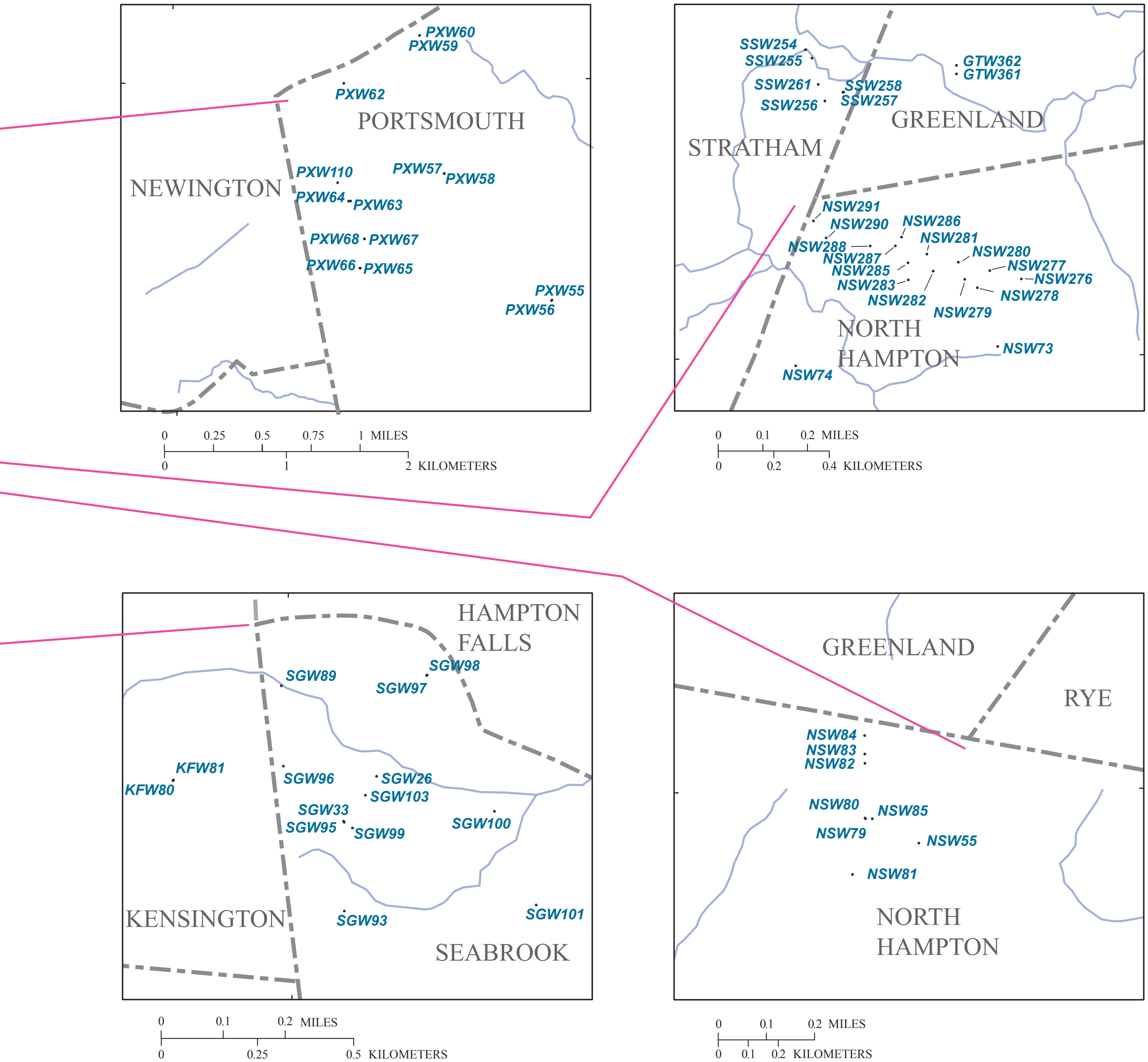
[1] Well use code: U, unused; D, domestic use; P, water supply (high use); S, summer use; I, intermittent.

[2] Analysis codes: N, analysis was not possible; C, contaminated (concentration greater than in atmosphere); M, modern (concentration within the range for modern atmosphere).



Streams and water bodies, including tidal and estuaries from 1:24,000
National Hydrography Dataset, 1999

Figure 9–1. *(A)* Ground-water monitoring wells in the study area. (This figure is the same as figure 7 on page 16–17 in the report.)


PXW60
PXW59
PXW62
PORTSMOUTH
NEWINGTON
PXW110
PXW57
PXW58
PXW64
PXW63
PXW68
PXW67
PXW66
PXW65
PXW55
PXW56
0 0.25 0.5 0.75 1 MILES
0 1 2 KILOMETERS
SSW254
SSW255
GTW362
GTW361
SSW261
SSW258
SSW256
SSW257
GREENLAND
STRATHAM
NSW291
NSW290
NSW286
NSW281
NSW288
NSW280
NSW287
NSW277
NSW285
NSW276
NSW283
NSW278
NSW282
NSW279
NORTH
HAMPTON
NSW73
NSW74
0 0.1 0.2 MILES
0 0.2 0.4 KILOMETERS
HAMPTON
FALLS
SGW98
SGW89
SGW97
KFW81
KFW80
SGW96
SGW26
SGW103
SGW33
SGW95
SGW99
SGW100
KENSINGTON
SGW93
SGW101
SEABROOK
0 0.1 0.2 MILES
0 0.25 0.5 KILOMETERS
GREENLAND
RYE
NSW84
NSW83
NSW82
NSW80
NSW85
NSW79
NSW55
NSW81
NORTH
HAMPTON
0 0.1 0.2 MILES
0 0.1 0.2 KILOMETERS

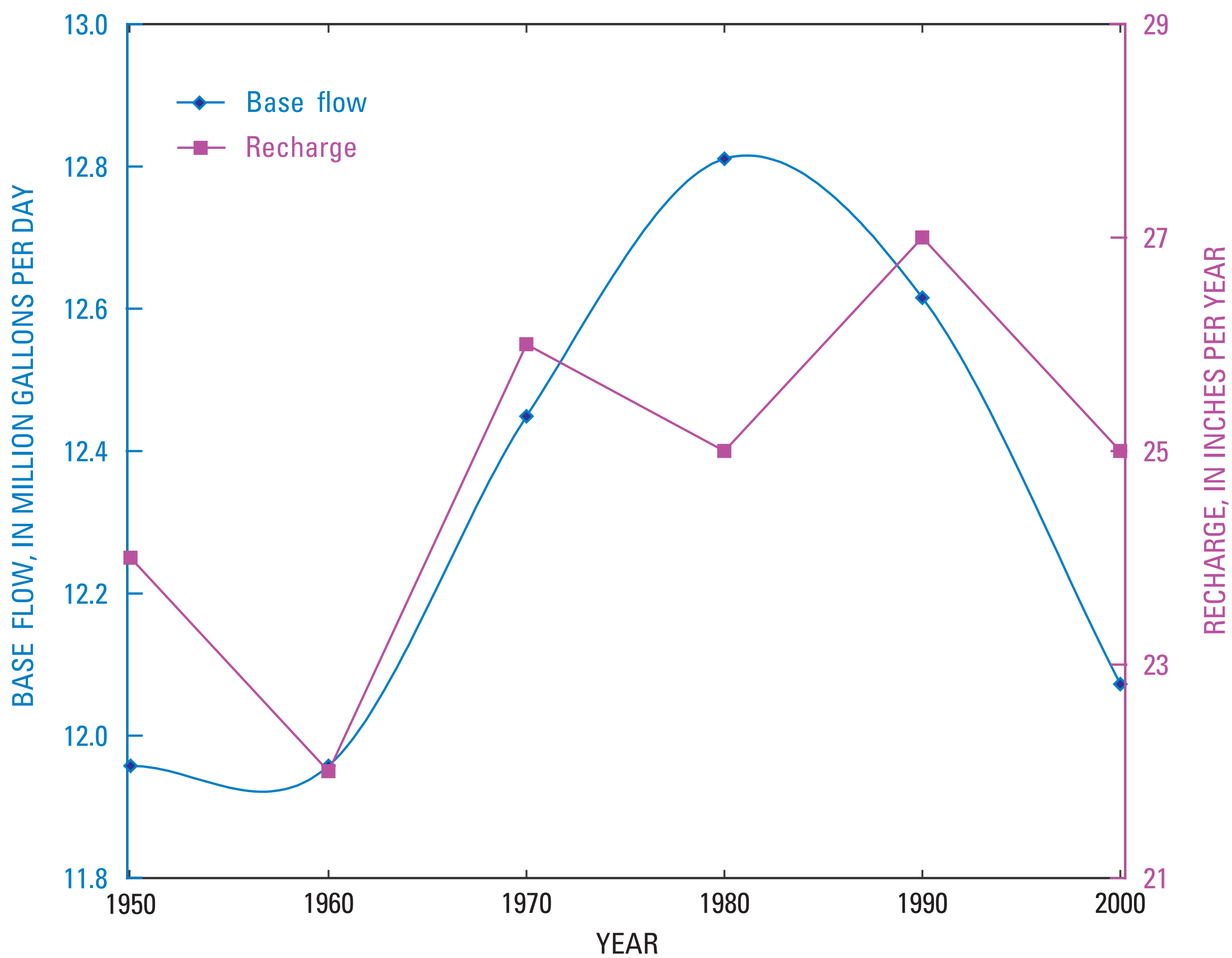


Figure 9–2. Simulated base flow in the Winnicut River and estimated recharge for 50 years from 1950 to 2000, Seacoast model area, southeastern New Hampshire.

influenced by climatic conditions and stresses during the period of ground-water flow through the system. The effects of seasonality and annual variations in recharge on the ground-water flow path, however, are likely to diminish with the age of the path (Reilly and Pollock, 1996). Water use has increased considerably over the apparent residence time of the ground water sampled. For example, withdrawals from wells near the source areas for some of the wells where CFC samples were collected were less in the decades before the sampled wells were installed. The CFC residence times were not compared to model-simulated residence times because of the uncertainties of the CFC-calculated ages and the inherent limitations of simulating ground-water flow in a fractured crystalline-bedrock aquifer with a bulk-property and EPM approach.

The length of the ground-water-flow path in the bedrock aquifer from recharge to discharge depends on several factors. Ground water flowing to large ground-water withdrawals likely follows both very short and long paths. Recharge near the withdrawal well follows short flow paths and, therefore, has relatively short residence times of months to a few years. Water recharged farther from the well, however, may travel farther or deeper in the aquifer and, therefore, has residence times on the order of many years or decades. Flow to a well near another withdrawal well will follow a path that is influenced by the interaction of both withdrawals. The residence-time analyses from large ground-water withdrawals (supply wells) indicate a mixture of young and old water (table 9–1). Wells with a low rate of use generally show less indication of mixing. For most samples it is not possible to determine the mixture of young and old water without additional data. The presence of young water in some of the supply wells, however, can be inferred by the presence of MTBE contamination (Ayotte and others, 2004). Because MTBE use greatly increased in 1990, MTBE contamination is most likely associated with water recharged after this date (Joseph D. Ayotte, U.S. Geological Survey, oral commun., 2006).

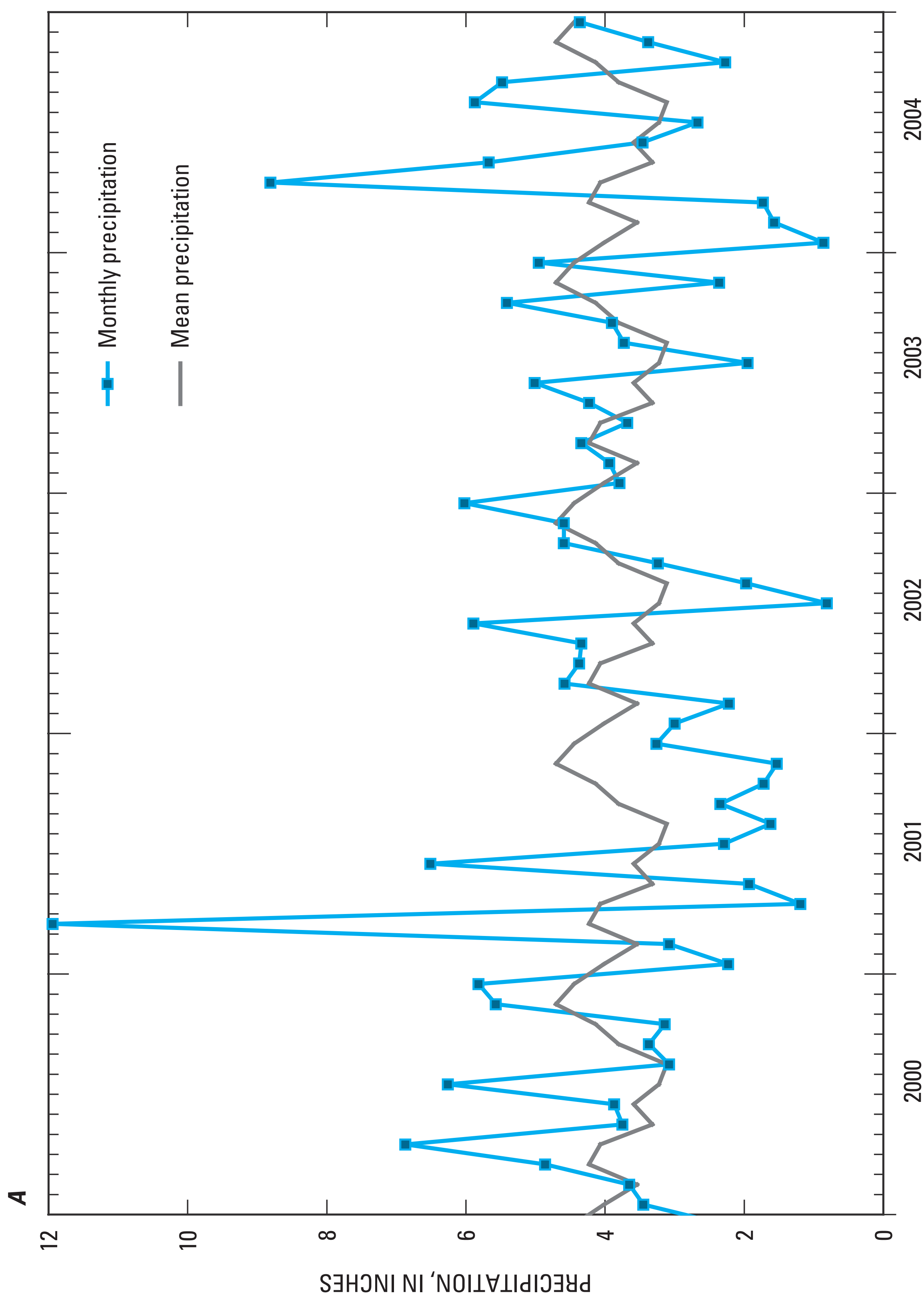
Residence times calculated by CFC-12 analysis for the water in monitoring wells with little or no use ranged from over 50 years (GTW-141) to about 30 years (HEW-44, fig. 9–1). In general, the less used bedrock wells intercepted water that was about 20 to 30 years old that recharged the aquifer in the 1980s. The longest estimated ground-water residence time was for water sampled in well GTW-141. This well is in a ground-water-discharge area near sea level at the base of the Winnicut River watershed in an area with a low ground-water-head gradient. The area immediately surrounding the well is lightly populated and supplied by individual wells where withdrawals are low. Well GTW-141 is 405 ft deep and was used for a few years in the 1980s to supply a small office prior to being discontinued. (A dug well was used at this location prior to the bedrock well). The percentage of young water in this well was estimated to be low (table 9–1).

Two nearby wells were sampled in Stratham in areas with steeper head gradients and closer to local topographic high areas. SSW-122 was installed for commercial supply and was sampled prior to the operation of the business. The ground water was estimated to be 21 to 33 years old. A very high concentration of MTBE (Ayotte and others, 2004) found in a bedrock well within a few hundred feet of SSW-122 (fig. 9–1) indicated that young water is in the bedrock aquifer in this area. Well SSW-121, however, is in an undeveloped area with few other ground-water withdrawals and is used only intermittently in the summer. Ground water at well SSW-121 was older (23 to 49 years) and likely contains little young water because withdrawal stresses are few.

Well HEW-44, with ground water estimated to be about 30 years old (table 9–1, fig. 9–1), is an unused water-supply exploration well 500 ft deep in an area with little water use. Presently the area near HEW-44 is being developed, and water-level fluctuations were measured in the well during nearby bedrock-well installations. This well is in an area of relatively low head gradients and historically few stresses. Well HEW-46 is in a similar environment but is higher in the watershed in an area of regional recharge. The residence time of the water was estimated to be about 20 years or more.

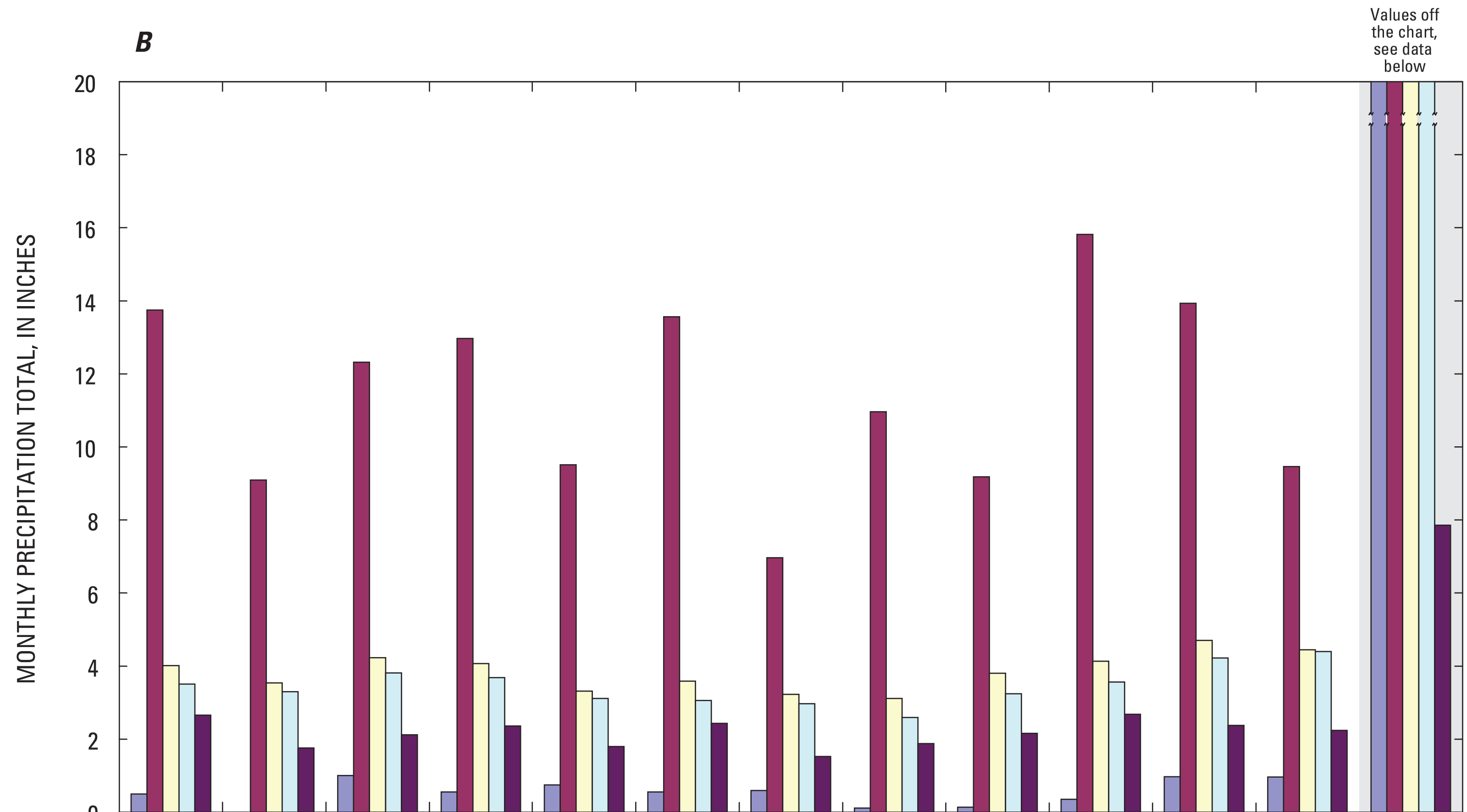
Ground-water residence-time analyses for wells in the Winnicut and Lovering Roads area (NSW-73 and -74, fig. 9–1) indicated a mix of water 28 to 36 years old along with young or modern water. The surficial aquifer is thin in the area, and bedrock ground water most likely contains young water induced from the surficial aquifer. Aquifer tests, discussed previously, have indicated that the surficial and bedrock aquifers are hydraulically connected in this area.

Similarly, ground water in the North Hampton-Hampton bedrock supply wells (NSW-76 and -77, fig. 9–1) was estimated to be 30 to 40 years old. Bedrock ground water in the Rye well field (RYW-45 and -51) was about 40 years old. The North Hampton-Hampton and Rye wells fields are in similar hydrogeologic settings, and both have well fields consisting of two bedrock wells (table 9–1). Wells NSW-76 and 77 are within a few hundred feet of each other and are likely influenced by nearby large withdrawals immediately to the west and topographically upgradient in the surficial aquifer. Water withdrawn from the surficial aquifer in this area has been reported to have chemical characteristics indicative of bedrock water. Given that the surficial-aquifer withdrawals capture water from the bedrock aquifer, it is very likely that withdrawals from the bedrock supply wells were influenced by the surficial-aquifer withdrawals.



Sources of data: Durham, State Climatologist; and Portsmouth and Greenland, National Oceanic and Atmospheric Administration.

Figure 9–3. *(A)* Monthly and mean precipitation at Portsmouth and Greenland, New Hampshire, from January 2000 through December 2004. (This figure is the same as figure 1–2 on page 56–57 in appendix 1.)



	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	Annual
MINIMUM	0.5	0	1	0.55	0.75	0.55	0.59	0.11	0.14	0.35	0.97	0.96	29.19
MAXIMUM	13.75	9.09	12.32	12.97	9.51	13.56	6.97	10.96	9.18	15.82	13.93	9.46	71.26
MEAN	4.02	3.54	4.23	4.07	3.32	3.59	3.22	3.11	3.81	4.14	4.71	4.44	45.37
MEDIAN	3.51	3.3	3.815	3.68	3.11	3.06	2.97	2.59	3.24	3.56	4.22	4.4	44.84
STD. DEVIATION	2.66	1.75	2.12	2.36	1.80	2.43	1.53	1.88	2.16	2.68	2.38	2.24	7.86

Sources of data: Durham, State Climatologist; and Portsmouth and Greenland, National Oceanic and Atmospheric Administration.

Figure 9–3. *(B)* Monthly precipitation statistics at Portsmouth and Greenland, New Hampshire, from 1955 through 2005.—Continued (This figure is the same as figure 1–2 on page 56–57 in appendix 1.)

Two domestic wells, HEW-47 and NSW-72 (table 9–1, fig. 9–1), with low estimated water-use rates of about 200 gal/d, were sampled that were in the same hydrogeologic setting as the North Hampton-Hampton and Rye well fields but were farther downgradient in the ground-water-flow system. The water sampled from well HEW-47 was young, about 20 years old, relative to the ages of water sampled from other low-use wells downgradient in the flow system. A young ground-water residence time in this area of the aquifer may be a result of the high-yield aquifer system and high rate of water usage. This aquifer serves a regional water-distribution network, and base flows in one of the primary drainages in the aquifer, the Little River, generally were lower, relative to the size of the drainage area, than base flows in other streams in the study area. Water sampled from the other domestic well in this area (NSW-72) was older (about 30 years old) than the water sampled from HEW-47 but was estimated to contain a high percentage (87) of young water. This part of the study area, where the bedrock aquifer is the high-yielding Rye Complex, has the potential for greater recharge and ground-water flow than other areas of the Seacoast.

Bedrock ground water sampled from well SGW-89 (well 2) and well SGW-93 (well 5) at a Seabrook supply well field near the Kingston town line (fig. 9–1) was fairly young, about 25 years old based on CFC-12 analysis. The CFC signatures for this well and well SGW-89, however, differ between the two wells; this difference indicates the possibility of different sources of water to the wells.

In an undisturbed ground-water-flow system, one with few withdrawals and low porosity, the ground-water residence time is primarily determined by the location of the water in the hydrologic system, the hydraulic conductivity, and the head gradient. Water moving to a well installed in a discharge area generally follows a longer flow path than water moving to a well near a topographic high. Ground-water withdrawals increase ground-water flow through the aquifer and may result in young water displacing older ground water. Without withdrawal stresses, very little water may move through or recharge a bedrock aquifer than would occur with stresses. The rate of water that recharges the bedrock aquifer depends on the rate of water recharging the overlying surficial aquifer, the hydraulic conductivity of the bedrock, and the stresses in the aquifer. A low-yielding bedrock aquifer has a low rate of recharge because water cannot readily move through it because of the low hydraulic conductivity. Stresses imposed on such an aquifer are less likely to be effective for the same reasons. A high-yielding bedrock aquifer may have a low rate of recharge unless withdrawals are present. With withdrawal stresses, a high-yield bedrock aquifer may have a recharge rate that is locally as high as the overlying aquifer. With continued or increasing withdrawals, the residence time of the water withdrawn may decrease because an increasing percentage of young water will be mixed into the regional ground-water system.

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