APPENDIX A

COLLECTION AND ANALYSIS OF ENVIRONMENTAL TRACERS FOR ESTIMATION OF RECHARGE RATES IN THE GAM MODEL OF THE CENTRAL CARRIZO-WILCOX AQUIFER

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Site Description

The study area is in the outcrop area of the Simsboro Formation in the central part of the Carrizo-Wilcox aquifer (fig. A-1). The Simsboro Formation generally consists of coarse-grained sediments, and recharge studies focused on this unit because recharge rates were expected to be higher in this than in other units of the Wilcox Group. The topography consists of rolling hills with relief of about 100 to 200 ft. The groundwater depth was not known a priori because very few wells in the Texas Water Development Board database were located in this unit. The regional climate is subtropical humid (Larkin and Bomar, 1983). Long-term (50 yr) mean annual precipitation in the central part of the Carrizo-Wilcox aquifer ranges from 29 inches in the southwest to 48 inches in the northeast of the modeled area.

METHODS

Theory

Environmental Tracers

Chloride
Chloride in the unsaturated zone or groundwater has been widely used to estimate recharge (Allison and Hughes, 1978; Scanlon, 1991; 2000; Phillips, 1994). Chloride in precipitation and dry fallout is transported into the unsaturated zone with infiltrating water. Chloride concentrations increase through the root zone as a result of evapotranspiration because chloride is nonvolatile and is not removed by evaporation or by plant transpiration.
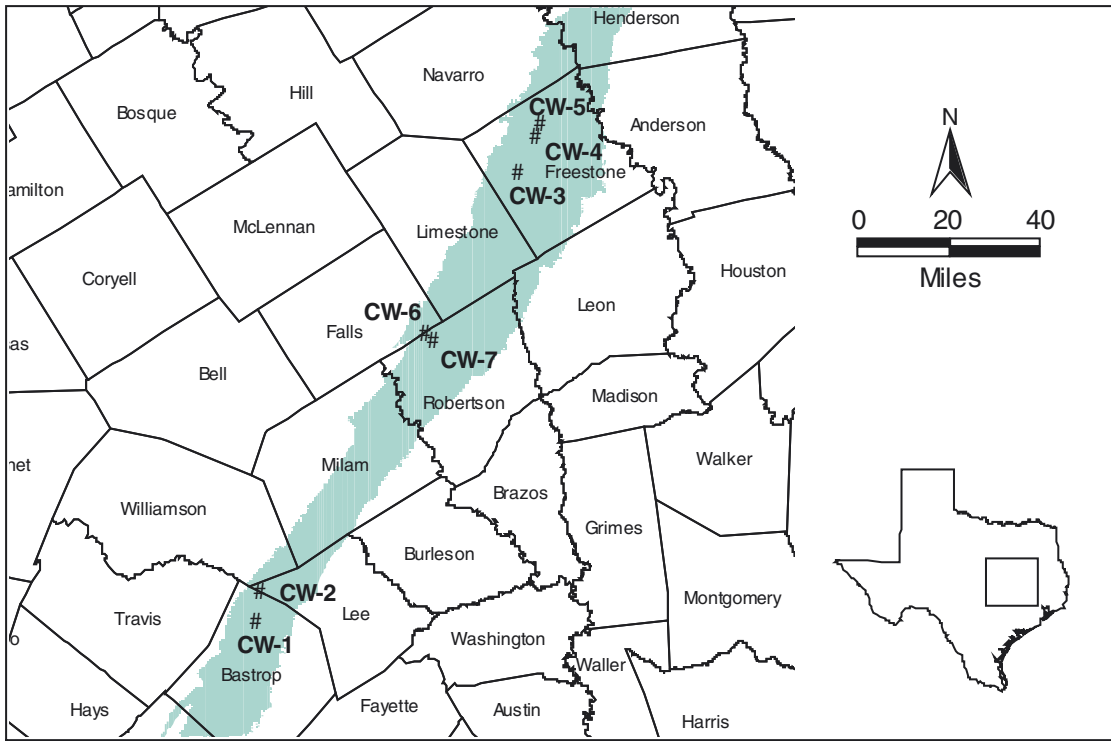
A-1

Figure A-1. Locations of boreholes installed to sample chloride in the unsaturated zone and tritium and tritium/helium in the groundwater. Shaded area represents outcrop of the Carrizo-Wilcox aquifer.

Below the root zone chloride concentrations should remain constant if recharge rates have not varied over time. Qualitative estimates of relative recharge rates can be estimated using chloride concentrations if precipitation and dry fallout are the only sources of chloride to the subsurface. Chloride concentrations are inversely related to recharge rates: low chloride concentrations indicate high recharge rates because chloride is flushed out of the system, whereas high chloride concentrations indicate low recharge rates because chloride accumulates as a result of evapotranspiration. Quantitative estimates of recharge can also be calculated using the chloride mass balance approach, which balances chloride input (precipitation and dry fallout, P) times the chloride concentration in precipitation (C_P) with chloride output (recharge rate times chloride concentration in the unsaturated zone pore water or groundwater (C_{uz} or C_{gw}):

$$PC_p = RC_{uz} = RC_{gw} \qquad\qquad R = \frac{PC_p}{C_{uz}} = \frac{PC_p}{C_{gw}} \qquad\qquad (1)$$

The age of the pore water at any depth in the unsaturated zone can also be estimated by dividing the cumulative mass of chloride from the surface to the depth of interest by the chloride input. There are many assumptions associated with the chloride mass balance approach: one-dimensional, vertically downward, piston water movement, no surface runoff, and no subsurface sources or sinks of chloride. The validity of these assumptions is difficult to determine; however, the sandy soils in the Simsboro Formation should result in predominantly piston flow and negligible runoff. This coarse-grained unit is expected to have no connate water from original marine deposition of these sediments; however, this assumption would not be valid for the low-permeability units in the Carrizo-Wilcox aquifer, such as the Hooper and Calvert Bluff Formations.

The chloride input to the system was estimated from chloride deposition in precipitation from the National Atmospheric Deposition Program (NADP, http://nadp.sws.uiuc.edu/). Data from seven stations in the immediate vicinity of the study area were interpolated. Chloride concentrations reported by the NADP represent wet precipitation and do not include any dry deposition. To account for dry deposition, chloride concentrations from NADP were increased by a factor of two, which was suggested Izbicki (personal communication, 2001). Because the uncertainties in the CMB approach are greater than the spatial variability in

chloride input, an average value of chloride input (0.9 mg/L) was used for the entire study area. An average value of precipitation (37.4 inches) was also used in the analysis.

Tritium

Historical tracers or event markers, such as bomb-pulse tritium (^{3}H), have been used widely in the past to estimate recharge (Egboka and others, 1983; Robertson and Cherry, 1989). Tritium is used to trace water movement because it is part of the water molecule. Tritium is a radioactive isotope of hydrogen with a half-life of 12.32 yr. Tritium occurs naturally in the atmosphere and enters the subsurface primarily through precipitation. Tritium fallout increased as a result of atmospheric nuclear testing that began in the early 1950s and peaked in 1963 (fig. A-2). The presence of bomb-pulse tritium in groundwater indicates that a component of the groundwater is young (< ~ 50 yr old). Bomb-pulse ^{3}H concentrations have been greatly reduced as a result of radioactive decay; therefore, the use of ^{3}H to date groundwater is generally being replaced by the use of tritium/helium-3 (^{3}H/^{3}He). Tritium decays to the noble gas helium-3. Tritium and tritiogenic helium-3 combined behave as a nondecaying tracer, and the ratio of ^{3}He to ^{3}H can be used to estimate the age of the groundwater (age being defined as the time since water entered the saturated zone):

$$t = -\frac{1}{\lambda} \ln\left[1 + \frac{^3He_{trit}}{^3H}\right] \qquad (2)$$

where λ is the decay constant ($\ln 2/t^{1/2}$; 0.05626), $t^{1/2}$ is the ^{3}H half-life (12.32 yr), and $^3He_{trit}$ is tritiogenic ^{3}He. Use of this equation assumes that the system is closed (does not allow ^{3}He to escape) and is characterized by piston flow (no hydrodynamic dispersion). The age of the water at the sampling point can then be used to determine the water velocity from the water table to the midpoint of the well screen depth. The recharge rate can then be calculated by dividing the velocity by the average porosity of the sediments.

Field and Laboratory Methods

Water Content and Chloride

Boreholes were installed primarily in open fields that the landowners claimed had been cleared for at least 40 yr. Seven boreholes were drilled in outcrop areas of the Carrizo-Wilcox aquifer in Bastrop, Lee, Robertson, and Freestone Counties (fig. A-1,
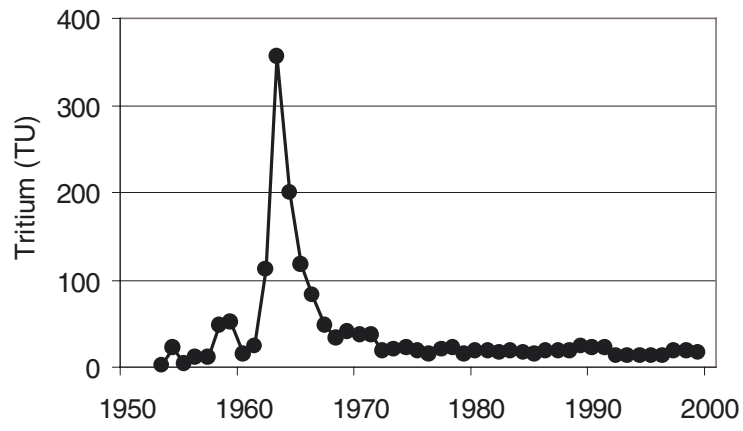
Figure A-2. Average annual atmospheric tritium fallout for Ottawa, Ontario.

table A-1). The boreholes were drilled with a hollow-stem auger without any drilling fluid, and samples were collected with a split spoon. Sediment samples were collected for laboratory measurement of water content and chloride concentrations. Gravimetric water content was measured in the laboratory by oven drying samples at $105^{o}C$ for 24 to 72 hr. To determine chloride content, double-deionized water was added to the dried sediment sample in a 1:1 ratio by weight. Samples were agitated on a reciprocal shaker for 4 hr. The supernatant was centrifuged and filtered through 0.45-µm filters. Chloride was analyzed by ion chromatography (detection limit 0.1 mg/L) at the New Mexico Bureau of Mines. Chloride concentrations are expressed as mg Cl per L of pore water.

Tritium and Tritium/Helium

Groundwater samples were collected from all seven wells for tritium analysis and from three wells for tritium/helium analysis. The samples for tritium analysis were collected through the drill stem and stored in 1-L bottles with polyseal caps. These samples were sent to the University of Miami Tritium Laboratory (http://www.rsmas.miami.edu) for tritium analysis using gas proportional counting with enrichment. Selection of the three wells for tritium/helium analysis was based on relatively shallow depths to unconfined groundwater (<50 ft). Wells were completed for tritium/helium sampling by inserting PVC pipe (2-inch ID) inside the drill stem, with screen lengths varying from 0.75 to 1.5 ft at the well bottom. The drill stem was pulled back to the surface and 20/40-sieve sand was packed around the well screens. The well annulus was backfilled to above the water table with cuttings, and a 5-ft-thick bentonite grout plug was installed. A 10-inch ID PVC pipe section 8 ft long was installed over the well pipe, and cuttings were backfilled to the ground surface. The ground surface around the wellhead was covered with a plywood plate, mounded with cuttings, and caps were installed on both the well and the outer protective PVC pipes. Well development was accomplished by surge-pumping until there was no visible sediment in the produced water. Water samples were pumped to the surface using a submersible pump (Redi-Flo 2, Grundfos Pumps Corp., Olathe, KS) that was connected to 3/16-inch ID plastic tubing. Flow rates ranged from approximately 0.2 to more than 2 gallons per minute during sampling. Approximately three well-bore volumes of water were produced prior to sample collection. Water samples for helium analysis were collected in copper tubes (3/8-inch ID),

Table A-1. Location of sampled boreholes, property owners, dates drilled, borehole depth, static water level below land surface (bls), and number of chloride samples collected in the unsaturated zone.

Borehole	County	Latitude	Longitude	Date drilled	Elevation (ft)	Total depth (ft bls)	Static water level (ft bls)	No. of Cl samples
CW-1	Bastrop	30.2917	–97.3056	2/6/2002	495	103.8	74.80	37
CW-2	Lee	30.3872	–97.2911	3/4/2002	578	53.3	43.25	30
CW-3	Freestone	31.6892	–-96.2917	3/5/2002	505	53.7	41.30	28
CW-4	Freestone	31.8006	–-96.2139	3/6/2002	400	38.8	24.80	26
CW-5	Freestone	31.8389	–-96.1992	3/7/2002	395	18.5	10.50	15
CW-6	Robertson	31.1850	–-96.6503	3/8/2002	485	48.6	37.35	25
CW-7	Robertson	31.1689	–-96.6281	3/9/2002	485	78.5	76.70	33

with a down-stream valve used to apply back pressure on the pump to ensure that dissolved gases remained under pressure in the sample. Finally the copper tubes were sealed at both ends with refrigeration clamps while under pressure. A total of four samples, each containing approximately 18 mL, were collected at each site.

Helium concentrations in the samples were measured at the University of Utah. Water vapor and CO_2 were removed initially at $-95^{\circ}C$ and $-195^{\circ}C$, respectively. Then N_2 and O_2 were removed by reaction with Zr-Al alloy, and Ar and Ne were adsorbed onto activated charcoal at $-195^{\circ}C$ and at $-233^{\circ}C$, respectively. Helium isotope ratios ($^3He/^4He$) and concentrations were analyzed on a VG 5400 rare-gas mass spectrometer. $^3He/^4He$ ratios are reported relative to the atmospheric ratio (R_{air}) using air helium as the absolute standard.

RESULTS

Water Content and Chloride Concentrations

The average water content in each of the profiles was not highly variable and ranged from 0.13 to 0.18 g/g (fig. A-3, table A-2). Minimum water contents ranged from 0.04 to 0.08 g/g. Maximum water contents ranged from 0.22 to 0.40 g/g and indicate that in some areas the sediments were close to saturation. Although the texture of the sediments was not analyzed in the laboratory, spatial variability in water content could be qualitatively related to variations in texture from core descriptions. Water contents were highest near the water table in most profiles.

Average chloride concentrations in the unsaturated zone ranged from 23 to 519 mg/L (fig. A-3, table A-2). Variability in mean chloride concentrations was high locally, as shown by differences in mean concentrations in CW1 and CW2 and in CW3, CW4, and CW5. Chloride concentrations were also highly variable within each profile as shown by differences in maximum and minimum concentrations (table A-2). There was no systematic variation in chloride concentrations with depth. Recharge rates were calculated for the portion of the profiles that generally represented the last 50 yr where possible. In some cases recharge rates were so low that a 50-yr section corresponded to a very narrow depth interval.
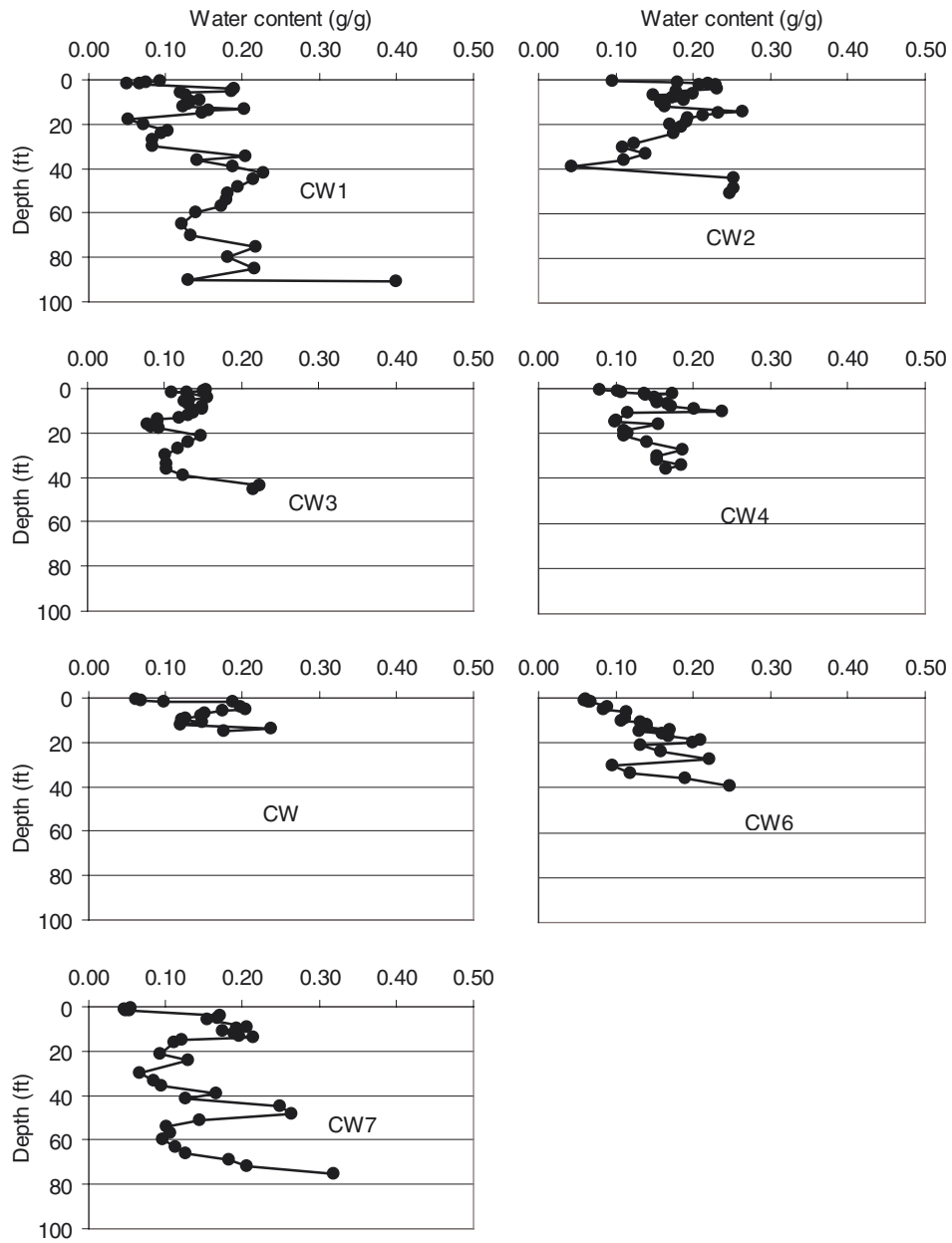
Figure A-3. Water content (weight basis) with depth.

Table A-2. Water content, chloride concentration, and recharge (rech) based on unsaturated zone (uz) chloride concentrations, chloride concentrations in groundwater (gw) and associated recharge rates, and age of the chloride profile.

BH no.	Water content uz (g/g)			Chloride uz (mg/L)			Rec (uz) (in/yr)	Cl (gw) (mg/L)	Rech (gw) (in./yr)	Age base (yr)
	mean	min.	max.	mean	min.	max.				
CW-1	0.21	0.08	0.34	245	10	1907	0.79	180	0.20	2815
CW-2	0.18	0.04	0.26	23	11	37	1.42	25	1.34	110
CW-3	0.13	0.08	0.22	35	12	125	1.02	5	6.22	112
CW-4	0.14	0.08	0.24	259	51	1131	0.24	32	1.06	846
CW-5	0.15	0.06	0.24	325	145	684	0.20	22	1.54	360
CW-6	0.13	0.06	0.25	239	72	560	0.20	33	1.02	700
CW-7	0.14	0.05	0.32	518	52	2206	0.20	107	0.31	2480

Recharge rates generally ranged from 0.2 to 1.4 inch/yr. The time required for chloride to accumulate in each profile ranged from 110 to 2,815 yr.

Groundwater chloride concentrations were generally lower than those in the unsaturated zone (5 to 180 mg/L) (tables A-2, A-3). Recharge rates based on the chloride mass balance approach ranged from 0.2 to 6.2 inches/yr. Recharge rates based on groundwater chloride were generally higher than those based on unsaturated zone chloride (CW3-CW6). In some cases; however, the recharge rates from the two data sets were similar (CW2, CW7). The lower recharge rate calculated for CW1 may not be representative of recharge in this area because groundwater was confined in this well. In addition, the low recharge rate for CW7 may reflect additional chloride from connate water because clay content was high in this borehole. The higher recharge rate at CW3 may represent focused recharge from ponded conditions because water was ponded in the vicinity of the borehole during drilling. Therefore, representative recharge rates based on groundwater chloride concentrations range from 1 to 1.5 inch/yr. The generally higher recharge rates based on groundwater chloride relative to unsaturated zone chloride are considered more representative of the regional system, whereas the unsaturated-zone data indicate that locally recharge rates are lower. Preferential flow may also result in lower chloride concentrations in the groundwater relative to the unsaturated zone.

Groundwater Tritium and Tritium/Helium

Groundwater tritium concentrations ranged from 0.76 to 3.57 TU (table A-4). These tritium levels were much greater than the detection limit for tritium (~ 0.2 TU) and indicate that a component of the water was recharged in the last 50 yr. Tritium/helium was also used to date the water in wells CW3, CW4, and CW6. There were problems with analysis of ^{3}He in water samples from CW6. ^{3}He concentrations were low in well CW3 and much higher in well CW4. The low ^{3}He concentrations in CW3 indicate a short residence time of the water of 2.2 yr, whereas the much higher ^{3}He concentrations in CW4 indicate a residence time of 21.4 yr. The times represent the time of ^{3}He accumulation since it was isolated from the unsaturated zone. Water velocities were calculated by dividing the distance between the water table and the center of the well screen by the age of the water and resulted in

Table A-3. Water content and chloride concentrations in soil samples from boreholes CW1-CW7.

Depth (ft)	Water content (g/g)	Chloride (mg Cl/kg soil)	Chloride (mg Cl/L water)	Depth (ft)	Water content (g/g)	Chloride (mg Cl/kg soil)	Chloride (mg Cl/L water)
CW1				CW2			
0.5	0.09	1.90	20.33	0.5	0.10	2.10	21.94
1.0	0.07	1.00	13.38	1.0	0.18	2.90	16.17
1.5	0.07	1.30	19.76	1.5	0.22	3.40	15.46
2.0	0.05	1.00	19.86	2.0	0.21	3.20	15.46
4.0	0.19	5.70	30.15	2.5	0.23	2.63	11.41
5.0	0.19	1.80	9.70	4.0	0.23	4.56	19.76
6.0	0.12	5.29	44.32	5.0	0.18	4.82	27.00
7.0	0.13	8.63	68.32	6.0	0.20	5.11	25.54
9.0	0.15	7.00	48.28	7.0	0.15	4.51	30.42
10.0	0.13	4.01	30.10	8.0	0.17	4.70	27.18
11.0	0.13	4.32	33.15	9.0	0.19	4.60	24.54
12.0	0.12	4.81	39.02	10.0	0.16	4.34	27.35
13.0	0.20	5.20	25.65	11.0	0.16	4.39	26.99
14.0	0.16	11.01	70.69	12.0	0.16	4.80	29.28
15.0	0.15	11.01	74.15	14.0	0.26	6.30	23.85
18.0	0.05	3.10	61.02	15.0	0.23	6.88	29.52
20.0	0.07	3.20	44.41	16.0	0.21	5.50	25.88
23.0	0.10	3.94	38.01	17.0	0.19	4.00	20.72
24.0	0.09	4.10	43.46	19.0	0.19	2.92	15.24
27.0	0.08	3.50	41.83	20.0	0.17	3.20	18.78
30.0	0.08	6.10	73.74	21.0	0.18	4.00	21.73
34.5	0.20	37.00	180.91	24.0	0.18	3.62	20.59
36.0	0.14	10.00	70.98	28.3	0.12	3.30	26.67
39.0	0.19	24.00	128.27	30.0	0.11	2.83	26.00
42.0	0.23	29.98	131.29	33.3	0.14	3.31	23.93
45.0	0.21	13.00	60.68	36.0	0.11	2.80	25.42
48.0	0.20	66.19	339.42	39.0	0.04	0.53	12.24
51.0	0.18	154.76	854.09	44.0	0.25	4.93	19.51
54.0	0.18	294.71	1649.57	48.3	0.25	6.29	24.99
57.0	0.17	329.80	1906.69	51.0	0.25	9.25	37.34
60.0	0.14	130.12	929.65				
65.0	0.12	59.07	489.77				
70.0	0.13	67.06	502.48				
75.0	0.22	60.16	277.50				
80.0	0.18	64.98	359.86				
85.0	0.22	31.02	143.89				
90.0	0.13	27.04	207.76				

Table A-3 (continued). Water content and chloride concentrations in soil samples from boreholes CW1-CW7.

Depth (ft)	Water content (g/g)	Chloride (mg Cl/kg soil)	Chloride (mg Cl/L water)	Depth (ft)	Water content (g/g)	Chloride (mg Cl/kg soil)	Chloride (mg Cl/L water)
CW3				CW4			
0.5	0.15	1.82	11.83	0.5	0.08	17.62	221.78
1.0	0.15	5.41	35.92	1.0	0.10	18.70	184.11
1.5	0.11	1.61	14.76	1.5	0.11	20.53	191.51
2.0	0.13	2.40	18.62	2.0	0.14	17.51	127.81
4.0	0.16	4.09	26.24	2.5	0.17	17.94	103.86
5.0	0.13	4.53	34.33	3.0	0.14	25.82	185.20
6.0	0.13	3.88	30.86	4.0	0.15	28.53	189.35
7.0	0.13	3.44	26.40	5.0	0.15	16.24	105.51
8.0	0.15	4.78	32.08	6.0	0.15	27.39	178.61
9.0	0.15	4.01	27.03	7.0	0.17	21.06	126.68
10.0	0.14	4.10	30.15	8.0	0.17	23.20	134.59
11.0	0.14	4.16	30.16	9.0	0.20	29.83	148.30
12.0	0.13	4.00	30.43	10.0	0.24	12.22	51.48
13.0	0.12	4.70	39.30	11.0	0.12	22.39	192.89
14.0	0.09	3.12	34.20	14.0	0.10	10.96	109.11
15.0	0.09	2.90	31.92	15.0	0.10	21.06	211.24
16.0	0.08	2.86	36.68	16.0	0.16	18.03	116.10
17.0	0.08	3.38	41.08	19.0	0.11	19.13	174.31
18.0	0.09	4.10	44.30	20.0	0.12	22.59	196.36
21.0	0.15	5.22	35.22	21.0	0.11	90.24	814.25
24.0	0.13	4.12	31.41	24.0	0.14	157.71	1130.63
27.0	0.12	5.31	44.89	27.0	0.19	74.99	401.65
30.0	0.10	5.57	55.00	30.0	0.15	47.06	307.55
33.7	0.10	3.90	37.87	32.1	0.15	72.01	471.45
36.0	0.10	4.40	42.69	34.0	0.18	47.73	258.85
39.0	0.12	15.50	124.72	36.0	0.16	66.81	405.76
43.7	0.22	4.37	19.58				
45.5	0.21	2.81	13.10				
CW5				CW6			
0.5	30.10	32.32	522.16	0.5	0.06	34.28	559.51
1.0	32.42	17.47	254.34	1.0	0.06	20.03	334.21
1.5	30.66	19.32	196.47	1.5	0.06	17.12	266.52
2.0	32.15	37.94	202.70	1.9	0.07	14.78	218.53
4.0	30.71	28.74	144.88	4.0	0.09	10.16	114.76
5.0	30.52	68.59	336.05	5.0	0.08	28.76	344.56
6.0	30.55	119.84	683.88	6.0	0.11	31.74	279.91
7.0	29.98	86.04	569.48	9.0	0.11	18.58	164.38
8.0	31.10	55.67	382.62	10.0	0.11	30.66	284.84
9.0	30.06	52.15	412.04	11.0	0.13	24.93	188.30
10.0	30.19	24.86	206.03	12.0	0.14	24.89	176.96

Table A-3 (continued). Water content and chloride concentrations in soil samples from boreholes CW1-CW7.

Depth (ft)	Water content (g/g)	Chloride (mg Cl/kg soil)	Chloride (mg Cl/L water)	Depth (ft)	Water content (g/g)	Chloride (mg Cl/kg soil)	Chloride (mg Cl/L water)
CW5				CW6			
11.0	30.16	32.44	219.27	13.0	0.14	20.02	143.09
12.0	29.98	39.36	329.65	14.0	0.17	12.34	72.48
14.0	30.06	46.36	195.36	15.0	0.13	17.62	134.98
15.0	30.08	37.94	214.79	16.0	0.16	24.48	153.71
				17.0	0.17	26.68	158.20
				19.0	0.21	25.24	120.20
				20.0	0.20	29.61	148.56
				21.0	0.13	28.71	216.90
				24.0	0.16	31.72	201.20
				27.0	0.22	39.70	179.09
				30.0	0.10	36.43	379.23
				33.6	0.12	53.83	452.71
				36.0	0.19	57.81	303.81
				39.0	0.25	92.91	375.35
CW7							
0.5	0.06	34.28	559.51				
1.0	0.06	20.03	334.21				
1.5	0.06	17.12	266.52				
1.9	0.07	14.78	218.53				
4.0	0.09	10.16	114.76				
5.0	0.08	28.76	344.56				
6.0	0.11	31.74	279.91				
9.0	0.11	18.58	164.38				
10.0	0.11	30.66	284.84				
11.0	0.13	24.93	188.30				
12.0	0.14	24.89	176.96				
13.0	0.14	20.02	143.09				
14.0	0.17	12.34	72.48				
15.0	0.13	17.62	134.98				
16.0	0.16	24.48	153.71				
17.0	0.17	26.68	158.20				
19.0	0.21	25.24	120.20				
20.0	0.20	29.61	148.56				
21.0	0.13	28.71	216.90				
24.0	0.16	31.72	201.20				
27.0	0.22	39.70	179.09				
30.0	0.10	36.43	379.23				
33.6	0.12	53.83	452.71				
36.0	0.19	57.81	303.81				
39.0	0.25	92.91	375.35				

Table A-4. Results of ^{3}He, ^{4}He, ^{20}Ne, ^{40}Ar, and N_2 measurements, and calculated tritiogenic helium-3 (^{3}He*) and ^{3}H/^{3}He ages.

BH no.	^{3}H (TU)	^{3}H error (2σ TU)	R/Ra[†]	^{4}He cc STP/g[‡]	^{20}Ne cc STP/g	^{40}Ar cc STP/g	N_2 cc STP/g	^{3}He* TU	Age (yr)
CW-1	0.76	0.18							
CW-2	3.25	0.22							
CW-3	3.3	0.22	1.072	4.41E-08	1.99E-07	4.72E-04	0.0150	0.4	2.2
CW-4	3.57	0.24	1.072	9.35E-08	2.97E-07	7.04E-04	0.0251	21.4	34.5
CW-5	2.43	0.2							
CW-6	3.05	0.2	0.986	5.80E-08	2.59E-07	5.66E-04	0.0184	-7.1	
CW-7	1.1	0.18							

[†] R is the ^{3}H/^{4}He ratio of the sample; Ra is the ^{3}He/^{4}He ratio of the air standard
[‡] STP Standard temperature and pressure
^{3}H   error reported as two standard deviations (2σ)

velocities of 0.4 (CW4) to 4 ft/yr (CW3). Recharge rates of 1.6 (CW4) to 16.7 inches/yr (CW3) were calculated by multiplying the velocities by the average porosity of 0.35. The recharge rate for CW4 of 1.6 inch/yr is similar to that estimated from the groundwater chloride concentration. The recharge rate for CW3 of 16.7 inches/yr is higher than that estimated from groundwater chloride concentration of 6.2 inches/yr.

DISCUSSION

The results of this study indicate that there is no systematic variation in recharge rates spatially. There was more variability locally in one area than there was between different areas. Recharge rates based on groundwater chloride ranged from 0.2 to 1.3 inch/yr in the southern zone and from 0.3 to 1.2 inch/yr in the northern zone. The low recharge rates in the southern and northern sampling areas may be related to confined conditions because these boreholes were deeper and overlain by clay-rich sediments relative to nearby boreholes.

Groundwater chloride concentrations seem to provide the most reliable recharge estimates and indicate that the average recharge rate ranges from about 1 to 1.5 inch/yr. The high recharge rate estimated for well CW-3 may be related to additional inputs of chloride from ponded water at the surface in nearby regions. Recharge rates based on unsaturated-zone chloride concentrations were generally lower than those estimated from groundwater chloride. This discrepancy in recharge rates may result from groundwater chloride not representing vertical recharge from the land surface in the area immediately overlying the well and generally lower recharge rates in the sampled unsaturated zones.

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