APPENDIX 9—Quantification of Recharge

Quantification of Recharge

Estimating recharge to a regional aquifer system is a difficult task. We used two methods to estimate recharge both as actual volumes over an estimated recharge area and as a relative proportion of surface infiltration. For the first recharge estimate, we used the water table fluctuation (WTF) method, where we analyzed the same well hydrograph used to estimate hydrologic parameters in the Yeso Formation. This method estimated recharge over a much smaller area and time period. For the second method, we used the chloride mass balance (CMB) method, where Cl concentrations are used to measure the relative volume reduction of water within the aquifer due to evapotranspiration (ET). CMB yields a good first approximation of the long term average recharge on a regional scale.

BACKGROUND

One approach to estimating the amount of recharge is the water table fluctuation (WTF) method (Healy and Cook, 2002). This method is based on the assumption that water level rises in unconfined aquifers are due to recharge water arriving at the water table. Recharge is calculated as equation (1):

$$R = Sy\Delta h/\Delta t \qquad (1)$$

where Sy is specific yield, h is water table height and t is time. The water level rise in a well (Δh) is measured as the difference between the peak of the rise and value of the extrapolated antecedent recession curve at the time of the peak. The time interval over which the water level rise occurs is Δt. This formulation results in recharge as length/time. If the time term is neglected, recharge can also be calculated as a percentage, assuming the water level rise can be associated with a known volume of precipitation from a distinct event.

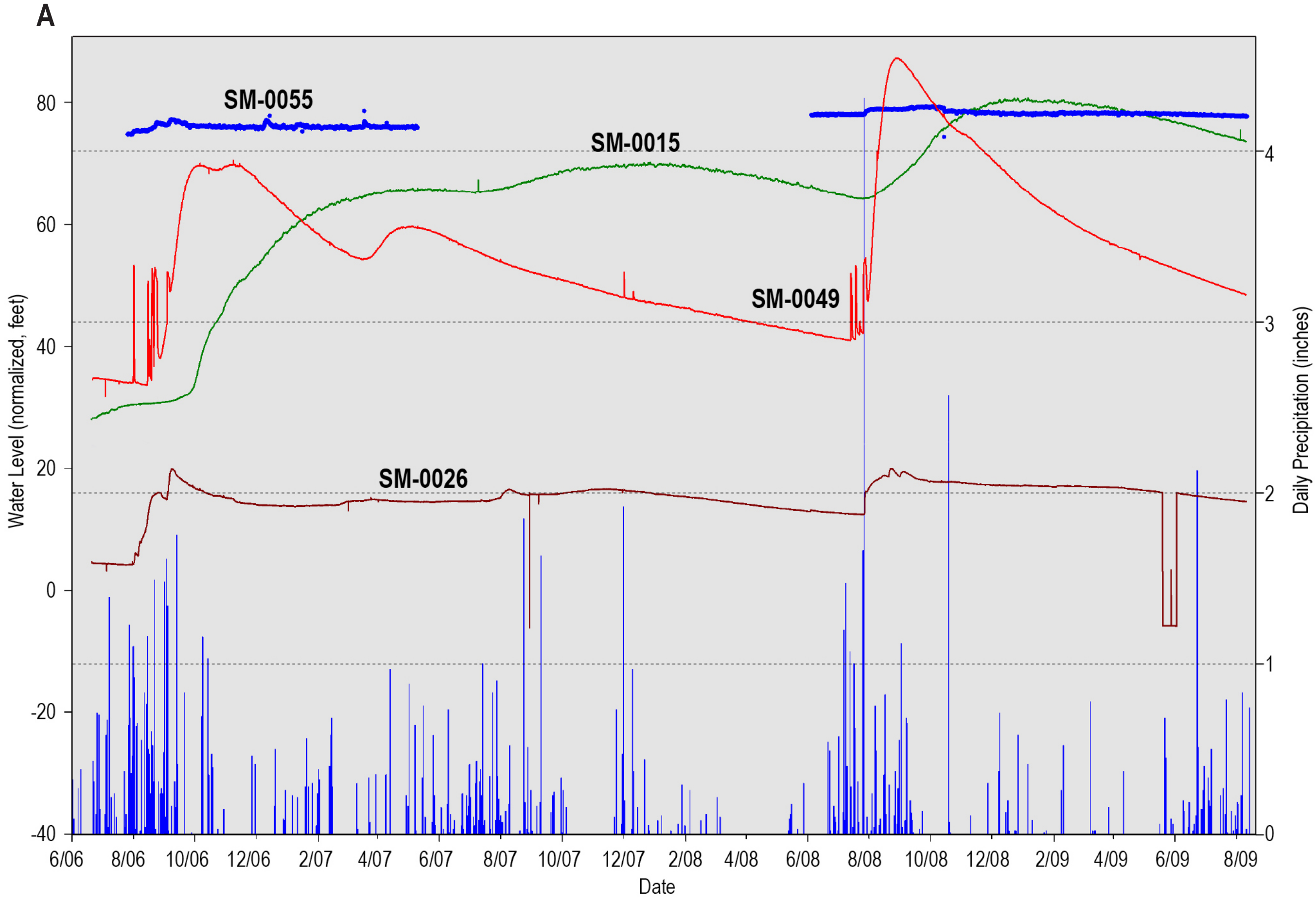
Several criteria must be satisfied for the water table fluctuation method to be valid and for the results to be meaningful estimates of recharge resulting from precipitation (Healy and Cook, 2002):

1) The aquifer must be unconfined;
2) The water level rise and subsequent fall must be sharp, and must be associated with an identifiable precipitation event;
3) The well must be located so that the water level changes are representative of the whole catchment; and
4) A specific yield value (or values) for the aquifer must be estimated.

Well SM-0049 is the only well in the study area for which all these criteria are potentially satisfied. The continuous hydrograph for this well shows no correlation with atmospheric pressure variations, indicating that the well is completed in an unconfined aquifer. There are numerous sharp water level rises in the hydrograph that can be confidently associated with precipitation events (Fig. 9.1). The surface water basin surrounding the well is likely the only source of groundwater feeding the well, based on its relationship to the regional water table and structural lineament patterns. Finally, as described in Appendix 10, we have calculated specific yield values for the Yeso Formation in the vicinity of the well from this hydrograph. This is important, as estimating the specific yield is the largest source of uncertainty in the WTF method (Healy and Cook, 2002).

Two of the water level rises in the SM-0049 hydrograph were examined to calculate recharge. These are from the early portion of the SM-0049 hydrograph (Fig. 9.1). The precipitation events that we interpret to have induced these water level rises are shown on the graphs (Figs. 9.1, 9.2 and 9.3). Note also that the data from the National Oceanic and Atmospheric Administration (NOAA) from a weather station in Cloudcroft (Fig. 9.1A) is comprised of daily records. Data from the Community Collaborative Rain, Hail and Snow (CoCoRHAS) network include some measurements that are cumulative, with multiple days of rainfall (e.g., the 5.95 inch event shown in Fig. 9.3). The precipitation amounts used in the recharge calculation are from the weather station nearest to the well (Figs. 9.2 and 9.3). In general, precipitation events as shown on the plots do not coincide exactly in time with water level rises, because the precipitation data was only recorded as daily totals, whereas the water levels were recorded every 15 minutes (later hourly).

Examination of Figure 9.2 shows that it can be broken into two parts, the first C1, induced by a



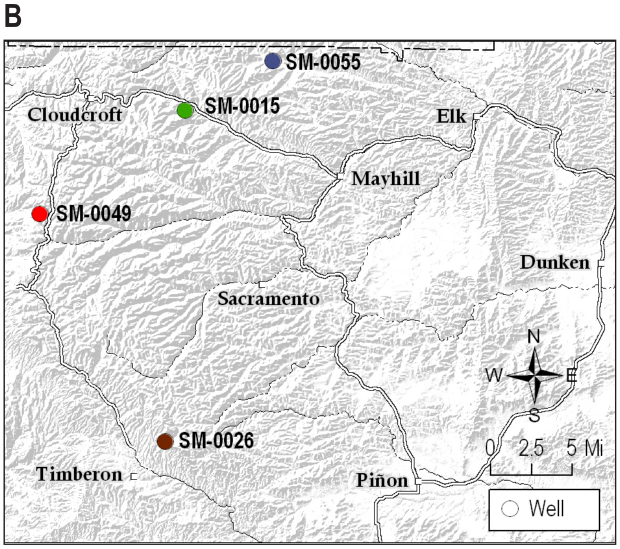


Figure 9.1–Sacramento Mountains water level responses to precipitation.
A–Continuous water level data with daily precipitation.
B–Map of well locations with continuous data loggers. The hydrographs (curves) show water level responses to precipitation from five wells with continuous water level recorders (data loggers). The vertical bars below indicate total daily precipitation (in inches) as measured by five weather stations near Cloudcroft.

precipitation event of 0.59 inches and the second, C2, induced by a precipitation event of 1.31 inches. The water level rises were measured as shown in the Figure 9.2. The recession associated with rise C1 has one slope, which we interpret as due to drainage of fractured limestone, with a calculated specific yield of 4.25x10-4. The recession associated with rise C2 has multiple slopes attributed to the drainage of different lithologies and thus specific yields (as described in Table 10.1), as described in Appendix 10. Here, we calculated the recharge as a summation of the water level change corresponding to each slope segment, multiplied by the specific yield associated with that slope segment. Recharge values for water level rises D1 and D2 (Fig. 9.3) were calculated similarly, with the recession of rise D2 again composed of multiple slopes and specific yields. The large precipitation event of 5.95 inches is at least three days of precipitation and appears to be associated with only a small water level rise. The 5.95 inches of precipitation may not have actually occurred over the basin of well SM-0049; therefore we calculated the recharge with and without this event as an input. The results of the recharge calculations are presented in Table 9.1. The recharge in acre-feet was calculated over the surface

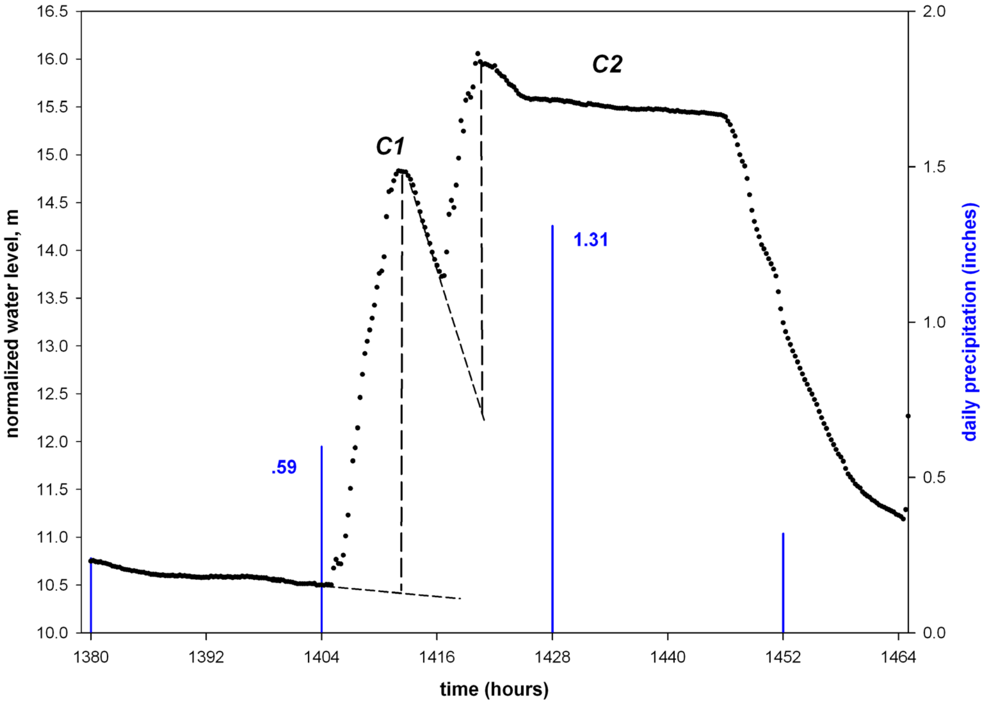


Figure 9.2–Expanded view of water level rise C from well SM-0049 hydrograph. The two individual rises are labeled C1 and C2, which occurred from August 19 to 21, 2006. Dashed vertical lines are the two water level rises measured from the extrapolated extensions of the previous recessions (dotted lines). Precipitation data are daily totals from NOAA and CoCoRHAS stations.

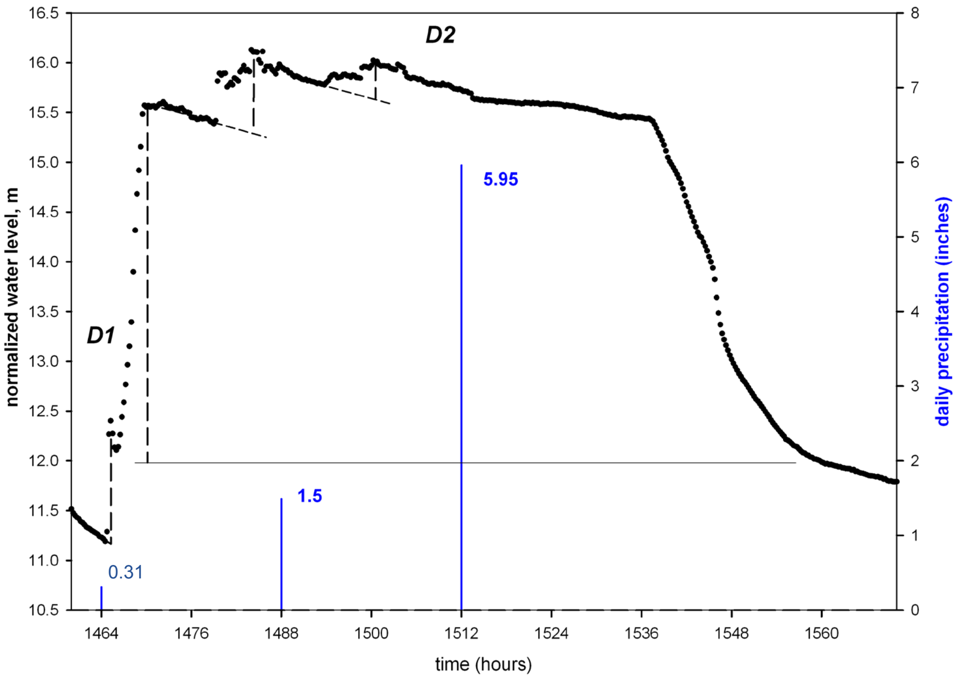


Figure 9.3–Expanded view of water level rise D from well SM-0049 hydrograph. The two individual rises are labeled D1 and D2, which occurred from August 21 to 24, 2006. Dashed vertical lines are the water level rises measured from the extrapolated extensions of the previous recessions (dotted lines). Water level rise for D2 is the sum of the three rises under the composite peak. Base of recession for rise D2 was assumed to be the horizontal line, because this peak is superimposed over a general water level rise that lasted several months. Precipitation data are daily totals from NOAA and CoCoRHAS stations.

water/groundwater basin of well SM-0049, which has a surface area of 12,220,084 square-feet.

The recharge values calculated from rises C1 and C2 are higher than those of D1 and D2. There are numerous possible explanations for the differences. The amount of recharge from a given storm event may depend on the intensity and duration, for which we have no data. These storm events came at the end of an extended dry period and the second pair of sharp water level rises (the D rises) are superimposed on a broader water level rise that extended for several months (Fig. 9.1). As observed on Figure 9.1, well SM-0015 exhibited a change from confined to unconfined behavior as water levels rose. Therefore, the conditions in the aquifer at well SM-0049 were probably dynamic during the time of these recharge events. Changes in infiltration and runoff rates, the thicknesses and conductivity of the saturated and unsaturated zones, and subsurface flow paths may all be expected to change under such dynamic conditions and could potentially affect the resulting recharge.

As a simple check on the validity of these numbers, we calculated the time it would take for recharge water to drain from the basin around the SM-0049 well. We assumed the volume of rock to store the water was equal to the area of the basin multiplied by the height of the water level rise. The cross sectional area of drainage flow is unknown. We estimated boundaries based on the sides and the sides plus the bottom of a cylinder of equivalent volume to this potential storage volume. Using these boundaries on the cross sectional area for flow, for water level rise C1, 1.64 acre-feet of recharge water would take between less than 1 to 86 hours to drain out of the basin. The actual duration of the recession for water level rise C1 is on the order of 12 hours when extrapolated back to the pre-rise water level. Though crude, this simple approach suggests that the estimates of hydrologic properties and recharge are reasonable. Taken together, the results of the water table fluctuation calculations suggest that probably 5-10% of the precipitation from summer thunderstorms over this small high mountain basin enters the groundwater system as recharge. Recharge percentages over this area from extended, less intense periods of rainfall, or from melting of winter snow pack may be quite different.

Table 9.1–Recharge calculations from groundwater hydrographs.

	Water level rise (m)	Rainfall (in)	Recharge (in)	Recharge (acre-ft)	Recharge (%)
C1	4.30	0.59	0.07	1.64	12
C2	3.04 = 2.49+0.20+0.35	1.31	0.20	4.67	16
D1	1.27	0.40	0.10	2.35	2.6
D2	4.55 = 3.40+0.76+0.39	1.50	0.11	2.57	1.5
D2	4.55 = 3.40+0.76+0.39	7.45	0.11	2.57	7.6

CHLORIDE MASS BALANCE

Chloride mass balance (CMB) is a widely used method of obtaining a first approximation of long-term average recharge on a regional scale (Wood and Sanford, 1995; Wood, 1999; Zhu et al., 2003; Sami and Hughes, 1996). Atmospheric chloride (Cl) (present as dust) is used as a tracer where differences between the average effective Cl concentration in surface infiltration and Cl concentrations in groundwater are due to the removal of water by ET. Therefore, the percentage of surface infiltration that becomes part of the saturated groundwater system can be estimated according to the mass balance equation (2):

$$R = P\frac{Cl_{eff}}{Cl_{GW}} \qquad (2)$$

Where R is recharge, P is average annual precipitation, Cl_{GW} is the Cl concentration in groundwater, Cl_{eff} is the effective chloride concentration of surface infiltration resulting from both wet and dry deposition. The CMB method can be used to estimate recharge if the following assumptions are met:

1) Cl in the groundwater originates from precipitation directly on the recharge area.
2) Cl is conservative in the system.
3) The Cl mass flux has not changed over time.
4) There is no recycling or concentration of Cl within the aquifer.

There is evidence according to chloride/bromide (Cl/Br) ratios that a small amount of high-Cl water mixes with fresh meteoric water from the high mountains within the aquifer systems (Appendix 8). Therefore, assumptions 1 and 4 may not apply. For this reason, we used Cl/Br ratios to identify water samples that contain non-atmospheric Cl sources and applied corrections so that we could use the CMB method. In most hydrologic systems, Cl behaves conservatively.

Although both annual average precipitation and Cl deposition vary with time, most researchers assume a constant Cl flux over time. Zhu et al. (2003) used different assumed steady state precipitation and Cl fluxes for late Pleistocene and Holocene, which represent two major climate periods. As was discussed in the main report, all groundwater sampled in the high mountains and Pecos Slope is less than 1500 years old. Therefore, we did not differentiate between different major climate periods and assumed a steady state precipitation and Cl mass flux.

Chloride input

Atmospheric Cl input includes both wet and dry deposition. Wet deposition consists of Cl that dissolves in rain drops during precipitation events, while dry deposition includes dry fallout of Cl that is retained on the surface and leached during recharge. For estimates of wet deposition in the study area, we used data from a precipitation monitoring site in Mayhill, NM, operated by the National Atmospheric Deposition Program. The mean value of monthly average Cl concentrations in precipitation from 1984 to 2007 was 0.12 mg/L. Dry deposition was more difficult to estimate. Popp et al. (1984) examined both wet deposition and dry deposition for several different ions in different locations in New Mexico. It appears that dry deposition of Cl is very significant and is often greater than wet deposition. For a precipitation sample in Albuquerque, NM, the dry deposition Cl concentration (2.5 mg/L) was an order of magnitude higher than the wet deposition Cl concentration (0.2 mg/L). Precipitation samples collected in Socorro and Raton, NM, also showed higher dry deposition Cl concentrations than wet deposition Cl concentrations in precipitation. We estimated the bulk Cl input concentration based on the two end-member mixing model discussed below.

Identification of end-members

As discussed in Appendix 8, Cl/Br ratios indicated the presence of at least one source of Cl in the subsurface. It is probably a high-Cl brine, similar to that observed in the Cloudcroft Apache Replacement well described in the main report and in Appendix 8. Although it appears that the amount of high-Cl water that is mixing with fresh groundwater is very small, the increase in Cl concentrations can be enough to result in significant underestimates of recharge with the CMB method. To account for this additional Cl, we used Cl/Br ratios and a two end-member mixing model, shown in Figure 9.4, to estimate the amount of non-atmospheric Cl in each sample. We developed the mixing curve assuming that Cl concentration is controlled by the removal of water via ET and the mixing of fresh groundwater (low initial Cl concentration and low Cl/Br ratio) with a high-Cl brine (high initial Cl concentration and high Cl/Br ratio) in the subsurface (Fig. 9.4). Figure 9.4A shows the Cl/Br ratio as a function of Cl concentration, where the mixing curve is curvilinear in shape. In Figure 9.4B, Br/Cl ratios as a function of 1/Cl results in a linear mixing curve.

We chose end-member Cl concentrations and Cl/Br ratios that defined a mixing curve where all data can be explained by the mixing of fresh groundwater with the brine and/or ET. We estimated a bulk Cl concentration of 0.55 mg/L and a Cl/Br ratio of 65 for the fresh water end-member, which was the lowest Cl/Br value observed for all spring and well samples. The Cl concentration (0.55 mg/L) was the largest Cl concentration that produced a mixing curve that allowed all data points to plot either on the curve or in the area that indicates a combination of mixing and ET. For the brine end-member, we used a Cl concentration of 10,000 mg/L and a Cl/Br ratio of 9000. We will discuss the sensitivity of recharge estimates to these end-member parameters below.

Estimation of recharge

The Cl concentration on the mixing curve that correlates to the sample Cl/Br ratio is the apparent Cl concentration that is a result of mixing only. For each data point, we defined this apparent mixing Cl concentration as the effective Cl concentration of surface infiltration, Cl_{eff} (Equation 2). We estimated the relative recharge (percentage of surface infiltration) for each sample by dividing the measured Cl concentration by this modified Cl_{eff} value. For spring samples, relative recharge estimates ranged from 14 to 100% with a mean value of 38%. The two springs with recharge estimates of 100% were SM-1018 and SM-1090, which were the main points that controlled the shape of the assumed mixing curve. Because, these two springs plotted on the mixing line, the Cl concentrations are assumed to be due to mixing only with no ET. For wells, relative recharge estimates ranged from 4 to 44%, with a mean value of 22%.

Because end-member Cl concentrations and Cl/Br ratios were determined based on the construction of one mixing curve that can account for all data, we analyzed the sensitivity of recharge estimates to these end-member parameters. Recharge estimates were very sensitive to the fresh water end-member Cl concentrations and Cl/Br ratios. There is a direct relationship between the fresh water end-member Cl concentration and estimated recharge. As the initial Cl concentration increases, recharge estimates also increase. The value of 0.55 mg/L was used because with higher values, some data points would not plot either on the mixing curve or in the region that indicates a combination of mixing and ET. Based on measured wet deposition concentrations and observed dry deposition Cl concentrations in New Mexico (Popp et al., 1984), 0.55 mg/L is a reasonable Cl value. As the Cl/Br ratio for the fresh water end-member increases, recharge estimates decrease. Again, the Cl/Br ratio of 65 was necessarily chosen to construct a mixing curve that could account for all data points. This value is a reasonable value for local precipitation. Recharge estimates were much less sensitive to brine end-member parameters. Increasing or decreasing Cl concentrations had little effect on recharge estimates. Decreasing the brine Cl/Br ratio results in a slight increase in recharge estimates.

The higher recharge estimates for springs was expected because most springs are located in the high mountains. Most groundwater that recharges regional aquifers adjacent to the high mountain aquifer system originates at high elevations and flows through at least some part of the shallow groundwater system. As water flows through the shallow groundwater and mountain surface water systems, it is available to be taken up by vegetation. The recharge estimates based on well samples are probably more representative of a recharge from the high mountains to adjacent aquifer systems.

Assuming the main recharge area is above the area encompassed by the 8,200 feet surface elevation contour, the recharge zone within the study area encompasses approximately 131,000 acres. The average annual surface infiltration in this area was estimated as a percentage of the average annual precipitation rate of 26 inches in Cloudcroft. Canaris

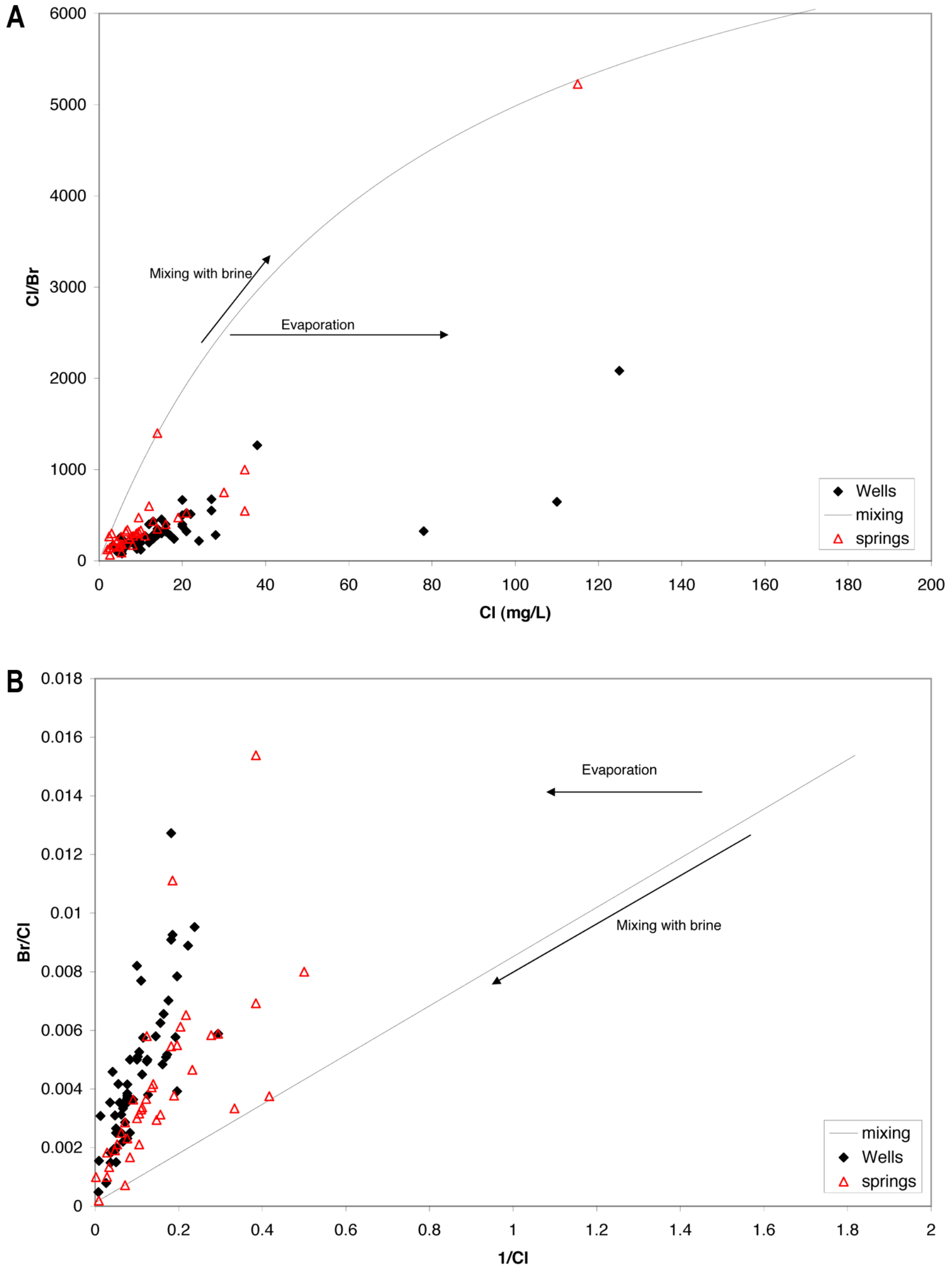


Figure 9.4–Chloride-bromide mixing curves.
A–The Cl/Br ratio as a function of Cl concentration, where the mixing curve is curvilinear in shape.
B–The plot of Br/Cl ratios as a function of 1/Cl results in a linear mixing curve.

et al. (2011) estimated that canopy interception in the high Sacramento Mountains can be as high as 40%, suggesting that a significant portion of annual precipitation never makes it to the surface, evaporating from the tree canopy. Using a canopy interception loss of 30%, annual surface infiltration was estimated to be approximately 18 inches. Using the CMB method results, we estimate recharge from the high mountain region going into the Pecos Slope aquifer to be 43,230 acre-feet/year.

DISCUSSION AND CONCLUSIONS

The estimated relative recharge rate of 22% of average annual infiltration is considered to be a fairly high estimate in the southwestern US. However, with the high average annual precipitation rate in the mountains (~26 in/yr), the thin hill slope soils and the highly permeable fractured bedrock, this high recharge estimate is reasonable. Using Darcy's Law, Duffy et al. (1978) estimated that approximately 133,000 acre-ft/yr flows from the Yeso Formation and the Glorieta Sandstone into the principal aquifer in the Roswell Artesian Basin (San Andres Limestone). This calculation was for a 100-mile long north-south transect that spanned the Rio Peñasco and Rio Hondo drainages. Our recharge estimate of 43,230 acre-ft/yr is based on a recharge area in our study area only. Adjusting the recharge estimate of Duffy et al. (1978) to the size of the southern Sacramento Mountains study area results in an estimated flux of 70,000 acre-ft/yr, which is greater than our recharge estimate.

SUMMARY

The relative recharge rate of 5-10% of surface infiltration that was calculated based on the WTF method of hydrograph analysis is a reasonable estimate for the small spatial and temporal scale considered. With the WTF method, recharge within a small drainage basin in the high mountains was estimated for a single precipitation event. It is highly probable that much of this recharge water will leave the system as ET as it makes its way through the high mountain aquifer system before reaching an adjacent aquifer such as the Pecos Slope aquifer or the Salt Basin aquifer. Therefore, a very localized recharge rate such as the one estimated by the WTF method probably correlates to a much smaller rate on a regional scale.

The recharge estimate based on the CMB method (~ 22% of surface infiltration within recharge area), represents the long term average recharge rate over the entire recharge source area. Based on water level data, geochemistry, and stable isotope data, areas in the high mountains above the 8,200-foot surface elevation contour make up the main recharge source areas for regional aquifer systems in the study area. Within this recharge zone in our study area, we estimate an annual recharge rate from the high mountain region going into the Pecos Slope aquifer to be 43,230 acre-feet/year.

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