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RECONNAISSANCE ESTIMATES OF NATURAL RECHARGE TO DESERT BASINS IN NEVADA, U.S.A., BY USING CHLORIDE-BALANCE CALCULATIONS

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ABSTRACT

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A chloride-balance method for estimating average natural recharge to groundwater basins in the Basin and Range Province of the western United States may be a useful alternative or complement to current techniques. The chloride-balance method, as presented in this paper, equates chloride in recharge water and runoff to chloride deposited in mountainous recharge-source areas by precipitation and dry fallout. Given estimates of annual precipitation on these source areas and chloride concentrations of bulk precipitation and recharge water, the rate of recharge can be estimated providing that: (1) no other major sources of chloride exist; (2) direct runoff to discharge areas in the basin is small or can otherwise be taken into account in the balance; and (3) the recharge sources for the basin are correctly delineated. The estimates are sensitive to the estimated rate of input of chloride from the atmosphere; this is the greatest data need for future applications of the method. Preliminary applications of the method to sixteen basins in Nevada, including Las Vegas Valley, indicate that the method can be a useful tool for hydrologists and resource managers. Correlation coefficients between recharge efficiencies for the basins — estimated on the basis of recharge estimates that use the chloride-balance method and two other currently used techniques — range from 0.54 to 0.95, depending on assumptions about where the method may be applied.

INTRODUCTION

The groundwater resources of many semiarid and arid basins in the western United States are limited and need to be carefully developed to avoid loss of their use over the long term. The extent of these resources is determined in part, and "ultimately [is] limited by [,] the average annual recharge and discharge circulating into and out of the system" (Eakin, 1962b). As a result, estimates of natural recharge and discharge for entire basins are of prime concern to decisionmakers in the western States.

Groundwater systems in the basins of the Basin and Range Province — an area of fault-block mountain ranges and intervening basins centered in Nevada and Utah — are characteristically recharged with water derived from nearby mountains. Precipitation in the mountains may range from 20 to more than 50 cm yr^{-1}. Precipitation on the basin floors is typically minimal (less than 15 cm) and susceptible to large losses due to evapotranspiration. Natural recharge derived from precipitation on the basin floor is, thus, generally assumed to be insignificant.

Estimating natural recharge to these basins is difficult and generally yields uncertain results. Several approaches have been used, with varying degrees of success. The approach most commonly applied in Nevada was developed by Maxey and Eakin (1949), and has been used in more than 200 basins there and in other western states. The Maxey–Eakin method entails: (1) estimating the total volumes of precipitation falling between specified altitudes in the mountains within the basin of interest; (2) reducing these volumes to account for evaporative losses; and (3) summing the resulting recharge volumes to arrive at an estimate of the total natural recharge from the mountains (Maxey and Eakin, 1949). Table 1 shows an example of the precipitation–recharge relation used in the Maxey–Eakin method. The Maxey–Eakin method was developed by a trial-and-error adjustment of "recharge efficiencies" to generate a balance between estimated recharge and estimated discharge in thirteen basins in eastern Nevada (Maxey and Eakin, 1949; Watson et al., 1976). Recharge efficiency is the percentage of total precipitation in the recharge-source areas of a basin that becomes recharge, on a long-term average basis. Very little precipitation runs off directly from the mountains to playas and other discharge areas in the basins studied by Maxey and Eakin, with two exceptions (Clover and Ruby Valleys), and thus the Maxey–Eakin method has been interpreted as estimating the potential for recharge rather than necessarily the actual recharge (e.g., Rush and Kazmi, 1965; Scott et al., 1971). In some basins, the geology, topography, and climate result in significant direct runoff to discharge areas, and the Maxey–Eakin method may have to be corrected for the volume of runoff that "rejected [as] recharge" (Rush and Kazmi, 1965).

The second widely applied method for estimating groundwater recharge in the basins of Nevada is the water-budget method. This method (1) assumes that a natural equilibrium between recharge and discharge exists in each basin, and (2) equates the total groundwater discharge by evapotranspiration, plus any

TABLE 1

Example of Maxey–Eakin empirical relation between annual precipitation rate and recharge efficiency in the hydrologic basins of Nevada

Precipitation range (cm yr^{-1})	Recharge efficiency (% of total precipitation)
> 50	25
40 to 50	15
30 to 40	7
20 to 30	3
< 20	0 to minor

known surface- or groundwater outflow to adjacent basins, to the total recharge (including groundwater inflow from adjacent basins). Thus, natural recharge from the mountains within a basin is assumed equal to the total known discharge from the basin, minus any known inflow to the basin. Commonly, mapping areas of phreatophytes and playas from which groundwater evaporates and estimating the consumption of groundwater by evapotranspiration therefrom is the most direct and practical approach to estimating water budgets in the sparsely populated basins of the Basin and Range Province.

In some basins, mathematical models have been fitted to hydrologic systems with consequent refinements of earlier recharge estimates. Other methods also have been applied in a few basins; they are described by Watson et al. (1976) along with an intensive review and evaluation of the Maxey–Eakin approach.

The present paper describes another approach to estimating natural recharge from surrounding mountains, which is based on estimated chloride balances for a given basin. Recharge estimates are developed by comparing total rates of chloride input from precipitation to chloride concentrations in the groundwater of the basin. This approach has seen applications in diverse physical settings at a variety of geographic scales: in watersheds in the Rocky Mountains (Claassen et al., 1986) and western Australia (Johnston, 1987), island-wide in Bermuda (Vacher and Ayers, 1980) and Guam (Ayers, 1981), and regionally in Israel (Mandel and Shiftan, 1981) and England (Irving, 1982). The applications presented here are at the scale of individual basins in the Basin and Range Province.

THE CHLORIDE-BALANCE APPROACH TO RECHARGE ESTIMATION

Chloride ions in natural groundwater of the Basin and Range Province are derived ultimately from: dissolution of evaporite minerals such as halite (NaCl), weathering of nonevaporite minerals, mixing with salty formation water, mixing with salty water associated with discharge areas or evaporite minerals, and the low concentrations of the ion in dry atmospheric fallout and precipitation (Feth, 1981). In basins that contain extensive evaporite deposits, in basins where significant recharge occurs through evaporite-rich playa surfaces on the basin floor, and in basins that receive a significant inflow of water from distant recharge-source areas through interbasin groundwater flow systems, one or more of the sources of chloride listed above may make significant contributions to the local groundwater. Within many basins, however, the nonatmospheric sources of chloride probably are negligible (Smith and Drever, 1976; Eugster and Jones, 1979; Kimball, 1981), and estimation of a simple chloride balance in part or all of a basin is possible. These potential sources are not always negligible, however (Phillips and Van Denburgh, 1971; Magaritz et al., 1981).

An idealized east–west cross section through two basin-range mountain blocks and one basin is shown in Fig. 1, along with principal components of the

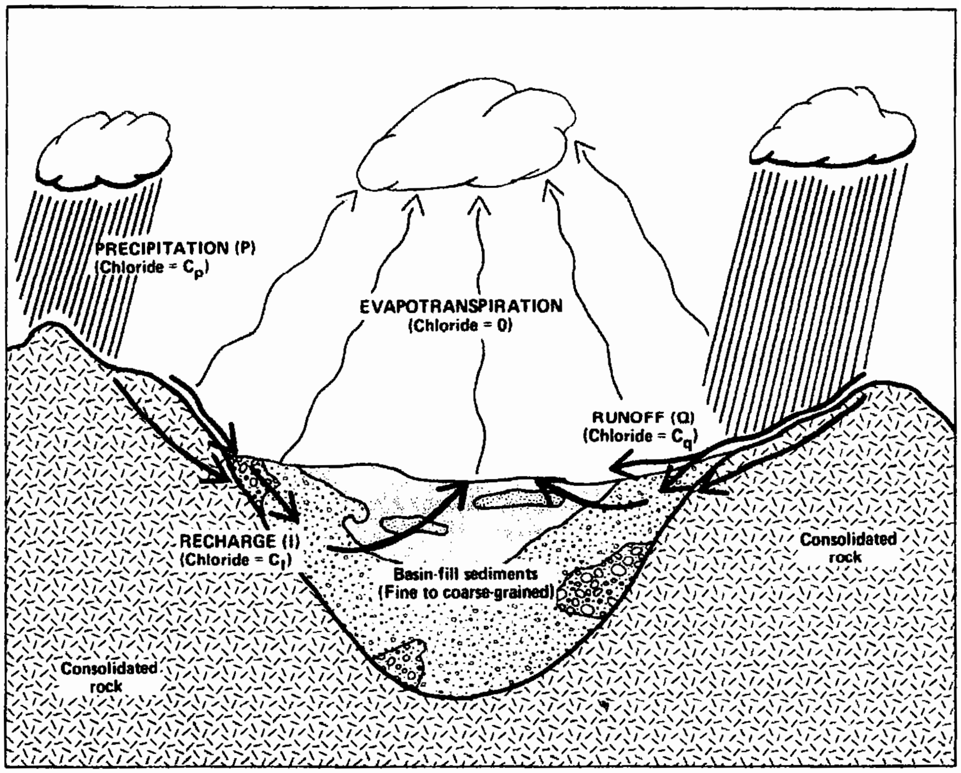

Fig. 1. Idealized profile of mountain blocks and basin in the Basin and Range Province with various components of a typical chloride balance. Not to scale.

water and chloride balances of a closed, undeveloped basin: precipitation, recharge, runoff, and evapotranspiration. In basins where nonatmospheric sources of chloride are negligible, natural recharge from surrounding mountains may be estimated at a reconnaissance level as follows: Given observed chloride concentrations in the combined rain, snow, and soluble dry fallout (defined as the bulk precipitation) on the recharge-source areas, and estimates of the total rate of precipitation on recharge-source areas, the rate of total chloride input to the recharge-source areas (km yr^{-1}) is:

$$C_p P \times 10^3 \qquad (1)$$

where C_p is the average chloride concentration of bulk precipitation ($\mathrm{mg\,l^{-1}}$); P is the average precipitation rate (in cubic hectometers per year, $\mathrm{hm^3\,yr^{-1}}$) and the factor 10^3 makes the dimensional units compatible.

Part of the water budgets for the basins recharges the mountains beneath the recharge-source areas, part runs off the recharge-source areas to percolate down through relatively small areas of the upper alluvial-fan surfaces, and part runs off the recharge-source areas and alluvial fans to directly reach the basin floor. The mass of chloride carried in groundwater and surface water can be specified in terms of the unknown recharge rate (including recharge on the upper fans), the estimated average rate of runoff reaching the basin floor, the estimated average chloride concentration of groundwater near the base of the fans, and the estimated average chloride concentration of runoff that directly reaches the basin floor. The concentration of groundwater at the base of the fan is assumed to be the concentration of recharge water, combining recharge directly beneath the source areas and recharge through the upper fans. The total rate at which chloride is carried into and onto the basin-fill aquifers ($\mathrm{kg\,yr^{-1}}$) is:

$$(C_I I + C_q Q) \times 10^3 \tag{2}$$

where C_I is the average chloride concentration of recharge water ($\mathrm{mg\,l^{-1}}$); I is the average recharge rate ($\mathrm{hm^3\,yr^{-1}}$); C_q is the average chloride concentration of runoff ($\mathrm{mg\,l^{-1}}$); and Q is the average runoff rate ($\mathrm{hm^3\,yr^{-1}}$).

Assuming that these two chloride rates are equal — that is, that a simple chloride balance between input to and output from the recharge-source areas exists — the recharge rate (I) is:

$$I = PC_p/C_I - QC_q/C_I \tag{3}$$

In many basins in Nevada, nearly all runoff onto the alluvial fans evaporates or percolates at the base of the mountains and the rate of runoff past the foot of the fans is negligible. In this common case, Q in eqn. (3) is negligible and:

$$I = PC_p/C_I, \quad \text{when } Q = 0 \tag{4}$$

A single variable describing the atmospheric input rate ($\mathrm{kg\,yr^{-1}}/1000$) can be substituted for PC_p where existing data makes a rate easier to estimate than a concentration.

In basins where the annual rate of runoff to the discharge areas is significant (that is, where a significant fraction of the potential recharge is "rejected"), chloride concentrations in the runoff are commonly one-half to one-quarter the concentration in groundwater. Among the basins considered later in this paper, e.g., runoff in Northern Butte, Fish Lake, Northern Railroad, Upper Reese River, and Spring Valleys are reported as containing chloride concentrations in this range (Frisbie et al., 1982; unpublished data in the U.S. Geological Survey National Water Information System, Carson City, Nevada, 1984). Because of these lower concentrations, eqn. (4) may in many cases be accurate enough for reconnaissance purposes, but eqn. (3) is still preferable where data is available with which to apply it.

ASSUMPTIONS

In addition to the issue of how to manage the runoff component of the chloride balance, numerous assumptions and choices must be assessed before applying the chloride-balance method. One assumption is that precipitation is the only source of chloride in the groundwater. Feth (1981) notes that where groundwater contains less than about 10 mg l^{-1} chloride, atmospheric sources are probably the major source. Close attention must be paid to other potential sources, with particular concern for mineralogical settings that might contribute chloride ions to the groundwater through dissolution or weathering. Evaporite minerals, such as salts that accumulate where (and when) large volumes of surface, ground, or sea water evaporated during geologic time, are particularly disruptive to applications of the method. Weathering of nonevaporite minerals generally contributes only small proportions of chloride (Feth, 1981); thus, a water is likely to be highly mineralized with other ions before weathering contributes a significant increment of chloride. The possibility of recharge water mixing with other, saltier water, of mixing with human-generated wastes, and of chemical changes in recharge water resulting from other human activities (Williamson et al., 1987) should also be considered before using the approach.

Errors also can occur when the sampling sites used to estimate recharge chemistry are too far down the groundwater flow paths. Sites far down a flow path within a single basin may yield water that shows the chloride-concentrating effects of evapotranspirative discharge and consumptive use. Evaporite minerals that readily dissolve in less mineralized groundwater also accumulate in discharge areas near the end of flow paths. Groundwater may also show the cumulative effects of slow, incremental additions of chloride released from aquifer materials along extensive flow paths, such as those in regional, interbasin groundwater flow systems (Mifflin, 1968). The method is therefore best restricted to basins where chloride concentrations in groundwater very near the mountainous recharge-source areas are known, and where recharge from these source areas is the quantity being estimated.

All these chloride sources, if undetected, result in overestimates of atmospherically derived chloride in groundwater and, consequently, underestimates of recharge [eqn. (4)]. Another interfering source would be chloride deposited on the recharge areas by means other than rain and snow. For example, dust from playas and evaporite beds on the basin floors can be blown far up into the mountains and may be a significant source. The best approach to minimize this source of error is to consider, where possible, the chloride contribution of bulk precipitation as defined by Whitehead and Feth (1964): that is, the solution that results when "melting snow, or rain falling on the land surface — whether in its native state or modified by man — collects and incorporates the products of dry fallout." Care must be exercised in collecting bulk precipitation to avoid interpreting every movement of dust within the recharge-source area as an input of "new" chloride. Otherwise dry-fallout components might be double or triple counted, and recharge overestimated [eqn. (4)].

The assumption that all the chloride deposited with the dryfall and wet-precipitation ultimately is contained in the recharge water has also been made in developing the method; that is, no chloride "sinks" exist. Removal of chloride from the recharge water during its passage from the recharge-source areas to the basin-fill groundwater systems is believed unlikely because of the chemistry of the ion. As Hem (1985, p. 118) has stated:

> "Chloride ions do not significantly enter into oxidation or reduction reactions, form no important solute complexes with other ions unless the chloride concentration is extremely high, do not form salts of low solubility, are not significantly adsorbed on mineral surfaces, and play few vital biochemical roles. The circulation of chloride ions in the hydrologic cycle is largely through physical processes."

Chloride ions in bulk precipitation can be lost in the short-term to the chemical precipitation of chloride salts upon evapotranspiration of the high-altitude precipitation. Many (if not most) precipitation events in the semiarid to arid settings of the Basin and Range Province do not result in recharge. In such instances, rainwater or snowmelt is completely evapotranspired before the water can become recharge, and what remains is an efflorescent crust of various salts. Chloride salts tend to be the last precipitated during evaporation because they are the most soluble. They also tend to be the first salts removed from these crusts by solution. When recharge or runoff finally does occur, virtually all of the chloride salts are redissolved into whatever volume of recharge water reaches the basin groundwater system. Thus, over the long term, the amount of chloride ion delivered to recharge-source areas in bulk precipitation should equal the amount dissolved in the recharge and runoff water.

Estimates of the total precipitation rate and the average chloride concentration of bulk precipitation on recharge-source areas are assumed to be accurate. When in error, these estimates may be either high or low; the resulting recharge estimates are high or low by the same proportion.

The Maxey–Eakin method also depends on accurate estimates of precipitation rates, and both methods depend on assumed altitudes below which precipitation contributes no significant recharge (the "cutoff" altitude). In this sense, the estimates generated by the chloride-balance and Maxey–Eakin methods are only partly independent. None of the preceding assumptions are shared with the water-budget method, and the chloride-balance method therefore generates estimates that are independent and complementary to those of the water-budget method. As a result of its independence from the water-budget method and partial independence from the Maxey–Eakin method, the chloride-balance method offers an opportunity to check, at a reconnaissance level, existing recharge estimates.

DATA REQUIREMENTS

The Basin and Range Province is sparsely populated, and hydrologic data also are sparse. In such areas, a significant advantage of the chloride-balance method is that only a few types of relatively simple data are required to apply it at a reconnaissance level. The data required are estimates of: (1) total precipitation on areas contributing recharge to the basin; (2) average concentration of chloride in bulk precipitation on areas contributing recharge; and (3) chloride concentrations in groundwater as it enters the groundwater basin. These requirements are sufficiently simple that the chloride-balance approach can be applied, in a preliminary way, to many basins in the Basin and Range Province with existing data. In particular, the choice of chloride as the chemical constituent considered in eqns. (1) through (4) is propitious. Chloride determinations are among the most common of routine water-quality analyses (Feth, 1981), and thus, generally more historical data are available for a chloride balance than might be available for less commonly determined constituents. Some of the historical data may be of poorer quality than might be acceptable in current data-collection programs, but they are nonetheless useful, given the reconnaissance nature of this estimator.

There are, on the other hand, very few historical data describing precipitation chemistry. The chloride concentration of bulk precipitation, C_p in eqn. (4), is the single most uncertain and difficult parameter to estimate. To support the analyses presented in this paper, 75 bulk and wet precipitation samples were collected from 32 sites (Fig. 2) in Nevada from 1981–83. Chloride concentrations of these samples, along with chloride concentrations reported in the literature for bulk and wet precipitation samples (some repeated and some one-time-only) from 42 additional sites on the eastern slope of the Sierra Nevada and in Nevada (Junge and Werby, 1958; Feth et al., 1964; Marchand, 1974; Brown and Skau, 1975; Leonard et al., 1981; Natural Resource Ecology Laboratory, 1986–87), were used to estimate a representative value for C_p.

The mean chloride concentration for the 32 sites sampled specifically for this application is 0.45 mg l^{-1} (standard deviation 0.35). This value is comparable to the overall average when results from the 42 other sites reported in the literature are included (mean for the 74 sites, 0.43 mg l^{-1}; median, 0.35 mg l^{-1}).

Perhaps the greatest weakness of using this data to estimate C_p is the relative number of bulk versus wet precipitation samples. Bulk precipitation was sampled only at eight of the 74 sites, and even those samples are heavily skewed toward winter samples. This is when most of the precipitation falls but not necessarily when the dry-fallout occurs. Thus, the data available to estimate precipitation chemistry are strongly weighted toward the wet component of chloride deposition in the recharge-source areas. For the samples from the seven bulk-precipitation sampling sites operated for this study, the mean concentration was 0.61 mg l^{-1} chloride (standard deviation, 0.35), while the mean wet-precipitation concentration (for the 25 wet-precipitation sampling sites) was 0.41 mg l^{-1} (standard deviation, 0.33). When the 42 sites from the literature are included, the average bulk-precipitation concentration is 0.6 mg l^{-1} chloride (from eight sites) and the wet-precipitation concentration is 0.4 mg l^{-1} (66 sites).

A large part of the difference may be due to the bulk-precipitation collectors themselves. Most bulk collectors catch and trap all dust and debris that falls into them between precipitation events. The soluble part of that dust and debris is dissolved into the water that arrives as precipitation during the next storm

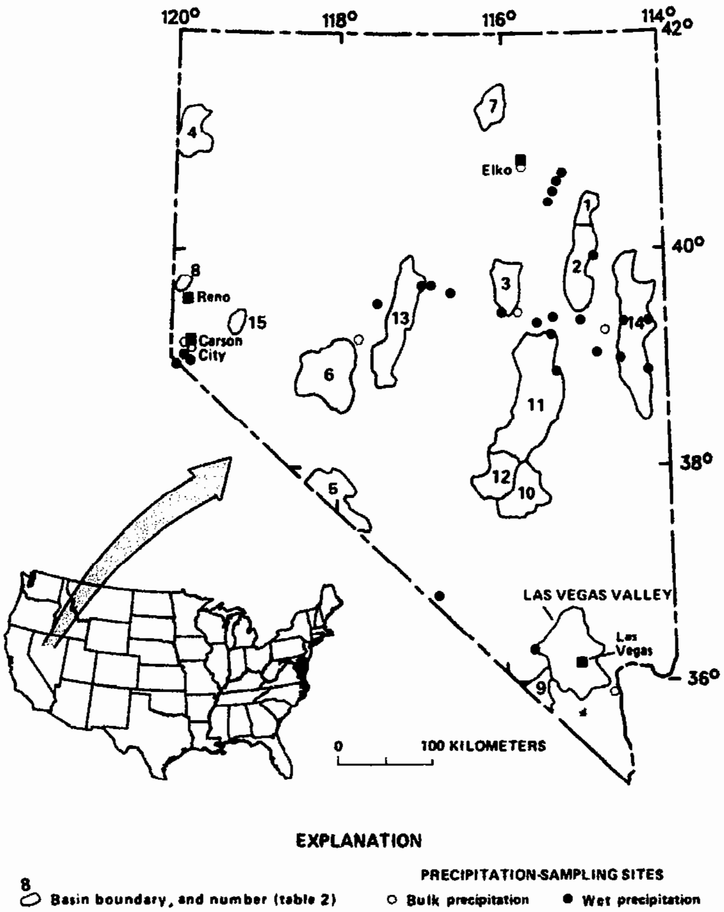

Fig. 2. Locations of Las Vegas Valley, the fifteen basins selected for trial applications of the chloride-balance method, and 32 precipitation-chemistry sampling sites in Nevada.

and the resulting solution is collected as the sample. The bulk-precipitation collectors used in this study and for the reported samples do not allow for remobilization of the dry fallout and do not differentiate between new fallout that enters the area from outside and the dust and debris that simply moves about within the local area. Consequently samples from bulk-precipitation collectors may not represent the net influx of chloride into an area, but rather the net influx plus a large component of locally transported dry particles. Thus, simply collected bulk samples may overestimate atmosphere inputs of chloride to recharge.

Because the number of bulk-precipitation sampling sites was small and the relation between simple bulk precipitation samples and total chloride inputs poorly understood, recharge estimates presented in this paper will be based on the average concentration for all 74 sites; that is, 0.4 mg l^{-1} chloride. The use of a single value to represent the conditions in the entire State might be difficult to justify in detailed studies but has proved adequate for the reconnaissance-level estimates presented herein (more on this later). What seemed to be a large number of sites sampled to estimate this value (74) proved inadequate to support a delineation of geographic or temporal variations in the concentrations of chloride in precipitation. Much more data collection would be required if the chloride-balance method is to see common use in Nevada or the other western States.

RECONNAISSANCE APPLICATIONS OF THE CHLORIDE-BALANCE METHOD TO BASINS IN NEVADA

Las Vegas Valley

As a detailed example of an application of the chloride-balance method, estimates of recharge to Las Vegas Valley from mountains to the west and north have been made. A discussion of the development and accuracy of these estimates follows.

The Las Vegas Valley hydrographic area covers 4050 km^2 of Clark County in southeastern Nevada (Fig. 2). Important features in the basin are shown in Fig. 3. The metropolitan areas of Las Vegas and North Las Vegas occupy the central, lowland part of the basin. The basin is bordered on the west by the Spring Mountains (with altitudes exceeding 3300 m), on the north by the Sheep and Las Vegas Ranges (with altitudes of 2400 m or more), on the east by Frenchman and Sunrise Mountains, and on the south by McCullough Range and River Mountains (with altitudes of less than 1200 m). The basin is drained to the southeast by Las Vegas Wash.

Large coalescing alluvial fans descend from the surrounding mountain ranges to the basin floor over distances of up to 16 km. The lithologic composition of these fans depends on the mountains from which they derived. Generally, the massive fan deposits on the west and north sides of the basin are made up of sediments derived from Paleozoic and Mesozoic carbonate and clastic rock. The smaller fan deposits to the south and east include sediments derived from volcanic-rock terrain and calcareous-gypsiferous deposits (Dinger, 1977). The occurrence of gypsiferous deposits (which include lesser amounts of other evaporite minerals) limits the application of the chloride balance method in the southern and eastern parts of the valley. The lower parts of the fans merge smoothly onto the basin lowlands, which are underlain primarily by basin-fill deposits present as interbedded and interfingering sequences of predominantly calcareous gravel, sand, silt, and clay of complex and variable structure (Plume, 1984).

Under natural conditions, groundwater in the basin-fill deposits was recharged primarily by runoff from snowmelt and precipitation events in the northern Spring Mountains and possibly the southern Sheep and Las Vegas Ranges (Fig. 3). Nearly all runoff from the mountains evaporates or percolates

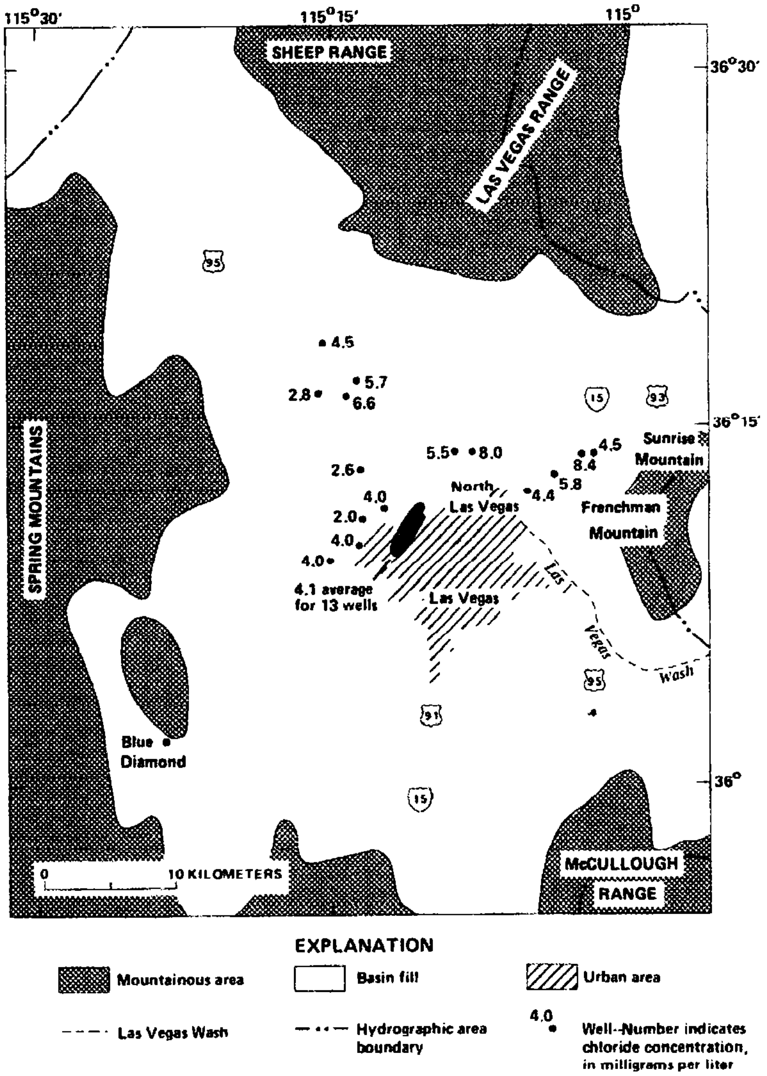

Fig. 3. Map of Las Vegas Valley, showing features mentioned in text and chloride concentration of groundwater from selected sites.

on the long alluvial fans above the basin floor. Groundwater flowed southeastward through the basin-fill deposits toward the east side of the basin. Precipitation in the other mountains bordering the basin contributed much lesser volumes of recharge. Groundwater discharge occurred primarily in the basin lowlands as springs, evaporation, and evapotranspiration (Harrill, 1976).

The average measured chloride concentrations in groundwater at sixteen selected sites on or at the base of the alluvial fans descending from the northern Spring Mountains and Sheep Range are shown in Fig. 3. The sites incorporate numerous wells of intermediate to great depth (60–300 m). The sites and analyses used to estimate the average chloride concentrations were chosen from data described by Kauffman (1978) as representing groundwater quality in the basin under natural conditions, and from data provided by the Las Vegas Valley Water District for many of their deep wells. Where possible, analyses of water samples taken from a single well at different times were used to estimate a single average concentration. Wells that yield water from approximately the same depth in close geographic proximity were used to estimate an average concentration for many of the sites. Analyses of water from wells deeper than 60 m were chosen to avoid the influence of groundwater from the shallow water table. The shallow groundwater in Las Vegas Valley in some areas contains higher solute concentrations due to the influences of evapotranspiration and secondary recharge resulting from human water uses. The dates of the chemical analyses ranged from 1912 to 1977.

Values chosen for application of the chloride-balance method to Las Vegas Valley were estimated as follows. The average of the chloride concentrations for the sixteen sites is 4.8 mg l^{-1}, with a median concentration of 4.5 mg l^{-1}. In generating his estimates of recharge to the basin, Harrill (1976) applied the Maxey–Eakin method and assumed that precipitation falling below 1200 m altitude does not contribute significantly to recharge. Above this altitude, an average total of 410 $hm^3 yr^{-1}$ of precipitation is estimated to fall within the surface drainage of Las Vegas Valley in the Spring Mountains north of the Blue Diamond area and in the Sheep and Las Vegas Ranges. This estimate is based on an altitude–precipitation relation developed by Quiring (1965) for the part of Nevada south of latitude 38.5° N and east of longitude 115.75° E. The tentative estimate of the average chloride concentration in precipitation above the cutoff altitude is 0.4 mg l^{-1}, as discussed above. Substituting these estimates in eqn. (4), the estimated recharge from the major source areas is:

$$410\,\mathrm{hm^3\,yr^{-1}}(0.4\,\mathrm{mg\,l^{-1}}/4.8\,\mathrm{mg\,l^{-1}}) = 34\,\mathrm{hm^3\,yr^{-1}}.$$

This quantity is equivalent to 28,000 acre-ft yr^{-1} — a unit of measure more familiar to many in the Nevada water-resources community.

This recharge estimate is in general agreement with previous recharge estimates for the basin, agreeing well with the Maxey–Eakin estimate of 34.5 $hm^3 yr^{-1}$ developed for the same source areas (J.R. Harrill, U.S. Geological Survey, written commun., 1982) and with the estimate of 30 $hm^3 yr^{-1}$ developed during the calibration of a numerical model of transient groundwater flow conditions in the principal aquifer of Las Vegas Valley (Harrill, 1976). The chloride-balance estimate is also reasonable given the range of earlier recharge estimates for the basin as a whole: Maxey and Jameson (1948) estimated total recharge to the basin at 37–43 $hm^3 yr^{-1}$, and Malmberg (1965) estimated the recharge to be about 31 $hm^3 yr^{-1}$. These latter estimates were based on an early form of the Maxey–Eakin method, water-budget considerations, estimates of underflow entering the lowland areas of the basin, and hydrograph analyses for selected wells.

The chloride-balance estimate of recharge to Las Vegas Valley from the northern Spring Mountains, Sheep Range, and Las Vegas Range is subject to considerable uncertainty (as are all the other recharge estimates). For the chloride-balance estimate, uncertainties arise from several sources. First, the estimate of average annual precipitation on the recharge-source areas is based on an empirical relation between annual precipitation rates and altitudes over a large area of southern Nevada, and on an assumed altitude below which recharge is not contributed. If another set of precipitation estimates (Hardman and Mason, 1949) is assumed, the estimated recharge rate would be approximately 31 $hm^3 yr^{-1}$, only slightly smaller than the estimate presented above. If, alternatively, the recharge-cutoff altitude of 1200 m is assumed to be 300 m higher or lower, the resulting recharge estimates would be 27 and 40 $hm^3 yr^{-1}$, respectively. Obviously, the recharge estimate is sensitive to the choice of cutoff altitude.

The chloride-balance estimate for Las Vegas Valley also may be subject to errors in the estimate of the average chloride concentration of recharge water. Chloride concentrations at the sixteen sites shown in Fig. 3 range between 2.0 and 8.4 $mg\,l^{-1}$. Some of the observed variations are probably due to the kinds of errors and complications of chloride balances discussed in previous sections. Much of the variation, though, is due to local and short-term variability of recharge processes and must be averaged if the long-term, large-scale average recharge is to be estimated. The mean concentration at the sixteen sites lies between 3.9 and 5.8 $mg\,l^{-1}$ at a 95% confidence level (if a normal distribution of values is assumed) and the sixteen chloride concentrations pass chi-square goodness-of-fit tests for normality at levels much higher than 95%. This range of concentrations yields a range of recharge estimates between 28 and 42 $hm^3 yr^{-1}$.

The chloride-balance estimate is, thirdly, dependent on the estimated average chloride concentration of precipitation in the recharge-source areas. Half of the reported and collected concentrations of chloride in bulk and wet precipitation samples (from 74 sites in Nevada and eastern California) fell between 0.2 and 0.6 $mg\,l^{-1}$. This range, if interpreted as a range of possible values for the average C_p, yields recharge estimates ranging from 17 to 51 $hm^3 yr^{-1}$. Obviously, the recharge estimate is quite susceptible to the influence of errors in the estimation of the average chloride concentration of precipitation. This is a large source of uncertainty, given the scarcity of data on bulk precipitation chemistry in Nevada.

Assuming that each of the variables in eqn. (4) is in error and that the worst-case errors are of the scales assumed above, estimates of recharge range between 11 and 75 $hm^3 yr^{-1}$. However, in light of recharge estimates by previous investigators, the estimate based on average values in eqn. (4) is believed to be most reliable (among the chloride-balance estimates).

The chloride-balance estimates are also subject to potential errors stemming from incomplete understanding of the flow system being assessed. For instance, groundwater sampled from along the base of the Spring Mountains has generally lower chloride concentration than that along the Sheep and Las Vegas Ranges. If this distinction is assumed to reflect differences in the recharge efficiencies in the two ranges, then separate estimates of recharge from the two mountain blocks can be calculated. The chloride concentrations at the ten sites along the Spring Mountains average 4.0 mg l^{-1} whereas nine sites along the alluvial fan of the Las Vegas Range average 5.9 mg l^{-1} (several sites were included in both averages). Again employing Quiring's precipitation–altitude relationship and a cutoff altitude of 1220 m, these values yield an estimated recharge from the northern Spring Mountains of 21 $hm^3 yr^{-1}$ and from the Sheep and Las Vegas Ranges of 13 $hm^3 yr^{-1}$. The Maxey–Eakin estimate of recharge from the northern Spring Mountains is 20 $hm^3 yr^{-1}$ and that from the Sheep and Las Vegas Ranges is 16 $hm^3 yr^{-1}$. Thus, the chloride-balance method agrees reasonably well with the Maxey–Eakin method at this scale as well as at the basin-wide scale.

For Las Vegas Valley, an even larger source of error might be improper delineation of the contributing recharge-source areas. In particular, neither of the estimates of recharge from the Sheep and Las Vegas Ranges in the previous paragraph is in close agreement with calibrated recharge values from a two-dimensional finite-difference model of groundwater flow in the principal aquifer of the basin by Harrill (1976). Recharge rates in Harrill's calibrated model were about 24 $hm^3 yr^{-1}$ from the northern Spring Mountains and 2.8 $hm^3 yr^{-1}$ from the Sheep and Las Vegas Ranges. A clue to understanding the difference between all the former estimates and the calibrated values lies in isotopic balances and regional-flow concepts developed by Winograd and Pearson (1976) that suggest that much of the water beneath the northernmost parts of the basin and Sheep Range flows northwest rather than south toward Las Vegas as has been assumed so far in this analysis. This unexpected northwest flow is part of a multibasin flow system in bedrock aquifers that underlie the basin-fill aquifers in this part of Nevada. The chloride-balance method yields an estimated recharge from the Las Vegas Range alone of 2.3 $hm^3 yr^{-1}$, whereas the Maxey–Eakin method yields an estimate of 1.0 $hm^3 yr^{-1}$. Thus, if it is accepted that a significant part of the recharge from the Sheep Range does not, in fact, reach Las Vegas Valley, the chloride-balance and Maxey–Eakin estimates agree fairly well with model-calibration results.

Other basins

The chloride-balance method was applied in a more cursory manner to fifteen additional basins in Nevada as a demonstration of its broader potential to estimate natural recharge in the Basin and Range Province. The basins are listed in Table 2 and their locations are shown in Fig. 2. Las Vegas Valley is not included in Table 2 because the recharge estimates presented in the discussion above do not address flow from all recharge-source areas of Las Vegas Valley, because the water chemistry of other parts of Las Vegas Valley is complicated by the common occurrence of evaporite minerals in the basin fill

TABLE 2

Estimates of recharge to selected basins in Nevada by the Maxey–Eakin, water-budget, and chloride-balance methods; see Fig. 2 for location of basins (hm^3 yr^{-1} except as indicated)

Basin name (county)	Geohydrologic setting	Dominant consolidated rocks	Estimated runoff to discharge areas	Estimated precipitation to source areas	Assumed cutoff altitude (m)	Chloride concentration in recharge			Recharge estimates			Reference
						Average (mg l^{-1})	Range (mg l^{-1})	Number of sites used	Chloride balance	Maxey Eakin	Water budget	
1. Northern Butte (Elko, White Pine)	3	C	1[1]	60	1800[2]	8.7	7.2–10	5	3[3]	5	11	Glancy, 1968a
2. Southern Butte (White Pine)	2(?)	VC	Negl.	240	1800[2]	6.2	4.2–4.9	4	15	19	15	Glancy, 1968a
3. Southern Diamond (Eureka)	3	VC	Negl.	280	1800[2]	8.9	6–14	11	13	15	15	Harrill, 1968
4. Duck Lake (Washoe)	2	V	Negl.	300	1500	10.5	10–11	2	11	11	9	Sinclair, 1963
5. Fish Lake (Esmeralda)	1	VI	4	310	2100	3.8	1.9–7	15	33	41	33	Rush and Katzer, 1973; Eakin, 1950
6. Gabbs (Mineral, Nye)	2	VI	Negl.	470	1500	33.0	32–35	3	6	6	5	Eakin, 1962a
7. Independence (Elko)	1	V	9	310	1800	10.2	5.8–14	4	12	20	15	Eakin, 1962b; Scott et al., 1971
8. Lemmon (Washoe)	4	VI	0.6	38	1500	7.5	1–13	34	2	2	2	Harrill, 1973
9. Mesquite (Clark)	5	CI	Negl.	37	1500	8.8	7–11	4	2	2	3	Glancy, 1968b
10. Penoyer (Nye, Lincoln)	2	VC	Negl.	120	1800	11.0	5–24	4	4	5	5	Van Denburgh and Rush, 1974
11. Northern Railroad (Nye, White Pine)	5	VC	3	760	1800	8.8	3–18	11	35	57	85[4]	Van Denburgh and Rush, 1974
12. Southern Railroad (Nye)	4	V	Negl.	160	1800	10.5	7.2–14	4	6	7	7[5]	Van Denburgh and Rush, 1974
13. Upper Reese River (Nye, Lander)	1	VC	31	730	1800	8.0	6.6–9.6	3	37	72	46	Eakin et al., 1965
14. Spring (White Pine, Lincoln)	4	C	5	970	1800	5.1	3.5–7	5	76	93	91	Rush and Katzer, 1965
15. Stagecoach (Lyon)	3	V	Negl.	12	1500	11.9	8.1–16	10	0.4	0.4	0.4	Harrill, oral commun., 1984

[1] One hm^3 yr^{-1} equals 811 acre-ft yr^{-1}

[2] Cutoff altitude was assumed to vary within the basin.

[3] All chloride-balance estimates were based on an assumed chloride concentration of 0.4mg l^{-1} in bulk precipitation.

[4] Corrected for that part of interbasin inflow to basin equal to discharge at Duckwater springs.

[5] Discharge element of water budget computed based on Maxey–Eakin recharge estimates.

Geohydrologic setting: 1, basin drained by stream or river; 2, closed basin; 3, subsurface flow into and out of basin; 4, subsurface outflow from basin; 5, subsurface inflow to basin. Dominant consolidated rocks: C, carbonate; I, intrusive; V, volcanic.

which precludes application of the chloride-balance method further south in the basin, and finally because no water-budget estimate of recharge for only the northern part of the basin exists. The fifteen basins listed in Table 2 were chosen to ensure a wide geographic coverage, a variety of areal extents and recharge efficiencies, and an availability of chemical analyses of groundwater at suitable wells and springs. Wells and springs were chosen on the basis of location, construction, and low solute concentrations that were believed to be indicative of water recharging the basin-fill deposits. The basins include a variety of hydrologic environments and geologic settings representative of conditions in the Basin and Range Province. These features are briefly summarized in Table 2. In each basin, the aquifer being recharged is composed of fluvial and lacustral basin-fill deposits that presumably have a mineralogy dependent on the mineralogy of surrounding mountain blocks.

The data employed, and the recharge estimates resulting from cursory application of the chloride-balance method [eqn. (4)] to the selected basins, also are summarized in Table 2, along with recharge estimates developed by the Maxey–Eakin and water-budget methods for the same basins. In half the basins, direct runoff to discharge areas such as playas or marshes is estimated to be 10% or more of the estimated potential recharge. With the exception of Independence and Upper Reese River Valleys, the chloride load in runoff is 15% or less of the load in recharge water (assuming that the chloride concentration of runoff is about one-half (or less) the recharge concentrations). In Independence Valley and Upper Reese River Valley, the rate of runoff is large relative to recharge and the simple form of the chloride-balance estimate [eqn. (4)] would arguably not be acceptable for any but the most cursory estimates (more on this later).

The chloride-balance estimates in Table 2 are subject to potentially significant errors from several sources, and are simply meant to approximate estimates that might be expected in more detailed applications of the method. The estimates usually are based on data in the reconnaissance-series reports, prepared cooperatively by the U.S. Geological Survey and published by the Nevada Department of Conservation and Natural Resources, that address the water resources of the selected basins. For the sake of simple presentation in this article, data from other sources generally were not included in these estimates. Definitive estimates for the basins should, of course, include all available and applicable data. The recharge estimates are based on the same estimates of total precipitation on the recharge-source areas as the Maxey–Eakin-method estimates presented in the reconnaissance-series reports. A chloride concentration of $0.4\,\mathrm{mg\,l^{-1}}$ for precipitation on the recharge-source areas is assumed and is subject to errors discussed above. Finally, the number of groundwater analyses used to estimate recharge chemistry in the basins ranges from 2 in Duck Lake Valley to 34 in Lemmon Valley. Because of the generally sparse data, fewer-than-optimal chemical analyses were used in these applications, and some are for groundwater at less-than-optimal locations. Ideally, chloride concentrations at many points along the margins of each basin would be used to estimate recharge from every segment of each recharge-source area in which the method appears to be valid (somewhat as in the Las Vegas example). Furthermore, usually the chloride-balance method would be applied as part of a more general review of the hydrologic and geochemical conditions in a basin, during which the assumptions underlying the chloride balance are assessed.

Estimates derived by the chloride-balance, water budget, and Maxey–Eakin methods are presented in Fig. 4a. The three estimates are generally in fair agreement. The correlation coefficient between chloride-balance and water-budget estimates (for all fifteen basins) is 0.92, between the chloride-balance and Maxey–Eakin estimates 0.97, and between the water-budget and Maxey Eakin estimates 0.93. These coefficients, however, are strongly influenced by the estimates for those basins with large recharge rates. A better measure of the overall agreement between the estimates is the correlation between the basin-wide recharge efficiencies — that is, the recharge estimates divided by the total precipitation volumes contributing to recharge. The correlation between efficiencies is less influenced by the few large basins. Figure 4b allows

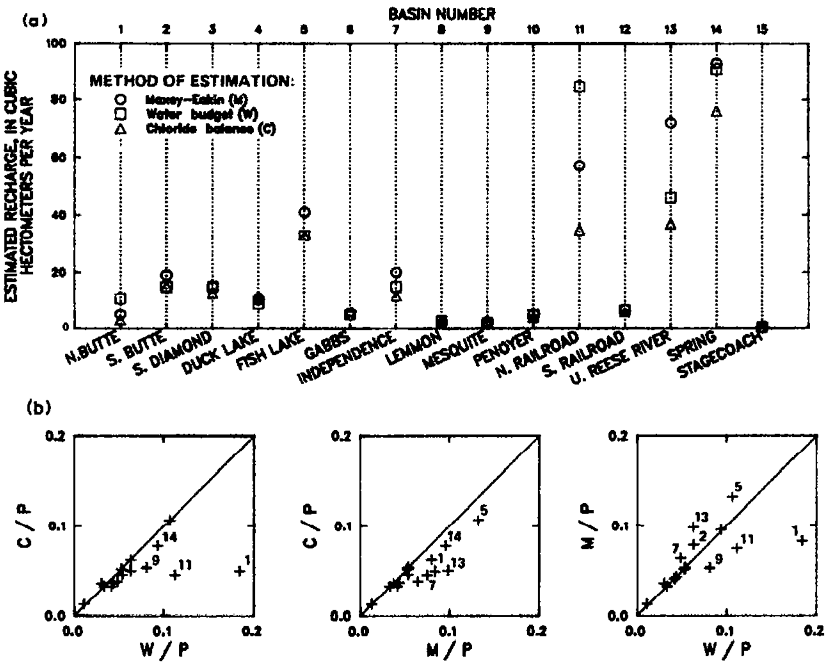

Fig. 4. Comparisons of estimates of natural recharge for fifteen basins in Nevada, using the Maxey–Eakin, water budget, and chloride-balance methods. (a) Rates of natural recharge; (b) ratios of estimates to precipitation rate (*P*) in recharge-source areas. Ratios indicated in terms of single-letter estimate designations in explanation, Fig. 4a, and outlying points are labeled with the same basin numbers as at top of Fig. 4a and Table 2.

visual comparison of the efficiencies for each combination of recharge estimates.

Comparison of chloride-balance and water-budget estimates, and the influence of interbasin flow

The chloride-balance and water-budget estimates are well correlated with two exceptions (the estimates for Northern Butte Valley and Northern Railroad Valley). The correlation coefficient between the recharge efficiencies implied by the chloride-balance and water-budget estimates for all fifteen basins is 0.54, but excluding the estimates for those two basins from the calculation, the coefficient rises to 0.95. The chloride-balance estimates are generally less than or roughly equal to the corresponding water-budget estimates.

Northern Railroad Valley and Northern Butte Valley (where the water-budget estimates are 2.4 and 3.7 times the chloride-balance estimates), along with Mesquite Valley (where the water-budget estimate is 1.5 times the chloride-balance estimate), are believed to receive significant inflow from areas outside their topographic limits (Glancy, 1968a, b; Van Denburgh and Rush, 1974). These subsurface inflows may limit or interfere with the use of the chloride-balance method in at least two ways (especially where the inflows are of uncertain origin or unknown magnitude).

First, the inflowing water originates from precipitation on areas not included in the assumed recharge-source areas for the basin. The overall recharge-source area for some interbasin flow systems may be quite extensive, farflung, and of wildly uncertain boundaries. The total precipitation, P in eqn. (4), estimated to be contributing to recharge may thus be much less than the total actually contributing.

Second, in the larger regional flow systems of Nevada, interbasin flows are commonly chloride-rich relative to locally derived groundwater recharge (Mifflin, 1968). Mifflin's fig. 13 shows that the chloride-plus-sulfate concentration in regional water may be 10 to more than 50 times as high as in water in small local systems. If uncorrected for mixing of the chloride-rich "regional" water with the more dilute "local" groundwater, the chloride balance for the basin and, in turn, the recharge estimate derived from that balance could be skewed. Unless the chloride concentration C_l in eqn. (4) is carefully estimated in such basins, to avoid unwittingly including samples of regionally derived groundwater in the characterization of the local recharge chemistry, chloride-balance estimates will be gross underestimates of even the locally derived component of basin recharge.

Northern Butte Valley and Mesquite Valley may fall into the category of basins where the first of these problems arises. No components of regional-scale flow systems are recognized in those basins, but parts of the ranges surrounding those basins are composed of permeable carbonate bedrock. Flow through these rocks could allow recharge developed outside the topographic boundaries of the basin, on the far side of the basin-bounding ranges, to leak into the basin and to supplement the locally derived recharge.

The discrepancy between recharge estimates for Northern Railroad Valley may represent a combination of both influences of interbasin flow on the chloride-balance estimate or perhaps an entirely different influence. The amount of water discharging from this basin not accounted for by either the Maxey–Eakin or chloride-balance recharge estimates is large (over $25\,\mathrm{hm}^3\,\mathrm{yr}^{-1}$). This amount of water probably is too much to be derived entirely from the immediately adjacent mountain ranges and so is believed to originate in other parts of a multibasin flow system with Railroad Valley as a regional groundwater sink in which water from perhaps five basins is discharged. This "excess" water is discharged from large warm-water springs, a large playa ($165\,\mathrm{km}^2$), and an even larger stand ($530\,\mathrm{km}^2$) of moderately dense to scattered phreatophytes (Van Denburgh and Rush, 1974). An alternate explanation of the low chloride-balance estimate is that Railroad Valley has an uncommonly large playa (even for Nevada) which could serve as a source for a greater-than-usual rate of dry deposition of chloride in the mountains surrounding the basin. This extra chloride input may invalidate the assumption that the chloride concentration of precipitation C_p in eqn. (4), is roughly $0.4\,\mathrm{mg\,l}^{-1}$ for this basin.

Southern Diamond Valley (Harrill, 1968) and Stagecoach Valley (J.R. Harrill, U.S. Geological Survey, oral commun., 1984) are believed to receive small subsurface inflows along localized segments of their boundaries. In these basins the recharge estimates were not significantly affected.

Comparison of chloride-balance and Maxey–Eakin estimates, and the influence of rejected recharge

Generally, chloride-balance estimates for the fifteen basins and the corresponding Maxey–Eakin estimates are well correlated (Fig. 4). The correlation coefficient between the recharge efficiencies implied by the two methods is 0.88, while the correlation coefficient between the Maxey–Eakin and water-budget estimates is only 0.67. The chloride-balance estimates, however, show an even greater tendency to be less than or equal to the Maxey–Eakin estimates than they did with the water-budget estimates.

The largest proportional discrepancies between the estimates are for Independence and Upper Reese River Valleys. The discrepancy for Fish Lake Valley is not proportionately as large but is very noticeable in Fig. 4b. It is probably significant that these three valleys have large rates of runoff directly to groundwater discharge areas, a water-budget component described as rejected recharge by Rush and Kazmi (1965). It is also significant that, in each case, the chloride-balance estimate agrees much better with the water-budget estimate than with the Maxey–Eakin estimate, and both are less than the Maxey–Eakin estimate. In basins with little runoff, all three methods are in general agreement. The Maxey–Eakin estimates tend to differ from the others in basins with runoff because they make no allowance for local topographic, climatic, and geologic conditions that prevent part of the runoff from recharging those basins.

On the other hand, the chloride-balance estimates presented are based on eqn. (4) which also neglects runoff. Assuming the water-budget estimates are good estimates of actual recharge in most of the basins, the close agreement between the chloride-balance and water-budget estimates in basins with significant runoff suggests that at the scale of these estimates the last term in eqn. (3) may be a small correction to eqn. (4). To the extent that this rule of thumb proves true, eqn. (4) may be used for reconnaissance recharge estimates even where direct runoff to the discharge areas occurs. Equation (3), however, is probably to be preferred in most applications.

An empirical estimate of C_p

In principle, the chloride-balance method cannot be applied without a reliable estimate of the rate of atmospheric input of chloride to recharge-source areas. However, in light of current uncertainties with respect to this rate, the comparison of recharge estimates thus far can arguably be reversed and the relatively close agreement between the chloride-balance and other estimates viewed as providing an empirical estimate of C_p for comparison with the observed concentrations in Nevada to date. The empirical estimate of C_p is obtained as follows: Water-budget estimates of recharge are used to estimate recharge efficiencies and then are compared to estimated chloride concentrations of groundwater in each basin in Fig. 5. A simple regression curve:

$$E = 0.004 + 0.38/C_1 \qquad (5)$$

can be fitted to the data points for all the basins, with an R^2 value of only 0.23. If the estimates for Northern Butte and Northern Railroad Valleys are omitted from the analysis — on the argument that the amount of precipitation and the recharge-source areas are poorly defined (as previously discussed) or that in some way the chloride concentration of recharge has been poorly estimated — the remaining thirteen data points can be fitted to nearly the same curve ($E = 0.42/C_1$) but with a much more favorable R^2 value of 0.83. Although none of the data used to derive this curve requires any assumption regarding the chloride concentration of bulk precipitation in recharge-source areas, the simple regression equation presented above, together with eqn. (4) [upon dividing both sides of eqn. (4) by total precipitation] implies a chloride concentration of roughly 0.4 mg l^{-1} for precipitation. Thus, for thirteen of the fifteen widely separated basins in Nevada that were selected for preliminary applications of the chloride-balance method, the single average precipitation concentration used herein is probably an adequate estimate for reconnaissance purposes. As noted previously, more exacting recharge estimates will depend on a better understanding of the temporal and spatial variations of the chloride concentrations of precipitation in Nevada.

SUMMARY

The average annual rate of groundwater recharge in desert basins of the Basin and Range Province is of crucial concern to water-resources managers.

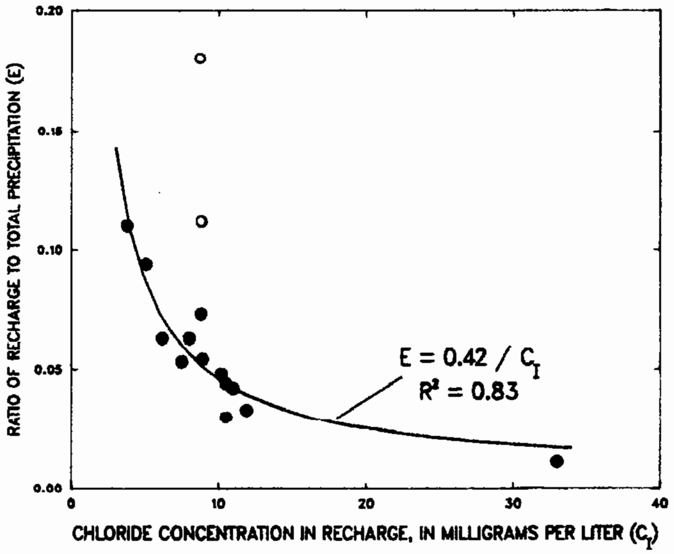

Fig. 5. Relation of recharge efficiency to chloride concentration of water recharging fifteen basins in Nevada. Recharge efficiency is calculated as the ratio of recharge rate estimated by water-budget method to estimated total precipitation rate in recharge-source areas. Solid curve represents least-square fit for basins in Table 2 (solid dots) other than Northern Butte Valley and Northern Railroad Valley (open circles).

Most current estimates of natural recharge in Nevada are based on two methods: the Maxey–Eakin method and the water-budget method. An alternate method, the chloride-balance approach, appears to be applicable to estimating recharge to the alluvial and lacustral fill aquifers of many of the basins.

The chloride-balance approach equates: (1) the rate at which chloride ions enter recharge-source areas in mountain ranges bordering the basins with (2) the rate at which dissolved chloride enters basin-fill aquifers at the basin margins and runoff to playas, marshes, and other discharge areas. The rate of recharge to many basins in which runoff is insignificant can be estimated if data are available that describe: (1) chloride concentrations in precipitation and dry fallout deposited on the recharge-source areas; (2) rates of annual precipitation in the recharge-source areas; and (3) chloride concentrations in groundwater near the point of entry into the aquifers (typically at the base of the mountains). The latter two data requirements are met already (to a differing extent) in many basins. Collection of precipitation-chemistry data will allow application of the method to many basins of the Basin and Range Province. Where runoff is important in all or part of a basin, estimates of runoff rates and runoff chemistry also may be required.

Potential contributors to significant error in applications of the method include: (1) sources of chloride other than precipitation and dry fallout; (2) use of chemical data atypical of the recharge portion of the basin flow system; (3) poor estimates of total annual precipitation; (4) poor delineation of the recharge-source areas; (5) poor estimates of average chloride concentrations in precipitation and dry fallout; and (6) failure to account for runoff that never contributes recharge or chloride to the groundwater. The first two sources of error are likely to be systematic and tend to result in overestimates of the chloride concentration in recharge water and, as a result, underestimates of the recharge rate. Contributors 3–5 probably are more random and might lead to either underestimates or overestimates of recharge. The last source of error should result in overestimation of actual recharge.

Comparisons of existing recharge estimates with the results of applications of the chloride-balance method to Las Vegas Valley and fifteen other basins in Nevada suggest that the chloride balance is a practical method for estimating, at a reconnaissance level, average rates of natural recharge to many desert basins of the Basin and Range Province of the western United States. Application of the method to Las Vegas Valley suggests that the method is most sensitive to uncertainties regarding delineation of recharge-source areas and chloride concentrations in precipitation and dry fallout. Applications to the other fifteen basins suggest that in practice: (1) one source of large errors may be unaccounted-for inflows to the basins; and (2) corrections to the chloride-balance method for rejected recharge may be small in many cases. More precise estimates may be practical within specific segments of some basins in which data availability and geochemical conditions are appropriate for development of detailed balances.

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