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# EVALUATION OF THE MAXEY-EAKIN METHOD FOR ESTIMATING RECHARGE TO GROUND-WATER BASINS IN NEVADA[1]

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ABSTRACT: An evaluation of the Maxey-Eakin method for calculating recharge to ground-water basins in Nevada was performed. The evaluation consisted of comparing Maxey-Eakin estimates with independent estimates of recharge, and analyzing the nature of the differences between the groups of estimates. In the comparison with the Maxey-Eakin estimates, two different groups of independent estimates were used: (1) 40 recharge estimates that were identified from water budgets contained in reports by the Nevada Department of Conservation and Natural Resources and (2) 27 recharge estimates that were identified from previous studies that used models. The results of the comparisons indicate generally good agreement between the Maxey-Eakin estimates and both groups of independent estimates. To quantify this agreement, an analysis was conducted to estimate the uncertainty in the Maxey-Eakin method. The analysis produced an upper bound on the standard deviation of the Maxey-Eakin estimate for a given basin. For the group of 40 water-budget estimates, the upper bound on the standard deviation for an individual basin is 4,800 acre-ft/yr, and the corresponding coefficient of variation of the Maxey-Eakin estimate is no greater than 44 percent. For the group of 27 model estimates, the upper bound on the standard deviation is 4,100 acre-ft/yr, and the corresponding coefficient of variation is no greater than 24 percent.
(KEY TERMS: ground-water recharge; arid west; Maxey-Eakin method; statistics; evapotranspiration; infiltration.)

## INTRODUCTION

The Maxey-Eakin method for estimating recharge to a ground-water basin has been applied to over 200 basins in Nevada, as well as in other western states, since its development by G. B. Maxey and T. E. Eakin over 40 years ago. It has been the primary method of recharge estimation used by the Nevada Department of Conservation and Natural Resources in its reconnaissance studies of ground-water recourses. Given the importance of the Maxey-Eakin method in estimating ground-water recharge to basins in Nevada, an evaluation of the method's reliability seems appropriate. The objective of this study was to evaluate the Maxey-Eakin method by comparing ground-water recharge estimates, which were derived using the Maxey-Eakin method, to recharge estimates that were derived independently using other methods.

The Maxey-Eakin method consists of an empirically-derived relationship between precipitation and recharge to a ground-water basin. In brief, the Maxey-Eakin recharge for a basin is computed by: (1) estimating the mean annual volumes of precipitation within several precipitation zones for the drainage basin, (2) scaling these volumes by a factor representing losses from evapotranspiration and surface-water runoff that does not become ground-water recharge, and (3) summing the resulting recharge volumes to obtain an estimate of total recharge to the ground-water basin.

Watson *et al.* (1976) review the development of the Maxey-Eakin method. They report that the precipitation zones used in the method were delineated by Maxey and Eakin (1949), based on a map of precipitation in Nevada by Hardman (1936). According to Maxey and Eakin (1949), discharge data for 13 basins in east-central Nevada were used to determine the recharge percentages by the trial-and-error balancing of recharge with estimated ground-water discharges. Watson *et al.* (1976) report that a total of 21 basins (Figure 1) were ultimately used in the development of the method, based on Maxey and Eakin (1949) and Eakin *et al.* (1951), and on personal communication with Maxey. Table 1 shows the precipitation zones, referred to by Watson *et al.* (1976) as Hardman zones,

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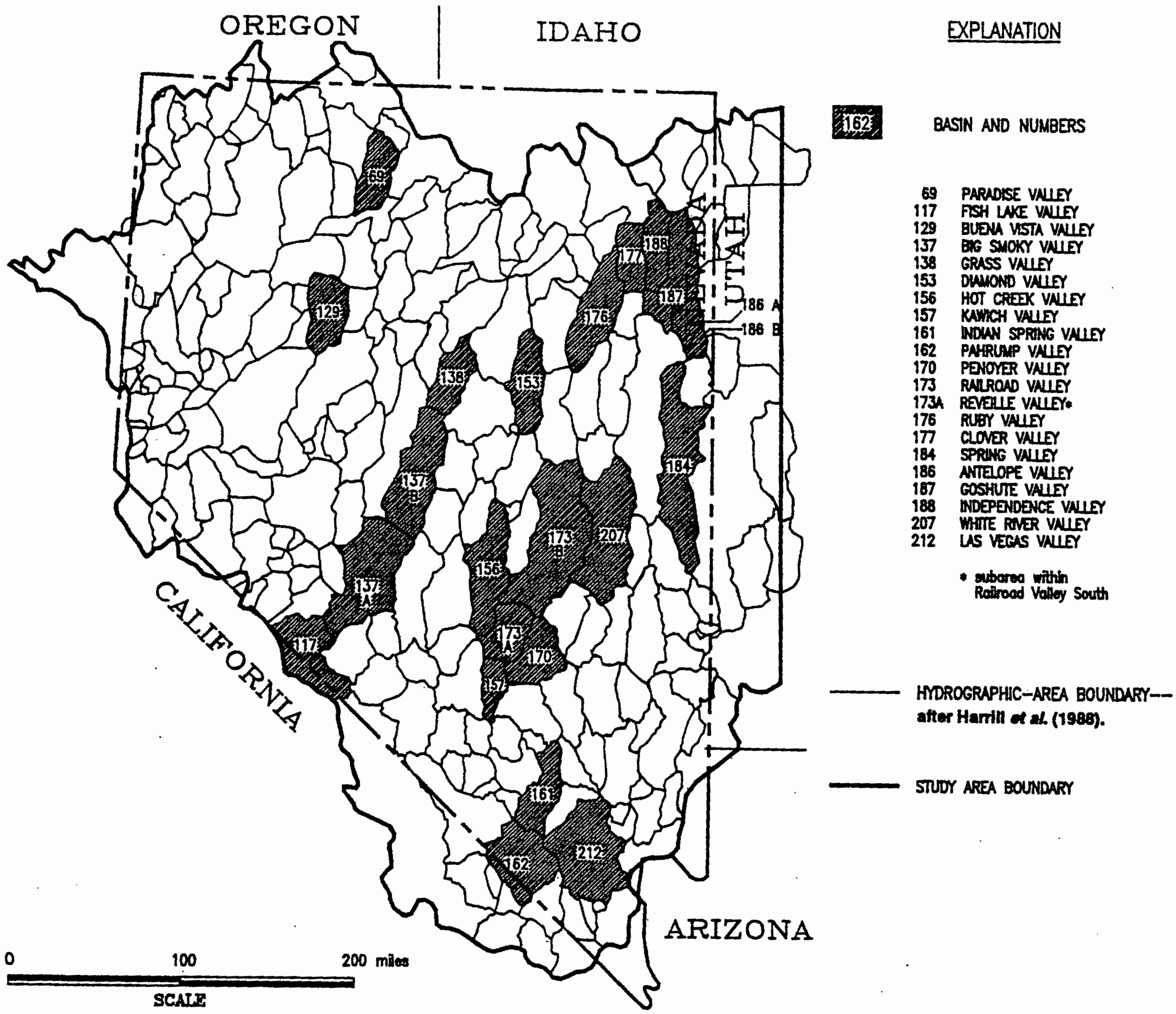


Figure 1. Location of the 21 Basins Used in Developing the Maxey-Eakin Method.

and the corresponding recharge coefficients that were developed by Maxey and Eakin. Accordingly, calculation of the Maxey-Eakin recharge for a given basin can be expressed in the form

$$ME = \sum_{i=1}^{5} a_i P_i \qquad (1)$$

where $ME$ is the Maxey-Eakin recharge for a basin, $P_i$ is the volume of precipitation within each of the five Hardman zones, and $a_i$ is the recharge coefficient for each of the five Hardman zones.

TABLE 1. Precipitation Zones and Corresponding Coefficients for the Maxey-Eakin Method. (Maxey and Eakin, 1949; Eakin *et al.*, 1951).

| Precipitation Zone | Maxey-Eakin Coefficient (percent) |
|---|---|
| > 20 in. | 25 |
| 15-20 in. | 15 |
| 12-15 in. | 7 |
| 8-12 in. | 3 |
| < 8 in. | 0 |

A schematic depiction of the Maxey-Eakin recharge is given in the water budget shown in Figure 2. In general, virtually all of the ground-water recharge to a basin originates as precipitation in the mountains. Some of that precipitation is lost to evapotranspiration, some infiltrates directly into the ground water, and some becomes surface-water runoff. Runoff from the mountains onto the alluvial fans provides an additional source of recharge to the ground-water basin. The bold arrows in Figure 2 indicate these two components of the Maxey-Eakin ground-water recharge.

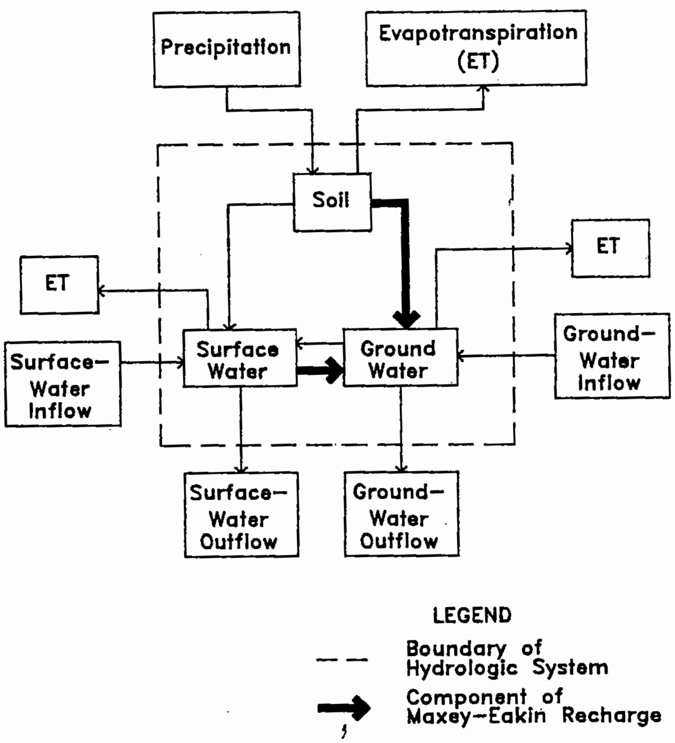


Figure 2. Generalized Water Budget for a Ground-Water Basin.

## APPROACH USED TO EVALUATE MAXEY-EAKIN METHOD

The general approach used to evaluate the Maxey-Eakin method involved identifying independent estimates of ground-water recharge to compare with the Maxey-Eakin estimates. Several steps were necessary to accomplish this. First, reports by the State of Nevada were reviewed to identify usable Maxey-Eakin recharge estimates. Second, independent estimates of ground-water discharge were identified from these reports, where these discharges were compared to the Maxey-Eakin recharge estimates based on the steady-state ground-water budget. Third, independent estimates of recharge derived from modeling studies were compiled. The following sections describe each of these procedures.

### *Screening of Maxey-Eakin Estimates*

Maxey-Eakin estimates of recharge within ground-water basins in Nevada are contained within two series of publications by the Nevada Department of Conservation and Natural Resources: the *Ground-Water Resources Reconnaissance Series,* which includes 60 reports written between 1960 and 1974, and the *Water-Resources Bulletins,* which include 44 reports that were produced between 1946 and 1976. A total of 233 Maxey-Eakin estimates were compiled from these reports. However, because of various reasons, some of the recharge estimates were considered potentially unusable in the analysis. The following criteria were used to classify the estimates and identify those which were usable. The categories are similar, but not entirely coincident, with those developed by Watson *et al.* (1976). The number in brackets after each category corresponds to the total number of estimates in that group.

1. A "standard" Maxey-Eakin estimate, as defined in Table 1, was identified and calculations were given in the report. [146]
2. The Hardman zones for precipitation were not developed (and recharge was not computed) or the zones were inconsistent with those normally used, as defined in Table 1. [26]
3. The water table or capillary fringe was thought to be too close to the ground surface to allow for significant ground-water recharge. Therefore, the Maxey-Eakin method was not applied. [3]
4. The Maxey-Eakin coefficients were changed from the standard values, as defined in Table 1. Common cases in which this occurred include (1) when precipitation was judged to be less than the Hardman zones indicated, and the Maxey-Eakin coefficients were reduced, and (2) when ground-water recharge was judged to be small because of great depth to the water table. [13]
5. Earlier or duplicate estimate for a basin was discovered. When two differing estimates for a basin were found, the most recent estimate was used. [14]
6. In computing the Maxey-Eakin recharge, values were rounded significantly or an error was made in the calculation, resulting in a greater than 10 percent difference between the computed and the reported values. [16]
7. An estimate reportedly based on the Maxey-Eakin method is given, but no calculations were supplied. [15]

The application of these criteria identify a total of 146 estimates that can be considered as "standard" applications of the Maxey-Eakin method, and 87 estimates that represent deviations from standard application of the method. The non-standard applications of the Maxey-Eakin method were eliminated from the analysis because they may represent instances where recharge was adjusted to more closely match an existing estimate of discharge. In these cases, the Maxey-Eakin estimates are not true independent estimates of recharge.

### *Screening of Water-Budget Estimates*

The second level of screening that was performed was to review the *Ground-Water Resources Reconnaissance Series* and *Water-Resources Bulletins* to identify independent estimates of recharge from the ground-water budgets contained within these reports. In basins in which no change in storage could be assumed, estimates of ground-water discharge were identified from the water budgets, and these estimates were taken as independent estimates of recharge. In a few cases, revisions of the ground-water budgets contained within the State publications were reported elsewhere, such as in publications by the U.S. Geological Survey or in journal articles. In these cases, the revised discharge estimates were used for comparison with the Maxey-Eakin recharge estimates.

As with the screening of the Maxey-Eakin recharge estimates, a classification system was developed in order to screen the discharge estimates. Following are the criteria that were used, where the number in brackets after each category refers to the total number of estimates within that group.

1. Water-budget estimate of discharge is usable as an independent estimate of recharge, and a corresponding Maxey-Eakin recharge estimate that is usable exists. [40]
2. Estimate is for a subarea within a major basin that could not be used individually because only the total discharge for the major basin was given. [31]
3. Components of the ground-water budget were determined by difference. Thus, the estimate of discharge is not independent of the Maxey-Eakin recharge. [64]
4. Ground-water inflow or outflow exists, but was not estimated. [23]
5. Ground-water inflow was estimated by an analog model, and the results are considered as provisional. [1]
6. Ground-water discharge from within the basin cannot be separated from the total discharge of both surface water and ground water. [6]
7. A major river flows through the basin, and surface-water inflow and outflow dominate the water budget in comparison to ground-water recharge and discharge within the basin. Therefore, mainstream areas were rejected. [26]
8. Significant evapotranspiration by phreatophytes occurs, but it was not estimated and included in the discharge estimate. [1]
9. Evaporation from playas, which is either unreliably estimated or not estimated, is a significant portion of the total discharge. [2]
10. Uncertainty, in the water budget results from transient interactions between a lake and ground water. Examples are: (a) lake desiccation that results from depletion of ground-water storage and (b) lowering of lake water levels, which affects ground-water storage. [4]
11. Either an earlier estimate that was later revised, or a duplicate of an estimate reported elsewhere. [9]
12. Discharge estimate was reported, but no Maxey-Eakin recharge was computed. [6]
13. Discharge estimate was reported, but corresponding Maxey-Eakin recharge estimate was rejected in preceding screening of Maxey-Eakin estimates. [16]
14. No water budget was reported. [2]

The results of this screening process indicated that, of the 229 existing water budgets reviewed, 40 estimates of discharge were usable as independent estimates of recharge and had corresponding Maxey-Eakin recharge estimates that were usable. Table 2 lists the 40 estimates, referred to as the "water-budget estimates," and Figure 3 shows their locations.

### *Screening of Model Estimates*

The third stage in compiling the data base was to conduct a literature review to identify other independent estimates of ground-water recharge for basins within Nevada. Sources for the estimates included publications of the U.S. Geological Survey, publications of the Desert Research Institute of the University of Nevada, and journal articles. A total of 27 independent estimates of recharge that were derived from techniques other than water budgeting were identified. The methods used to derive these recharge estimates include the following, where the numbers in brackets refer to the total number of estimates: chloride mass balance [12], deuterium-calibrated

TABLE 2. List of the 40 Water-Budget Estimates of Recharge.

| Hydrographic Area* | Basin | Maxey-Eakin Recharge (acre-ft/yr) | Water-Budget Discharge (acre-ft/yr) | Reference |
|---|---|---|---|---|
| 16 | Duck Lake | 9000 | 7000 | Sinclair (1963) |
| 18 | Painters Flat | 1300 | 1200 | Glancy and Rush (1968) |
| 21 | Smoke Creek Desert | 13000 | 18620 | Glancy and Rush (1968) |
| 22 | San Emidio Desert | 2100 | 3200 | Glancy and Rush (1968) |
| 24 | Hualapai Flat | 7000 | 6700 | Sinclair (1962a); Harrill and Soule (1969) |
| 29 | Pine Forest | 10000 | 14100 | Sinclair (1962b) |
| 53 | Pine | 45500 | 24000 | Eakin (1961); Eakin and Lamke (1966) |
| 55 | Carico Lake | 4300 | 4500 | Everett and Rush (1966) |
| 71 | Grass (Humboldt) | 12000 | 16800 | Cohen (1964); Eakin and Lamke (1966) |
| 84 | Warm Springs | 6000 | 2000 | Rush and Glancy (1967) |
| 85 | Spanish springs | 600 | 1000 | Rush and Glancy (1967) |
| 86 | Sun | 50 | 25 | Rush and Glancy (1967) |
| 92 | Lemmon | 1800 | 900 | Rush and Glancy (1967) |
| 95 | Dry | 2400 | 2300 | Rush and Glancy (1967) |
| 96 | Newcomb Lake | 300 | 130 | Rush and Glancy (1967) |
| 97 | Honey Lake (E only) | 1500 | 10500 | Rush and Glancy (1967) |
| 111 | Alkali N | 400 | 300 | Van Denburgh and Glancy (1970) |
| 113 | Huntoon | 800 | 300 | Van Denburgh and Glancy (1970) |
| 114 | Teels Marsh | 1300 | 1400 | Van Denburgh and Glancy (1970) |
| 117 | Fish Lake | 33000 | 27000 | Rush and Katzer (1973) |
| 118 | Columbus Salt Marsh | 700 | 3800 | Van Denburgh and Glancy (1970) |
| 119 | Rhodes Salt Marsh | 500 | 600 | Van Denburgh and Glancy (1970) |
| 121 | Soda Spring E | 600 | 700 | Van Denburgh and Glancy (1970) |
| 121 | Soda Spring W | 100 | –270 | Van Denburgh and Glancy (1970) |
| 125-127 | Eastgate, Cowkick, Stingaree | 6000 | 6000 | Cohen and Everett (1963) |
| 128 | Dixie | 6000 | 9200 | Cohen and Everett (1963) |
| 132 | Jersey | 800 | 800 | Cohen and Everett (1963) |
| 133 | Edwards Creek | 8000 | 7600 | Everett (1964) |
| 134 | Smith Creek | 9600 | 7000 | Everett and Rush (1964); Thomas *et al.* (1989) |
| 136 | Monte Cristo | 500 | 400 | Van Denburgh and Glancy (1970) |
| 138 | Grass (Lander) | 13000 | 13000 | Everett and Rush (1966) |
| 150 | Little Fish Lake | 11000 | 10000 | Rush and Everett (1966) |
| 153 | Diamond Total | 21000 | 21000 | Eakin (1962); Harrill and Lamke (1968) |
| 156 | Hot Creek | 7000 | 6100 | Rush and Everett (1966) |
| 170 | Penoyer | 4300 | 3800 | Van Denburgh and Rush (1974) |
| 178 | Butte S | 15000 | 12000 | Glancy (1968) |
| 178 | Butte N | 3900 | 8700 | Glancy (1968) |
| 179 | Steptoe | 85000 | 70000 | Eakin *et al.* (1967) |
| 183 | Lake | 13000 | 11500 | Rush and Eakin (1963) |
| 184 | Spring | 75000 | 74000 | Rush and Kazmi (1965) |

*Harrill *et al.* (1988).

mixing-cell flow model [11], numerical ground-water flow models [3], and infiltration model [1].

Because most of these estimates were obtained using models, this group of estimates is referred to as the "model estimates." The 27 model estimates are listed in Table 3, and Figure 4 shows their locations. The types of model estimates are discussed briefly below.

The 12 chloride mass balance estimates of recharge were reported in two publications (Dettinger, 1989; Thomas *et al.*, 1989). In the study by Dettinger, a total of 16 estimates were derived. However, only 11 of the estimates were used in this analysis. The estimates in three basins (North Butte, Mesquite, and North Railroad Valleys) were excluded based on the discussion of their recharge estimates by Dettinger (1989). Dettinger noted that the chloride balance estimates in these basins may be inaccurate because subsurface inflows that were not considered may have resulted in an underestimate of recharge. Therefore, these three estimates were rejected. An additional estimate (Independence Valley) was rejected because there was no documented Maxey-Eakin recharge estimate with which to compare it. Finally, one of the estimates (Upper Reese River Valley) was rejected because the corresponding Maxey-Eakin recharge estimate was computed in a non-standard way. In addition to the 11 estimates by Dettinger (1989), one chloride mass balance estimate was obtained for Smith Creek Valley from Thomas *et al.* (1989).

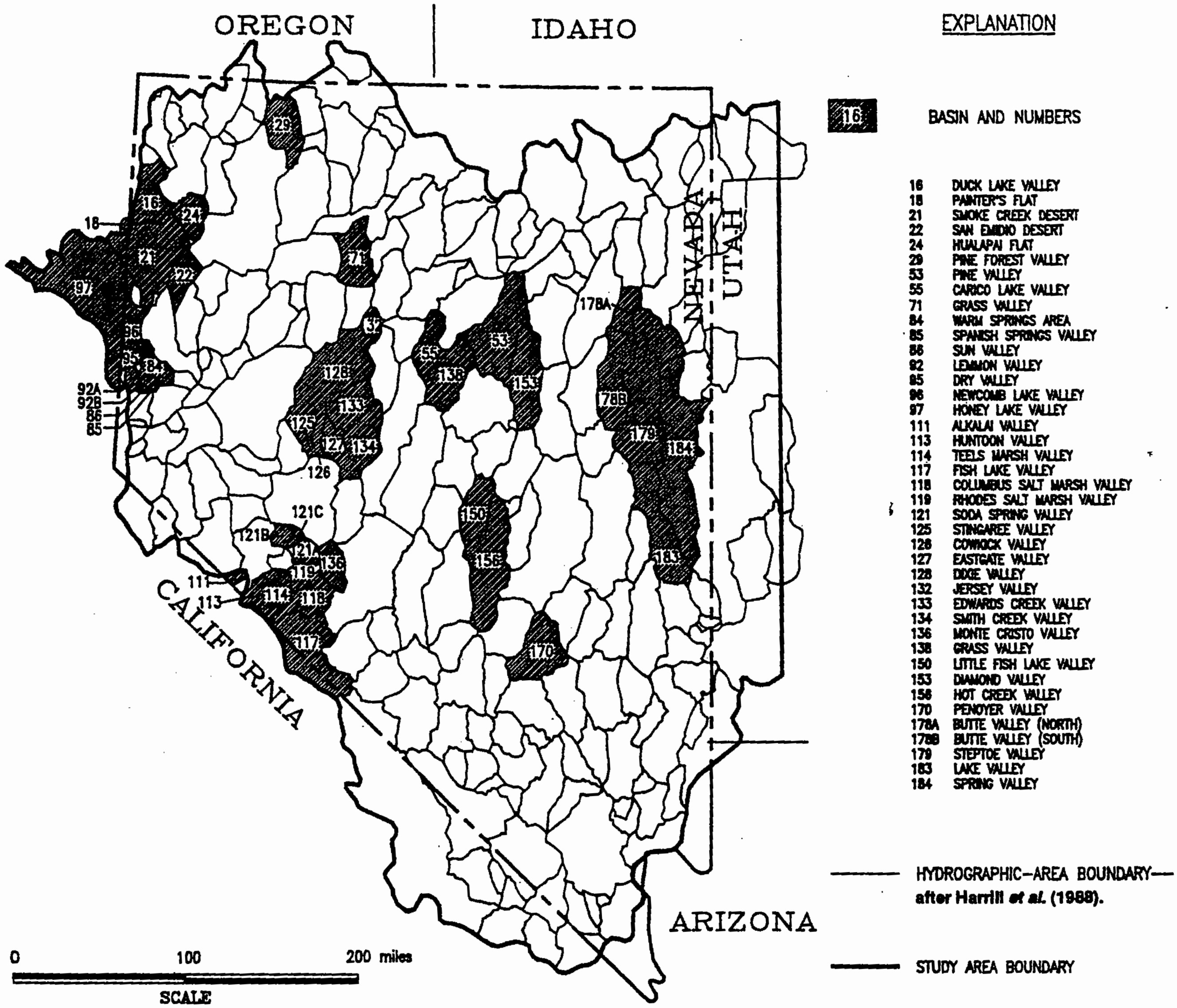


**Figure 3. Location of the 40 Water-Budget Estimates of Recharge.**

Eleven independent estimates of recharge were derived using a deuterium-calibrated mixing-cell flow model of the White River Flow System in southeastern Nevada (Kirk and Campana, 1990). The model consists of an interconnected network of cells through which water and deuterium are routed. A two-layer hydrologic system was modeled, which assumed a carbonate layer underlying an alluvial layer. Assumptions regarding the flow paths were made, and the model was calibrated using the spatial distribution of the deuterium isotope. Three slightly different flow scenarios were calibrated, producing a consistent set of recharge values. For this analysis, where a range of recharge values was reported by Kirk and Campana (1990), the mean recharge from the three scenarios was selected.

Three independent estimates of recharge were obtained from numerical ground-water flow models. The first estimate (Harrill, 1976) was developed by simulating steady-state ground-water flow conditions in Las Vegas Valley. Recharge was one of the parameters varied in the model, along with transmissivity values, in order to match measured hydraulic heads. The second estimate (Harrill, 1986) for Pahrump Valley, was developed in a similar way. The third estimate (Handman *et al.*, 1990) was obtained from a numerical ground-water flow model for a subarea within Honey Lake Valley. The recharge values

TABLE 3. List of the 27 Model Estimates of Recharge.

| Hydrographic Area* | Basin | Maxey-Eakin Recharge (acre-ft/yr) | Model Estimated Recharge (acre-ft/yr) | Type of Estimate | Reference |
|---|---|---|---|---|---|
| 16 | Duck Lake | 9000 | 9000 | chloride balance | Dettinger (1989) |
| 92 | Lemmon | 1800 | 1800 | chloride balance | Dettinger (1989) |
| 97 | Honey Lake Total | 95000 | 99000 | infiltration model | Handman *et al.* (1990) |
| 97 | Honey Lake Subarea | 17000 | 22200 | ground-water flow model | Handman *et al.* (1990) |
| 103B | Stagecoach | 400 | 400 | chloride balance | Dettinger (1989) |
| 117 | Fish Lake | 33000 | 27000 | chloride balance | Dettinger (1989) |
| 122 | Gabbs | 5200 | 5200 | chloride balance | Dettinger (1989) |
| 134 | Smith Creek | 9600 | 8300 | chloride balance | Thomas *et al.* (1989) |
| 153 | Diamond S Subarea | 12000 | 10500 | chloride balance | Dettinger (1989) |
| 162 | Pahrump | 26000 | 37000 | ground-water flow model | Harrill (1986) |
| 170 | Penoyer | 4300 | 3200 | chloride balance | Dettinger (1989) |
| 171-172 | Coal/Garden | 12000 | 11000 | deuterium model | Kirk and Campana (1990) |
| 173 | Railroad S | 5500 | 5000 | chloride balance | Dettinger (1989) |
| 174 | Jakes | 17000 | 20700 | deuterium model | Kirk and Campana (1990) |
| 175 | Long (WRFS) | 10000 | 5000 | deuterium model | Kirk and Campana (1990) |
| 178 | Butte (S) | 15000 | 12000 | chloride balance | Dettinger (1989) |
| 180 | Cave | 14000 | 12000 | deuterium model | Kirk and Campana (1990) |
| 181 | Dry Lake | 5000 | 6700 | deuterium model | Kirk and Campana (1990) |
| 182 | Delamar | 1000 | 1800 | deuterium model | Kirk and Campana (1990) |
| 184 | Spring | 75000 | 62000 | chloride balance | Dettinger (1989) |
| 206 | Kane Springs | 500 | 1000 | deuterium model | Kirk and Campana (1990) |
| 207 | White River | 38000 | 35000 | deuterium model | Kirk and Campana (1990) |
| 208 | Pahroc | 2200 | 2000 | deuterium model | Kirk and Campana (1990) |
| 209 | Pahranagat | 1800 | 1500 | deuterium model | Kirk and Campana 91990) |
| 210 | Coyote Springs | 2100 | 5300 | deuterium model | Kirk and Campana (1990) |
| 212 | Las Vegas N Only | 28000 | 27600 | chloride balance | Dettinger (1989) |
| 212 | Las Vegas | 30000 | 30000 | ground-water flow model | Harrill (1976) |

*Harrill *et al.* (1988).

initially selected for use in this model were derived from an infiltration model, but were adjusted during model calibration.

The study of Honey Lake Valley (Handman *et al.*, 1990) provided a second independent estimate of recharge that was based on the results of an infiltration model. Direct infiltration of precipitation was estimated using a numerical model that determines the soil-moisture budget based on precipitation, temperature, soil characteristics, and vegetative cover. Surface-water infiltration was separately estimated from streamflow data and added to the direct infiltration computed by the model to obtain an estimate of the total ground-water recharge to Honey Lake Valley.

## DISCUSSION OF RESULTS

The screening processes described previously resulted in 40 water-budget estimates of recharge (Figure 3 and Table 2) and 27 model estimates of recharge (Figure 4 and Table 3) for comparison to their corresponding Maxey-Eakin recharge estimates (Tables 2 and 3). In this analysis, the two groups of estimates were compared separately to the Maxey-Eakin estimates to see if any differences in the groups were apparent.

### *Scatter Diagrams*

As a qualitative evaluation of the degree of agreement between the Maxey-Eakin recharge estimates and the two groups of independent estimates, scatter diagrams were prepared. Figures 5 and 6 show the scatter for the groups of 40 water-budget estimates and 27 model estimates of recharge, respectively. A line having a slope of one is shown on both plots for comparison. If the pairs of estimates were in perfect agreement, all of the points would fall on this line. The scatter of the points about the line is a measure of the degree of agreement between the Maxey-Eakin estimates and the independent estimates. From the scatter diagrams, one may conclude qualitatively that the general agreement between the Maxey-Eakin estimates and the independent estimates indicates that the Maxey-Eakin method is fairly good.

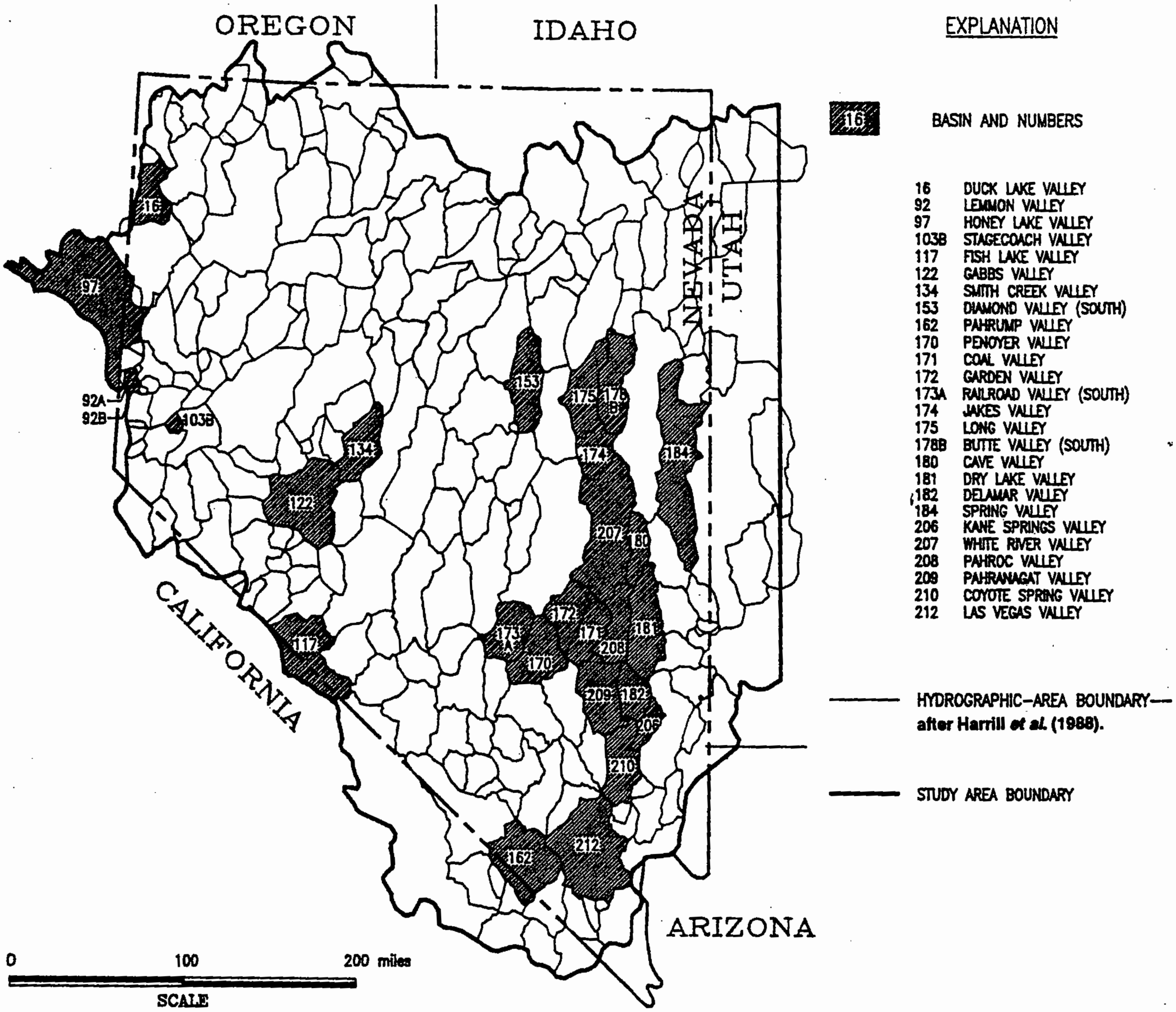


**Figure 4. Location of the 27 Model Estimates of Recharge.**

*Analysis of Uncertainty*

A quantitative analysis can be performed to evaluate the uncertainty in both groups of Maxey-Eakin estimates: the 40 water-budget estimates and the 27 model estimates. Several definitions are necessary for the analysis. For each pair of estimates within a group, the difference between the estimates is the residual $R$, which is given by the relation

$$R = ME - I \tag{2}$$

where $ME$ is the Maxey-Eakin recharge estimate (acre-ft/yr), and $I$ is the independent estimate of recharge (acre-ft/yr).

The variables $ME$ and $I$ can be considered as random variables, each with a probability distribution having an expected value and associated uncertainty: a mean and a variance. Accordingly, the values $ME$ and $I$ can each be broken down into random-variable components

$$ME = ME' + e_{ME} \tag{3}$$

and

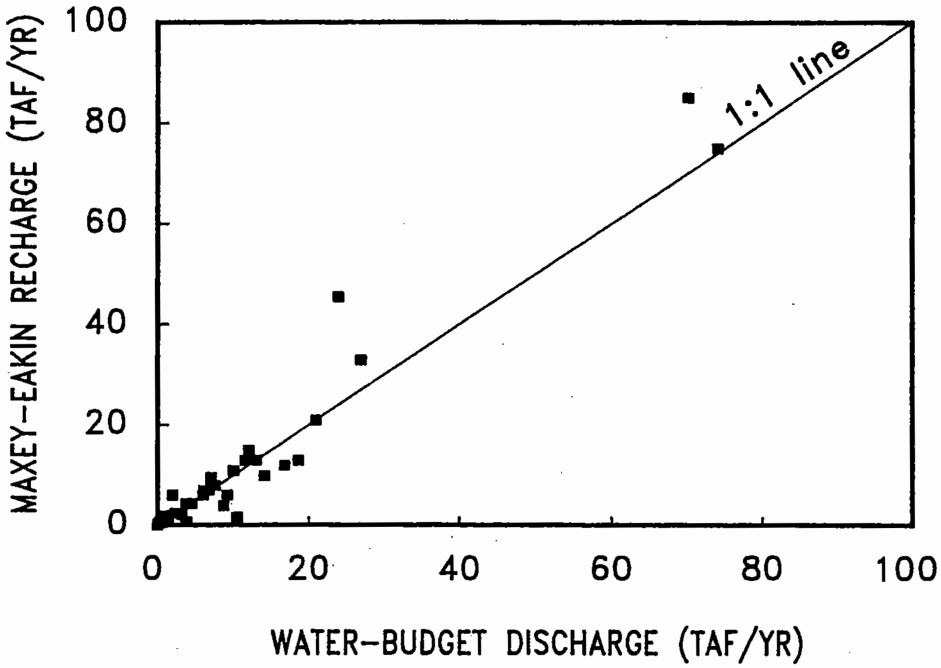


**Figure 5.** Scatter Diagram of Maxey-Eakin Estimates vs. Water-Budget Estimates (40 points), in Thousand Acre-Feet Per Year (TAF/YR).

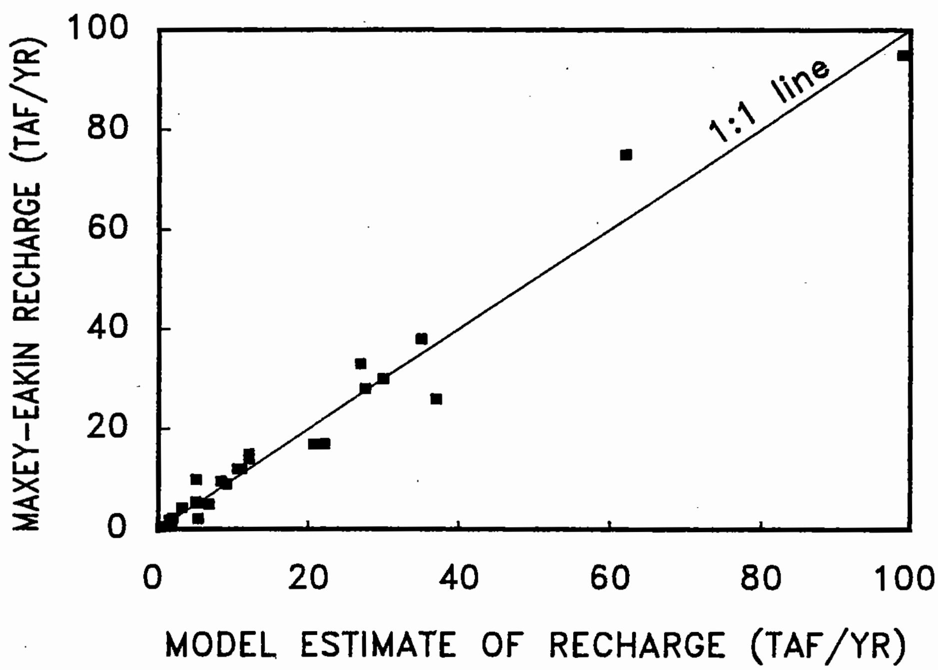


**Figure 6.** Scatter Diagram of Maxey-Eakin Estimates vs. Model Estimates (27 points), in Thousand Acre-Feet Per Year (TAF/YR).

$$I = I' + e_I \tag{4}$$

where $ME'$ is the true value for the Maxey-Eakin recharge, $I'$ is the true value for the independent estimate of recharge, $e_{ME}$ is the error in the Maxey-Eakin recharge estimate, and $e_I$ is the error in the independent estimate of recharge. However, by definition,

$$ME' = I' \tag{5}$$

Therefore, substituting Equations (2), (3), and (4) into Equation (5) above gives the expression:

$$R = e_{ME} - e_I \tag{6}$$

The degree of uncertainty in the Maxey-Eakin method can be evaluated by determining the structure of the random variable $e_{ME}$: the variance or the standard deviation of the distribution. The appropriate formula for the variance of a function of the form $y = g(x_n)$ is as follows (Benjamin and Cornell, 1970):

$$Var[y] = \sum_{i=1}^{n} \left[\frac{\partial g}{\partial x_i}\right]^2 Var[x_i] \tag{7}$$

where it is assumed that the $x_i$ are not correlated. Applying this relation to Equation (6) produces the relation

$$Var[R] = Var[e_{ME}] + \mathrm{Var}[e_I] \tag{8}$$

Finally, rearranging gives

$$Var[e_{ME}] = Var[R] - \mathrm{Var}[e_I] \tag{9}$$

This relationship gives the variance in the Maxey-Eakin errors as a function of the variance in the residuals and the variance in the independent-estimate errors. The term $Var[R]$ can be computed directly from the residuals. However, the term $Var[e_I]$ is not known. Therefore, the known value of $Var[R]$ will provide an upper bound on the value of $Var[e_{ME}]$, since Equation (9) dictates that

$$Var[e_{ME}] \le Var[R] \tag{10}$$

Because it has the same units as the estimate, the standard deviation is a more convenient measure of uncertainty than the variance. The above relation can be expressed in terms of standard deviations by taking the square root of both sides, giving

$$\sigma[e_{ME}] \le \sigma[R] \tag{11}$$

The relation expressed by Equation (11) can now be applied to both groups of estimates: the 40 water-budget estimates and the 27 model estimates. As calculated from the 40 water-budget residuals, $\sigma[R]$ is 4,800 acre-ft/yr. Therefore, as an upper bound on $\sigma[e_{ME}]$, the standard deviation of the Maxey-Eakin estimate for a particular ground-water basin in this group is 4,800 acre-ft/yr. For the group of 27 estimates, the upper bound on the standard deviation of the Maxey-Eakin estimate is 4,100 acre-ft/yr.

The coefficient of variation $c_v$, which gives a measure of the relative dispersion or closeness of the set of values, can be computed from the relation

$$c_v = \frac{\sigma}{\mu} \tag{12}$$

where $\sigma$ is the standard deviation of the distribution, and $\mu$ is the mean of the distribution. For the group of 40 estimates, the maximum standard deviation of 4,800 acre-ft/yr is divided by the mean Maxey-Eakin estimate, which is 10,800 acre-ft/yr, to obtain a coefficient of variation no greater than 0.44, or 44 percent. For the group of 27 estimates, the maximum standard deviation of 4,100 acre-ft/yr is divided by the mean Maxey-Eakin estimate, which is 17,400 acre-ft/yr, to produce a coefficient of variation no greater than 0.24, or 24 percent.

The results of this uncertainty analysis indicate that the degree of uncertainty in a Maxey-Eakin estimate is somewhat less for the group of model estimates than for the group of water-budget estimates. As the model estimates were generally derived later in time than the water-budget estimates and presumably utilized previous knowledge about a basin, this result is not surprising. Furthermore, because model calibration is typically an iterative process, the expected end result is a better equilibrated system; hence, producing a smaller variability of recharge estimates.

### *Comparison to Previous Work*

A previous evaluation of the Maxey-Eakin method was performed by Watson *et al.* (1976), with the objective of examining the statistical validity of the method. In that analysis, a multiple-linear regression was performed to compute the five Maxey-Eakin coefficients based on data from the *Ground-Water Resources Reconnaissance Series.* The regression was of the form

$$Y = \sum_{i=1}^{5} a_i P_i \tag{13}$$

where $Y$ is the water-budget discharge (dependent variable), $P_i$ is the volume of precipitation within each Hardman zone (independent variable), and $a_i$ is the Maxey-Eakin coefficient for each Hardman zone (regression coefficient). The regression was computed by Watson *et al.* (1976) using 63 observations that were collected by screening the *Ground-Water Resources Reconnaissance Series* according to a set of criteria similar to that used in this study.

The results of the analysis by Watson *et al.* (1976) were reported as the computed Maxey-Eakin coefficients and their corresponding 95 percent confidence intervals. Because the 95 percent confidence intervals for the five coefficients were relatively large, they concluded that the predictive capability of the Maxey-Eakin method is suspect.

Based on these conclusions, other authors have dismissed the reliability of the Maxey-Eakin method. For example, Lerner *et al.* (1990) cite Watson's study as an illustration of the low accuracy of simple precipitation-recharge relations. Lerner *et al.* (1990) conclude that the wide confidence intervals make the coefficients unusable for prediction, despite being derived from a large, carefully assembled database. Burbey and Prudic (1991) also reference the Watson study, noting the conclusion that "the method could not reliably predict recharge other than provide an approximation."

However, it may not be appropriate to draw conclusions about the overall reliability of the Maxey-Eakin method based on the individual confidence intervals for each coefficient. What is most important is the overall predictive reliability of the Maxey-Eakin method when compared with independent estimates of recharge. This predictive reliability is only indirectly related to the confidence intervals for the individual Maxey-Eakin coefficients. Rather, the predictive reliability is measured by the standard error of prediction of the regression, which is nearly equivalent to the standard deviation of the residuals. Therefore, the overall predictive reliability of the Maxey-Eakin method can best be evaluated by the type of uncertainty analysis presented here.

In addition to the difference in analytical approach, the current study is distinguished from Watson *et al.* (1976) by an expanded and improved data base. In order to separate the effects of the two differences, the technique used by Watson *et al.* (1976) was applied to the current data set. A multiple-linear regression of the form used by Watson *et al.* (1976) was performed using the group of 40 water-budget estimates identified in this study. The results of this regression are compared to the results obtained by Watson *et al.* (1976) in Table 4.

TABLE 4. Results of Multiple-Linear Regressions.

| Precipitation Zone (in.) | Maxey-Eakin Coefficients (percent) | | 95 Percent Confidence Intervals (percent) | |
|---|---|---|---|---|
| | Watson *et al.* (1976)* | This Analysis** | Watson *et al.* (1976) | This Analysis |
| > 20 | 24 | 20.3 | ±15 | ±10.4 |
| 15-20 | 19 | 20.4 | ±16 | ±10.0 |
| 12-15 | –1 | –3.5 | ±6 | ±5.5 |
| 8-12 | 4 | 6.7 | ±2 | ±2.5 |
| < 8 | 0 | 1.1 | ±1 | ±1.4 |

*63 observations.
**40 observations.

Table 4 shows that, for three of the five precipitation zones, the approximate 95 percent confidence intervals computed in this analysis are smaller than those by Watson *et al.* (1976). This indicates less variability in those Maxey-Eakin coefficients, which suggests that the data base of 40 observations used in this analysis is somewhat better than the data base used by Watson *et al.* (1976). Despite these improvements, however, it appears that the final conclusion reached by Watson *et al.* (1976) would not have changed if the current data base had been available. This is because both analyses generally indicate high variability of the Maxey-Eakin coefficients as computed by regression.

The approach used in the current analysis suggests that the Maxey-Eakin method provides estimates of recharge that are generally in good agreement with independent estimates. This conclusion contradicts that of Watson *et al.* (1976) because the two analyses have used different statistical indicators as a measure of predictive reliability. The methods used in this report are more appropriate to evaluate the total uncertainty in the Maxey-Eakin method. The predictive reliability of the Maxey-Eakin method should not be judged by the standard error of the individual coefficients as computed by regression.

## CONCLUSIONS

Based on the findings from this analysis of the Maxey-Eakin method, the conclusions of this study are:

1. The Maxey-Eakin method provides fairly reliable estimates of recharge to ground-water basins in Nevada;
2. Using a group of 40 independent estimates of recharge obtained from water budgets, an analysis of the uncertainty in the method indicates that the standard deviation of a Maxey-Eakin estimate for a given ground-water basin is not more than 4,800 acre-ft/yr, with a maximum coefficient of variation of 44 percent; and
3. Using a group of 27 independent estimates of recharge obtained from models, the uncertainty analysis indicates that the standard deviation of a Maxey-Eakin estimate for a given ground-water basin is not more than 4,100 acre-ft/yr, with a maximum coefficient of variation of 24 percent.

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