



# Development and evaluation of the Maxey-Eakin recharge method

Daniel B. Stephens<sup>1</sup> · Todd Umstot<sup>1</sup>

Received: 6 April 2018 / Accepted: 17 October 2018 / Published online: 3 November 2018  
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

## Abstract

The Maxey-Eakin method affords a convenient means to estimate natural groundwater recharge and has been widely applied to desert basins in the Southwestern United States. The method relies simply on recharge percentages applied to volumes of precipitation within a basin, with recharge percentage increasing with precipitation. It has been presumed that the method was developed for closed desert basins, where recharge equals natural discharge. The recharge coefficients were derived through a trial-and-error process using an annual precipitation map of Nevada dated 1936, applied to natural discharge by phreatophytes in 13 valleys in Nevada. Details of the derivation have not been published and have not been reproduced by anyone. The identity of the valleys used in the derivation cannot be confirmed. The 1936 precipitation data likely underestimated the mean annual precipitation, and field measurements indicate that the estimates of natural discharge by phreatophytes were also underestimated. Nevertheless, the method has been extensively utilized, even outside Nevada, apparently with good results. The wide applicability of the recharge coefficients may be attributed more to the excellent professional judgment of the developers than to the trial-and-error process that relied on phreatophyte uptake and the 1936 precipitation map of Nevada.

**Keywords** Groundwater development · Groundwater management · Groundwater recharge/water budget · Water supply · USA

## Introduction

The Maxey-Eakin method (Maxey and Eakin 1949) is the most widely used method to estimate groundwater recharge in the Great Basin of the United States (D’Agnese et al. 1997). In Nevada, for example, previous studies of recharge to the 256 hydrographic basins applied the Maxey-Eakin method 221 times (Lopes and Evetts 2004). The Maxey-Eakin equation is popular because of its simplicity and its reliance only on annual average precipitation data. The percent of precipitation that becomes recharge is a coefficient,  $\beta$ , whose value depends only on the long-term average annual precipitation:

$$R = \sum_{i=1}^N \beta_i \cdot \bar{P}_i \cdot A_i \quad (1)$$

where  $R$  is recharge ( $L^3 T^{-1}$ ),  $N$  ( $\leq 5$ ) is the number of precipitation zones,  $A_i$  is the plan view area of the precipitation zone,  $\bar{P}$  is the average long-term precipitation within the zone, as

indicated in Table 1.  $\beta$  has also been referred to as a recharge coefficient, recharge efficiency, and recharge percentage.

Essentially, to compute recharge for a groundwater basin, one simply quantifies the plan-view area within each of the precipitation zones in Table 1, and then multiplies this area by (a) the average annual precipitation in the zone and (b) the corresponding recharge coefficient. The total recharge for a basin is then computed stepwise from the sum of the recharge values for each precipitation zone.

The purpose of this report is to develop a thorough understanding of the development and technical bases for the Maxey-Eakin method, which was developed over 65 years ago. While there have been prior critical evaluations of the reliability of the Maxey-Eakin method (e.g., Watson et al. 1976; Avon and Durbin 1994; D’Agnese et al. 1997; Berger et al. 2008) and improvements on the calculation approach (Wilson and Guan 2004), many details about the derivation of the Maxey-Eakin method have not previously been brought to the general attention of practitioners, although the publication by the Southern Nevada Water Authority (Donovan et al. 2009) is an excellent detailed reference on the development of the Maxey-Eakin method. Even fairly recently, updates to the Maxey-Eakin approach to compute recharge continue to be developed using some of the same basic data believed to have been used to derive the original Maxey-Eakin equations (e.g., Epstein et al. 2010).

✉ Daniel B. Stephens  
dan.stephens@dbstephens.com

<sup>1</sup> Daniel B. Stephens & Associates, Inc, 6020 Academy Road NE, Suite 100, Albuquerque, NM 87109, USA

**Table 1** Maxey-Eakin recharge coefficients

Precipitation zone in inches (in cm)	Recharge coefficient, $\beta$
<8 (<20.32 cm)	0
8–12 (20.32–30.48 cm)	0.03
12–15 (30.48–38.1 cm)	0.07
15–20 (38.1–50.8 cm)	0.15
>20 (>50.8 cm)	0.25

This article first presents the published original description of the methodology, followed by a reconstruction of the steps that may have led to the method, including identification of the original basins, as well as the groundwater discharge and precipitation data for those original basins.

## Method description

The first publication of the Maxey-Eakin method was in 1949 in Bulletin 8 of the Nevada Department of Water Resources. This publication was a reconnaissance-level report prepared by the US Geological Survey (USGS) in cooperation with the Nevada Office of the State Engineer on the groundwater resources in the White River Valley in east-central Nevada (Maxey and Eakin 1949). In the section of that report dealing with recharge, the first published description of the methodology appears:

“The average annual amount of recharge to ground water in White River Valley can be estimated from the precipitation and from the results of recharge studies in comparable areas. This requires a determination or estimate of the average annual precipitation for the drainage area, from which the recharge is calculated as a percentage. An estimate for the precipitation in the White River Valley was made from a precipitation map (footnoted to Hardman 1936) for the state of Nevada in which zones of average range of precipitation are designated. The zones are divided into the following ranges: less than 8 inches (<20.32 cm), 8 to 12 inches (20.32–30.48 cm), 12 to 15 inches (30.48–38.1 cm), 15 to 20 inches (38.1–50.8 cm) and over 20 inches (>50.8 cm). The amount of water from the successive zones that reaches the ground-water reservoir is estimated as 0, 3, 7, 15, and 25 percent of precipitation in the respective zones. The percentages are adapted for this area from preliminary recharge studies in east-central Nevada. These studies consisted of estimating the ground-water discharge by natural losses from 13 valleys in east-central Nevada. The recharge from each valley was also estimated, using the rainfall-zone map as a basis. The recharge estimates were then balanced by trial-and-error with the discharge estimates.”

Additional perspective behind development of the Maxey-Eakin method is revealed in unpublished notes by Jim Harrill (US Geological Survey, unpublished data, 2007; hereafter referred to as “J. Harrill, unpublished data, 2007”) of a conversation he had with Tom Eakin in February 2007. According to Tom Eakin, the Maxey-Eakin method was developed in the 1940s as a reconnaissance tool to provide a rapid and consistent means of assessing water availability for potential power requirements in Nevada (J. Harrill, unpublished data, 2007). It was understood then that recharge in a basin depended on precipitation, much of which was concentrated in the mountain ranges, and that some fraction of the precipitation became recharge. It was assumed that the lower bound of zero recharge occurred where precipitation averages less than 8 in (20.32 cm) per year. Tom Eakin recalled that the bottom of the lower recharge zone approximated the break in slope of the mountain mass and the alluvial apron that surrounded the valley floor (J. Harrill, unpublished data, 2007).

To constrain the prediction of recharge from precipitation, Eakin explained that the authors desired to incorporate some basic information about the hydrogeologic system that could be quantified—namely, the groundwater discharge (J. Harrill, unpublished data, 2007). Over the long-term in a natural system, the rates of recharge and discharge are in dynamic equilibrium where the rates are about equal. Therefore, knowing the long-term natural discharge in a natural system gives an independent check on the estimate of recharge. In Nevada during development of the Maxey-Eakin method, many basins had little to no groundwater pumping and were in a long-term natural state. Further, many of these basins were assumed to be closed basins where there was no significant groundwater underflow into or out of the basin and the only sources of groundwater discharge were springs, evaporation from groundwater beneath playas, and water uptake by phreatophyte vegetation in the vicinity of the playa. In a closed basin, all of these natural discharge sources are expressed at the land surface and the quantity of natural discharge can be estimated by mapping the area of the playa and the phreatophyte vegetation and applying relatively well-known rates of evapotranspiration. Assuming recharge and natural discharge were equal, these rates of natural discharge were then used in development of the Maxey-Eakin method.

From Water Resources Bulletin 8 (Maxey and Eakin 1949) and Bulletin 12 (Eakin et al. 1951 and reports therein), both authors considered their method to be an estimator of recharge suitable for a reconnaissance-level analysis. They also believed that their model could be a better predictor of recharge for a particular basin if these recharge coefficients could be adjusted in accord with the authors’ observations and confidence in the available data such as precipitation, water-table depth, drainage, and evapotranspiration. In applying their method, for example in Goshute-Antelope Valleys, Eakin et al. (1949) changed the recharge coefficient associated with the 8–12 in (20.32–30.48 cm) precipitation zone in Hardman’s 1936 map from 3 to 1%. In Clover and Independence Valleys, the area of the 8–12 in

(20.32–30.48 cm) precipitation zone on the Hardman map was trimmed by 40% (Eakin and Maxey 1951b). In Ruby Valley, the 5–8 in (12.7–20.32 cm) precipitation zone, where recharge had been considered nil, was included with the area of the 8–12 in (20.32–30.48 cm) precipitation zone because they believed it to “more approximate the local conditions” (Eakin and Maxey 1951a; p. 81). Obviously, professional judgement played an important role in calculating recharge for specific basins.

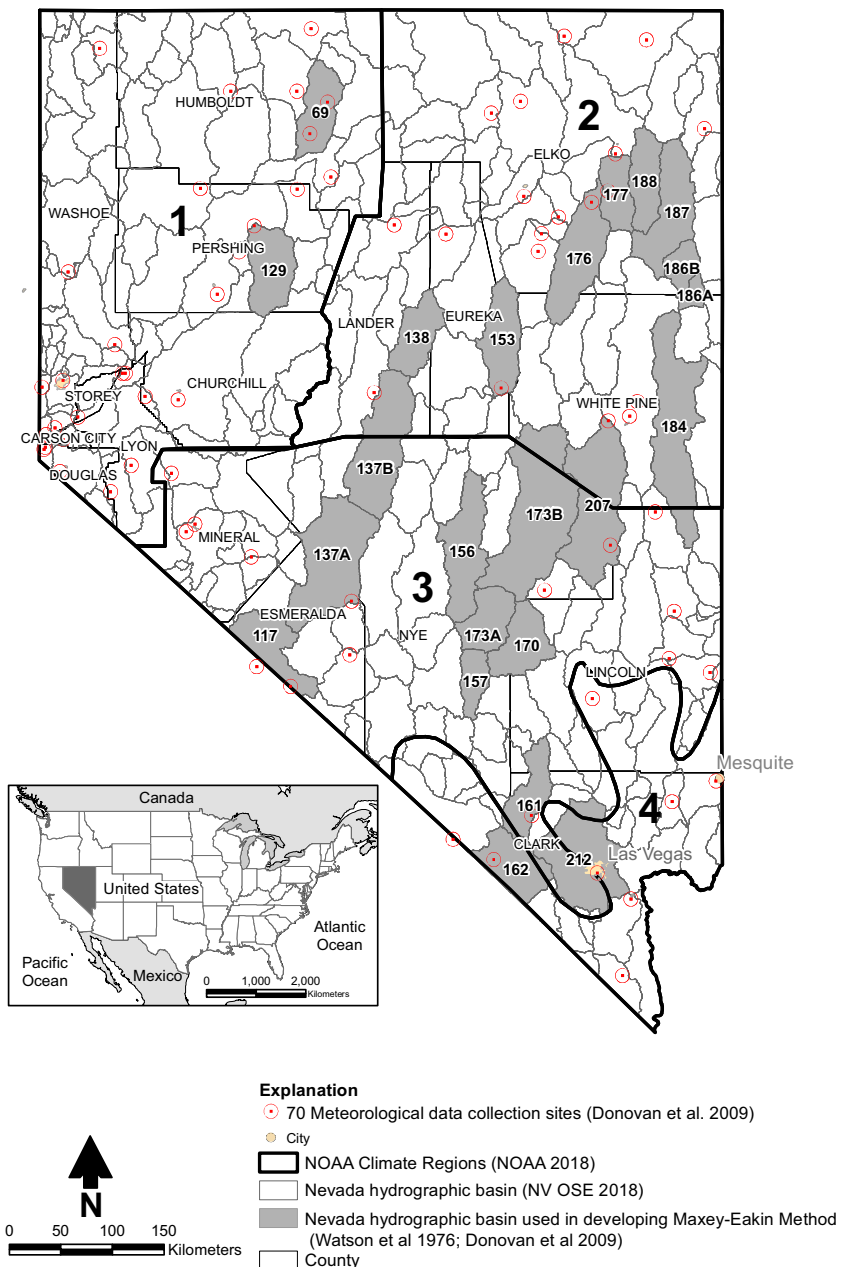
### The Maxey-Eakin groundwater basins

The early groundwater reports were reviewed to determine if development of the Maxey-Eakin method could be reproduced.

The first question to be addressed: What basins did Maxey and Eakin rely on to derive their trial and error based approach?

There are conflicting reports on the number of basins used in their derivation. Most of the reconnaissance reports of the early 1950s (e.g., bulletins 8 and 12) refer to 13 basins, but nowhere were these identified. In contradiction to this reference to 13 basins, Maxey and Eakin (1950, p. 151) also report in Bulletin 12 that there were 15 valleys in east-central Nevada used to develop the method, but these were not identified either. Berger et al. (2008) stated that 19 Hydrologic Areas of Nevada (HAs) were used in the original Maxey-Eakin method development, but they did not identify these basins. Watson et al. (1976, p. 340) reported that Dr. Maxey identified 21 basins that were considered for the derivation (Fig. 1). The 21 valleys

**Fig. 1** Locations of hydrographic basins in Nevada (USA) used in developing the Maxey-Eakin method



**Table 2** Identity of original valleys used to derive recharge coefficients

Hydrologic basin No.	Original Maxey-Eakin Valley					
	Valley	Watson et al. (1976)	Donovan et al. (2009)	Nichols (2000)	Field work prior to 1949?	Natural discharge computed in bulletins?
69	Paradise	✓ <sup>a</sup>	✓ <sup>b</sup>	–	✓	✓
117	Fish Lake	✓ <sup>a</sup>	✓ <sup>b</sup>	–	–	✓ <sup>c</sup>
129	Buena Vista	✓ <sup>a</sup>	✓ <sup>b</sup>	–	✓	✓
137B	Big Smoky (N.) <sup>d</sup>	✓ <sup>a</sup>	✓ <sup>b</sup>	–	–	✓ <sup>c</sup>
138	Grass	✓ <sup>a</sup>	✓ <sup>b</sup>	–	✓	✓
153	Diamond	✓ <sup>a</sup>	✓ <sup>b</sup>	✓	–	✓
156	Hot Creek	✓ <sup>a</sup>	✓ <sup>b</sup>	✓	✓	–
157	Kawich	✓	✓	✓	✓	✓
161	Indian Spring	✓	✓	–	✓	–
162	Pahrump	✓	✓	–	✓	–
170	Penoyer	✓	✓	✓	✓	✓
173A	Reveille	✓	✓	✓	✓	–
173B	Railroad	✓	✓	✓	✓	✓
176	Ruby	✓	✓	✓	✓	✓
177	Clover	✓ <sup>a</sup>	✓ <sup>b</sup>	✓	✓	✓
184	Spring	✓ <sup>a</sup>	✓	✓	–	✓ <sup>c</sup>
186	Antelope N.	✓	✓	✓	✓	–
187	Goshute	✓	✓	✓	✓	✓
188	Independence	✓	✓	✓	✓	✓
207	White River	✓	✓	✓	✓	✓
212	Las Vegas	✓	✓	–	✓	–
Total		21	21	13	17	15

<sup>a</sup>G.B. Maxey, University of Nevada, Reno, personal communication, 1974

<sup>b</sup>Additional valleys not referenced by Maxey and Eakin but referenced by Maxey

<sup>c</sup>Discharge computed post 1948/1949

<sup>d</sup>Bulletin 41 (Rush and Schroer 1971) refers to discharge in the Robinson (1953) Big Smoky Valley report, but could not verify dates of field work

included 12 valleys described in bulletins 6, 8, and 12, as well as 9 others that were used in the derivation of the recharge coefficients (Table 2). (It appears that Watson et al. have errors in the footnotes to their Table 2 for Clover and Hot Creek; the footnote for these valleys should have been a ‘c,’ as they are included in Bulletin 12. This change would give them 14 valleys from the early bulletins.) Donovan et al. (2009) also identified 21 valleys, but they indicated that Spring Valley comprised one of the ‘original’ 13 (Table 2). (Actually, the determination by Donovan et al. (Donovan et al. 2009, their Table 3) that Spring Valley was referenced by Maxey and Eakin in the bulletins appears to be an error.) Nichols (2000, p. C10) also identified 13 ‘original’ valleys, but these were different than those of Donovan. To further confound and contradict the aforementioned recollections and interpretations, several decades after their initial work, Eakin recalled that there were only 12 valleys used in the initial study, and that these were in central and northern Nevada; however, none were specifically identified (J. Harrill, unpublished data, 2007).

Two approaches were taken to sort through this confusion and attempt to independently verify the basins that could have

**Table 3** Comparison of estimated natural discharge by groundwater evapotranspiration (modified from Nichols 2000, Table C7)

Valley	Acre-feet per year (million m <sup>3</sup> /year)	
	Bulletin 12 (1951)	Nichols (2000)
Antelope	100 (0.12)	4,000 (4.93)
Clover	19,900 (24.55)	84,500 (104.23)
Goshute	10,075 (12.43)	42,500 (52.42)
Hot Creek	4,600 (5.67)	5,000 (6.17)
Independence	9,500 (11.72)	47,000 (57.97)
Railroad (northern part)	80,000 (98.68)	85,000 (104.85)
Ruby	67,600 (83.38)	167,000 (205.99)
Hot Creek	4,600 (5.67)	5,000 (6.17)
Total	196,375 (242.22)	444,000 (547.67)

been used to develop the Maxey-Eakin method. The first approach considers the reports that Maxey and Eakin individually or together authored, and for which field work was completed prior to publication of Bulletin 8. The second approach considers the valleys where natural discharge estimates were published prior to publication of Bulletin 8.

### Field investigations prior to publication of Bulletin 8

The studies to evaluate Nevada's groundwater resources were authorized under a joint agreement between the State Engineer of Nevada and the USGS starting in 1944. It appears that as many as 80 valleys were investigated by the late 1940s. The studies for valleys near Las Vegas, with field work from 1944 to 1946, were among the first to be published as a series of Nevada Water Resources bulletins. In 1947, George Burke Maxey was coauthor of Bulletin 6 (Maxey and Robinson 1947), which summarized groundwater in Las Vegas, Indian Springs, and Pahrump valleys. There is no indication that Eakin worked on the studies for the three valleys near Las Vegas. Maxey's coauthor for the Las Vegas work was his supervisor, Thomas W. Robinson, District Engineer for the USGS.

Maxey and Robinson recognized the orographic effect on precipitation and assumed that higher precipitation led to increased recharge. For example, in the Las Vegas, Pahrump, and Indian Springs studies (Bulletin 6), the recharge percentages were set as 0 % where precipitation was less than 10 in (25.4 cm) or below 6,000 ft. (1,830 m) elevation, 20% from 6,000 to 8,000 ft (1,830–2,440 m), and 25% above 8,000 ft (2,440 m). The 25% estimate would be the same value estimated by USGS colleagues Fiedler and Nye (1933) for the mountains near Ruidoso, New Mexico.

Maxey worked on the studies for many other basins, conducting reconnaissance site visits and collecting field data mostly in the period from 1946 to 1948, before leaving Nevada for graduate study at Princeton University (Thomas and Shamberger 1979). Thus, he came to be coauthor of Bulletin 8 on White River Valley (Maxey and Eakin 1949) and Bulletin 12, a compendium of five reports covering a total of 11 valleys in eastern Nevada. So, in the few years prior to publication of the first application of the Maxey-Eakin method (Bulletin 8) in 1949, Maxey had been working on studies for at least 14 valleys, as they called them: Las Vegas, Pahrump, and Indian Springs (bulletins 5 and 6), White River (Bulletin 8), and Goshute, Antelope, Ruby, Clover, Independence, Railroad, Hot Creek, Reveille, Kawich, and Penoyer (Bulletin 12). Goshute and Antelope valleys were treated as one hydrologic basin by the authors, effectively reducing the total number of valleys analyzed by Maxey to 13, the same number reported in Bulletin 8. However, if the Indian Springs Valley is dropped because there were “insufficient data” to compute discharge, one obtains the 12 valleys referred to by Eakin.

Because one can tally 13 valleys where recharge was computed in the early reconnaissance reports, it is not unreasonable to assume that these in fact were the ‘original’ valleys Maxey and Eakin used to derive the recharge coefficients by a trial and error process. If they were, then one might expect that the computations of recharge for the original valleys described in the bulletins would use the recharge coefficients in Table 1 and show the computed volumes of precipitation obtained at the various zones on the Hardman map. However, in four of the valleys, the authors made significant changes to the precipitation areas or recharge coefficients to account for local conditions, presumably to make the estimates of recharge more reliable—either based on professional judgment or due to more refined computations of groundwater discharge. The fact that such modifications were made provides some evidence that either (1) there was an earlier, preliminary phase where at least some of the precipitation or discharge data were different than those published in the bulletins or (2) basins other than those in the bulletins were used to derive the coefficients.

In fact, as of 20 April 1949, months before Bulletin 8 was published, there had been groundwater investigations in “50 of the 80 odd valleys. . . by the Ground Water Branch of the Geological Survey” (Loeltz et al. 1949, p. 5). Only a small portion of the 50 investigations completed during this time led to publications as bulletins; where are the notes of those other investigations? Eakin (1950) referred to “. . . several mimeographed and typewritten reports completed in arid and semi-arid valleys throughout the state, in addition to the 8 water resources bulletins published by May, 1950.” Some of the mimeographed and typewritten reports may contain clues on the origins of the 13 Maxey-Eakin basins. For example, one of these is likely an unpublished report on Grass Valley (Robinson et al. 1949) that contains Hardman precipitation volumes and natural discharge computations of exactly the type needed for the derivation. Kip Allander (US Geological Survey, personal communication, 2018) indicated that this was intended to be Bulletin 9, but it was not officially released. There is also reference in the White River Valley bulletin (Maxey and Eakin 1949, p. 41) to an analysis of recharge in Jakes Valley, but no other documentation of the Jakes Valley investigation from that time was found. Thus, there is evidence that there were valleys other than those described in the bulletins that potentially could have been among the 13 where “preliminary recharge studies” were conducted, as originally described by Maxey and Eakin (1949).

There is other evidence that perhaps some of the valleys listed by Watson et al. (1976; Table 2) and Donovan et al. (2009) may not have been among the original 13 valleys. In Reveille and Kawich valleys for instance, neither precipitation nor discharge were reported in Bulletin 12 (Maxey and Eakin 1950), so it is doubtful they could have been among the



original valleys. Some of the valleys reported to have been among the Maxey-Eakin originals also were not closed basins because natural evapotranspiration was not the only outflow; these include White River, Fish Lake, and Paradise valleys. White River Valley also had significant recharge flowing in as underflow from the adjacent Jakes Valley. Additionally, the 21 valleys span much of the state (Fig. 1), and do not appear to be limited to “east-central Nevada.” These characteristics are not consistent with the description of the method development by Maxey and Eakin (1949) or the recollections of Tom Eakin (J. Harrill, unpublished data, 2007), providing further evidence that there were other as yet unidentified basins that were included in the derivation.

Furthermore, Las Vegas, Pahrump, and Indian Springs valleys also may not have been among the valleys used in the 13 preliminary studies (Table 1). Maxey and Eakin (1949, pp. 40–41) state:

“The recharge estimates were then balanced by trial-and-error with the discharge estimates. They also compare favorably with percentages determined in Las Vegas Valley by means of precipitation gages maintained at different altitudes.”

One interpretation of this quote suggests that development of the recharge coefficients occurred after the Las Vegas Valley study was completed. There is no indication from the bulletins that the Hardman precipitation map was used or even known to exist at the time of the Las Vegas area studies. Recharge was not computed by the Maxey-Eakin method in the early bulletins on the Las Vegas area valleys. Review of Bulletin 6 also suggests that these three valleys were not among the original 13 valleys because Las Vegas Valley was not in dynamic equilibrium at that time. Thus, if the three Las Vegas area basins were not part of the 13 valleys, that leaves only 10 valleys, unless Goshute-Antelope are separated, giving 11 valleys. Which valleys would make up for these?

Nichols (2000, p. C10) in fact proposed a tally of the 13 original Maxey-Eakin basins (Table 2) that does omit the three Las Vegas area valleys. He then includes two other valleys from east-central Nevada—Diamond and Spring Valley—while counting Goshute and Antelope valleys separately, making 13 valleys.

However, no evidence was found that there was a field investigation under a Nevada-USGS joint agreement in Diamond or Spring Valley in the 1940s, when the Maxey-Eakin method was developed. Likewise, there was no evidence found of field work related to estimating natural discharge in Big Smoky Valley (northern part) at that time (Table 2). These three were among the additional valleys Maxey identified in 1974 (Watson et al. 1976) that were not in the early bulletins.

Due to the poor documentation of the derivation of the method, it is not surprising that there is much confusion on

the number and identities of the valleys Maxey and Eakin may have considered. The number and identities of the basins used to develop the Maxey-Eakin method could not be independently confirmed. The fact that reconnaissance studies were simply published as water resources bulletins and authored by Maxey and/or Eakin, as tallied for example by Watson et al. (Watson et al. 1976, their Table 2) and Donovan et al. (2009), does not appear to be sufficient evidence that these valleys were the ones used in development of the method, as will be discussed further in the following.

### Valleys where natural discharge was computed

This evaluation also tried to identify the ‘original’ groundwater valleys from those where natural discharge was quantified in the reconnaissance publications prior to publication of Bulletin 8. The description of the Maxey-Eakin method in Bulletin 8 specifically refers not just to 13 valleys, but to 13 valleys where natural discharge was quantified. If natural discharge was computed for a valley that was among those where “preliminary recharge studies” were conducted, it seems reasonable that such an important calculation would be included in the bulletin. Actual discharge computations or references to them were found for 10 of the basins described in these early bulletins authored or coauthored by Maxey where reconnaissance work was conducted prior to 1949, including White River, Paradise, Fish Lake, Goshute-Antelope, Ruby, Clover, Independence, Railroad, Hot Creek, and Penoyer valleys (Table 2). If the Spring Valley study by Robinson et al. (1949) is included, there are precipitation data and natural discharge computations for 11 valleys, counting Goshute-Antelope as one valley.

As noted previously, Nichols (2000) also indicated he could account for 11 of the 13 Maxey-Eakin basins, while speculating that the other two valleys were Diamond and Spring valleys. However, his tally of 11 valleys included Reveille and Kawich valleys, for which no discharge data were reported in Bulletin 12. No natural discharge computations appear for Las Vegas, Indian Springs, and Pahrump valleys. Neither these valleys nor Reveille and Kawich valleys were likely among the group of the original 13 valleys (Table 2).

The fact that there was a reconnaissance investigation published as a bulletin by Maxey and/or Eakin (e.g., Maxey and Robinson 1947; Maxey and Eakin 1949; Eakin et al. 1951), as first noted by Watson et al. (1976), is not sufficient evidence that those valleys were used in the trial and error analysis to develop recharge coefficients with the 1936 Hardman precipitation map.

Thus, while at least 13 valleys could be identified where reconnaissance-level studies were ongoing prior to publication of the Maxey-Eakin method, no more than 11 valleys could be identified where discharge computations were published; one of these was not investigated by either Maxey or Eakin, and some of these arguably are not in east-central Nevada (Fig. 1). Perhaps natural discharge was computed and used in

development of the method, but was inexplicably not reported in bulletins. Natural discharge estimates by phreatophytes in closed desert basins would have been relatively easy to conduct at a reconnaissance level, based on evapotranspiration rate estimates from other locations, plant type, area, vegetation density, and water-table depth. Such computations could have been recorded in field notebooks or unpublished “mimeograph and typewritten” Open-File Reps. Nevertheless, it can be concluded that as of 1949, when the Maxey-Eakin method was developed, because the 13 basins where discharge was determined could not be located, that there is no way to reproduce the work as Maxey and Eakin described it.

## Groundwater discharge

The Maxey-Eakin method was reported to be based on 13 valleys where there was a balance of recharge with “discharge by natural losses.” Annual groundwater discharge is a surrogate for the long-term average annual groundwater recharge due to precipitation falling within a closed basin, assuming there is no interbasin flow. It is also assumed that discharge from a groundwater basin, and the discharge determined at the time of the Maxey-Eakin study, is representative of the long-term mean, or dynamic equilibrium condition.

Eakin explained that for the derivation, discharge from the selected basins in central and northern Nevada was determined from the evapotranspiration where there were phreatophytes and where the depth to groundwater was 50 ft (15.24 m) or less (J. Harrill, unpublished data, 2007). Within these areas, they assumed that the net discharge by phreatophytes was 0.1 ft (0.03 m) per year. The product of the basin area where the water table was within 50 ft (15.24 m) and the net evapotranspiration rate gave them the basin discharge—which they equated to basin recharge, assuming that the basin was in dynamic equilibrium. Regarding the preliminary estimate for average evapotranspiration, 0.1 ft/year (0.03 m/year), Eakin explained that they expected that “future detailed and controlled investigations probably would result in values at least as much as the initial estimate and with the hope that could be higher” (J. Harrill, unpublished data, 2007).

In fact, review of the valleys in Bulletin 12 actually shows that phreatophyte evapotranspiration rates were estimated to range from 0.03 to 0.7 ft/year (0.01–0.21 m/year), depending on the type of vegetation (desert shrubs and meadow grasses) and on the depth to groundwater, up to 80 ft (24.38 m). Different evapotranspiration rates were applied in White River Valley (Bulletin 8, p. 44), where Maxey and Eakin believed that native phreatophyte (e.g., salt grass) water consumption was 0.8 ft/year (0.24 m/year) and negligible if the depth to the water table was more than 15 ft (4.572 m). It is possible that ongoing evapotranspiration research was evolving and became known to the authors as they completed their

basin evaluations, leading to the changes in the consumptive use values. Alternatively, subjective factors such as vegetation density affected the estimates of groundwater discharge published in the bulletins. Additionally, the water resources bulletins show that the groundwater discharge also included lake evaporation (where the lake was supplied by surface runoff), spring flows, and groundwater pumping for industrial and agricultural use (Eakin et al. 1951).

The bulletins would then appear to comprise the “future detailed and controlled investigations” that Eakin described in the aforementioned text—that is, the valleys in the bulletins were not necessarily the valleys where “preliminary recharge studies” were conducted, as described originally in Bulletin 8. Eakin’s recollection also suggests that the discharge calculated in the bulletins with phreatophyte evapotranspiration rates other than 0.1 ft/year (0.03 m/year) would therefore not be the same as discharge rates used for deriving the Maxey-Eakin recharge coefficients. As a result, it is not surprising that those who used the discharge rates published in the early bulletins, along with the Hardman 1936 map, have yet to reproduce the recharge coefficients in Table 1.

Regarding the phreatophyte evapotranspiration rates published in the early bulletins, the annual average evapotranspiration rates referenced in the bulletins are based on studies elsewhere in the Great Basin—e.g., in Owens Valley, California (Lee 1912) and in Escalante Valley, Utah (White 1932). The discharge rates are not from detailed studies in the individual valleys of Nevada. Rather, they are estimates based in part on the out-of-state measurements tempered by professional judgment, which considered the effects of water-table depth, vegetation mix, and density. Thus, there could be considerable uncertainty in the volume of discharge computed for the presumed original Maxey-Eakin basins, especially when considering that some of these groundwater discharge areas are on the order of 100,000 acres.

Nichols (2000) evaluated the accuracy of the evapotranspiration rates assumed for the different vegetation types, variable water-table depths, and soil conditions in Nevada basins. He combined LANDSAT imagery and micrometeorological methods to calculate groundwater evapotranspiration in 16 contiguous valleys in eastern Nevada. Of these valleys, eight were among those that have been presumed to be original Maxey-Eakin basins published in Bulletin 12. A comparison of natural groundwater discharge computed from the Nichols study and evapotranspiration estimates from the reconnaissance investigations is provided in Table 3. The agreement ranges from very good to poor. In all cases, however, the Nichols calculations exceed the reconnaissance study estimates, in one case by 40 times. Overall, the Nichols calculations of the total groundwater evapotranspiration from these eight presumed original valleys is roughly twice that published in Bulletin 12. If Maxey and Eakin underestimated the natural discharge in their original basins, then the original

recharge coefficients computed with the 1936 Hardman precipitation map would be biased low.

Also note from the published bulletins that no formal analysis establishing a dynamic equilibrium condition was conducted as a prerequisite for a valley to be included as part of the Maxey-Eakin equation derivation, although water level time-series data for wells were included for many of the valleys studied in the bulletins. There was no indication from the studies published in the bulletins that reductions in discharge due to pumping were explicitly taken into consideration in the analysis of natural, pre-development groundwater discharge. Potentially significant pumping had occurred at least in Las Vegas, Indian Springs, Pahrump, Paradise, and Fish Lake valleys. If natural discharge in a valley was diminished by pumping, and if discharge in those valleys was used in the derivation, then the original Maxey-Eakin recharge coefficients obtained by a “trial and error process” with the Hardman 1936 precipitation map would tend to be biased low.

## Precipitation

The Maxey-Eakin method was originally developed using a precipitation map for the state of Nevada published in 1936 (Hardman 1948). The timing of this publication was critical in the development of the method. It has been argued that, strictly speaking, the only precipitation data to use with the Maxey-Eakin recharge coefficients are those from the Hardman precipitation map from 1936 (Berger et al. 2008); therefore, it is especially important to understand how this precipitation map was developed. To what extent is this map likely representative of long-term average precipitation that could be paired with natural discharge measured by evapotranspiration from closed groundwater basins in the mid- to late 1940s?

The Nevada precipitation map by George Hardman, then Chief of the Department of Irrigation of the Nevada Agricultural Experiment Station in Reno, appears to have been motivated by the great drought of the early 1930s in order to quantify and better manage Nevada’s limited water resources for agricultural development. To develop the map, Hardman relied on the existing US Weather Bureau precipitation records in Nevada. At that time, a number of basins had no precipitation gages. Most available gages in the couple of decades of gaging data prior to about 1930 were located in the valleys in a limited elevation range; therefore, in the higher elevations where recharge was likely most abundant, the precipitation record was fairly poor. Hardman (1948) indicated that state-wide, there were 107 recording precipitation gages, but only about 70 gages from that period were found among the National Climate Data Center daily records (Donovan et al. 2009). According to Hardman (1948), at the time the 1936 map was prepared, only 17 of the 107 recording stations were at elevations between 6,000 and 7,000 ft (1,829 and

2,134 m), and only seven were above 7,000 ft (2,134 m) for the entire state. In some instances where the record was short and represented a drought or wet period, Hardman adjusted the mean precipitation at that location to reflect what he believed was the long-term condition. Figure 1 illustrates the great detail in the 1936 precipitation map compared to the very sparse distribution of the precipitation recording stations.

The additional detail on the precipitation map was obtained from topographic maps and maps of vegetation. To map precipitation at the elevations where data were unavailable, Hardman relied on and extrapolated from the relationship between mean annual precipitation and elevation established by the available records. Hardman also reasoned that vegetation is a good indicator of the long-term precipitation, and there were more state-wide data available for native vegetation than for precipitation. Hardman (1948) wrote:

“In Nevada, certain plant associations occur in fairly close relation to broad zones of precipitation. . . Sagebrush is the aspect vegetation in the 8 to 12 inch (20.32–30.48 cm) precipitation zone. Pinon-juniper seems to be best developed in the zone where the precipitation is about 12 to 15 inches (30.48–38.1 cm) but may extend above and below the zone boundaries . . . Grass and mountain brush become more pronounced on the areas with 15 to 20 inches (38.1–50.8 cm) of moisture. On the areas receiving above 20 inches (50.8 cm) of total precipitation there are grass lands, forests, or alpine vegetation.”

In the basin and range terrain of Nevada, the increased precipitation is typically well correlated with elevation, and significant vegetation changes can occur over short distances in basins with significant relief. Hardman compiled vegetation zone information obtained from the Nevada Agriculture Experiment Station, the US Forest Service, the Intermountain Forest and Range Experiment Station, and the USGS (Hardman 1948). His precipitation map was made to comply as closely as possible with the vegetation zones. These precipitation zones coincided with the zones of various vegetation types he identified: less than 5 in annual precipitation, 5–8 in (12.7–20.32 cm), 8–12 in (20.32–30.28 cm), 12–15 in (30.48–38.1 cm), 15–20 in (38.1–50.8 cm), and over 20 in (50.8 cm). Maxey and Eakin lumped the two lowest precipitation zones together, but otherwise adopted these zones in the development of their recharge coefficients.

Based on the low density of precipitation gages and the subjective techniques employed to map precipitation over an extensive area of diverse terrain, it is clear that locally there is likely considerable uncertainty in the Hardman precipitation map. Nevertheless, in the absence of better data at the reconnaissance level, the use of vegetation as a surrogate for precipitation would seem to be a reasonable approach that actually may be preferable in some instances to relying on short-term precipitation gage records.



While elevation and vegetation data played an integral part in developing the 1936 map, Hardman still incorporated the available precipitation records. Although not all the precipitation data Hardman used to generate his 1936 map are known, the general climatic conditions are examined to assess whether there may have been a bias in the precipitation data available to him, which was primarily from about 1915 to 1930 (Jeton et al. 2005). The Palmer Drought Severity Index (PDSI; NOAA 2016) in Fig. 2 shows that a period of considerable drought occurred from 1924 to 1936 in the south-central portion of Nevada, which includes many of the Maxey-Eakin basins.

Figure 3 shows the Hardman precipitation maps and precipitation maps generated for later periods, 1961–1990 and 1971–2000, predicted using the model PRISM (Parameter-elevation Regressions on Independent Slopes Model); PRISM Group, Northwest Alliance for Computational Science and Engineering, Oregon State University (PRISM) (2018). In this figure, the Hardman maps generally show lower precipitation compared with PRISM maps for later years. The 1961–1990 period was found to be most representative for long-term analyses and best-fit measured data collected by the National Weather Service (Jeton et al. 2005), but some of the precipitation stations used in PRISM may have been mislocated (Donovan et al. 2009).

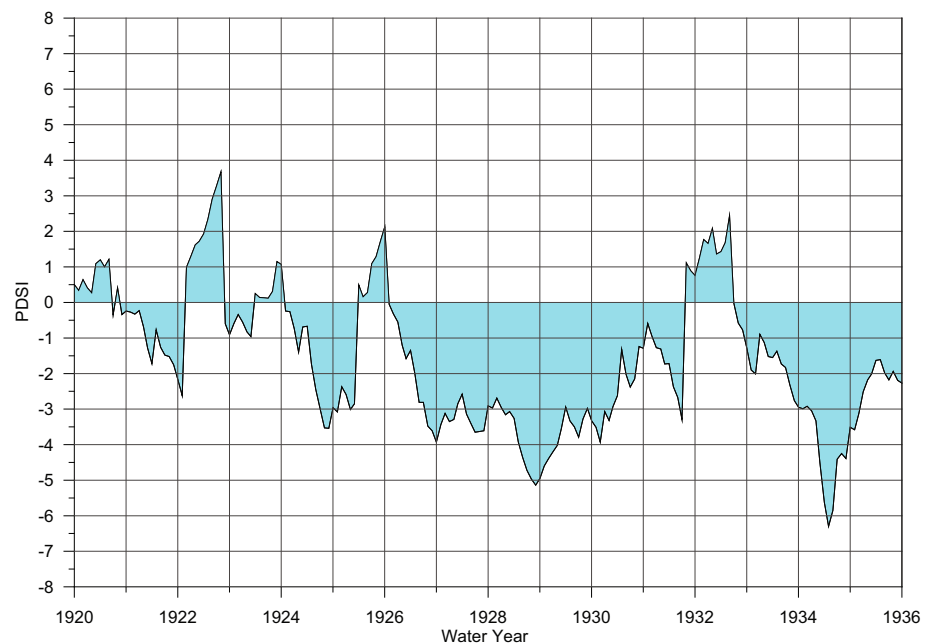
For the 21 ‘original’ basins considered by Watson et al. (1976), the total volume of precipitation above the 8 in/year (20.32 cm/year) contour based on PRISM (1961–1990) is 7% greater than the volume obtained from the Hardman 1936 map and 4% greater than the precipitation volume obtained using the Hardman 1965 map. However, PRISM (1971–2000) precipitation volumes were 25–20% greater than the Hardman 1936 and 1965 maps, respectively (DBS&A 2008a).

The measured precipitation data suggest that the recharge coefficients derived by Maxey and Eakin were likely based on a period of record that was drier than normal, although the vegetation data likely compensated for this to some degree. The implication is that if Maxey and Eakin had available precipitation from a wetter period to pair with natural discharge in the valleys, their recharge coefficients would have been somewhat smaller. Likewise, if precipitation data other than Hardman’s 1936 map, including Hardman’s 1965 map in Fig. 3 (Hardman 1965), were used with the original Maxey-Eakin coefficients, the predicted recharge volume might be somewhat overestimated, as noted by Berger et al. (2008).

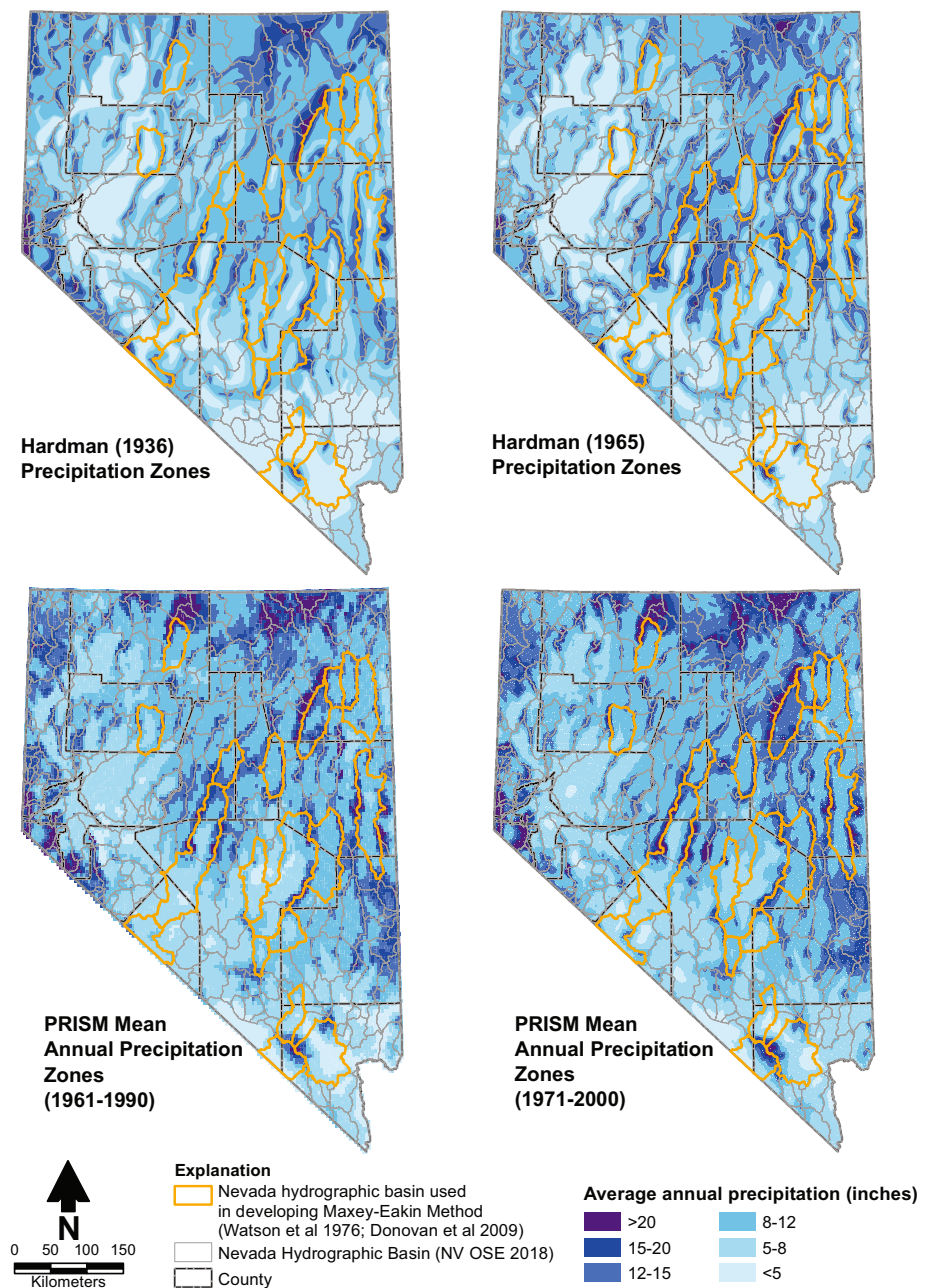
Within a valley, the area of the precipitation zone in the Hardman 1936 map is also important to evaluate. Significant differences were found between the original determination by planimeter of the precipitation zone areas used by Maxey and Eakin to determine recharge volumes and the same areas obtained by GIS estimates (up to 400%). For the 21 basins listed by Watson et al. (1976), GIS software was used to recalculate the areas within each of the elevation zones in the Hardman 1936 precipitation map. The precipitation zone areas were corrected and then recharge was recalculated using the original Maxey-Eakin coefficients (Table 4).

Maxey and Eakin noted where there was a “lack of agreement in the recharge and discharge estimates for any one valley.. .” this “. . . probably results primarily from insufficient detailed control for the precipitation map” (Eakin et al. 1949). D’Agnese et al. (1997) also concluded that the Maxey-Eakin method “is extremely dependent on the prediction of average annual precipitation which is poorly understood and quantified;

**Fig. 2** Palmer Drought Severity Index Nevada Region 3 (South-Central Nevada), 1920–1936



**Fig. 3** Precipitation maps of Nevada from Hardman 1936, Hardman 1965, and from PRISM 2018



therefore, a more accurate characterization of precipitation may lead to more accurate recharge estimates if the recharge coefficients are likewise revised.”

It is tempting to use the modern precipitation estimation methods such as PRISM, in lieu of Hardman 1936 data, to develop revised Maxey-Eakin recharge coefficients. Such has been done for the Maxey-Eakin valleys by Epstein (2004), DBS&A (2008a), and Berger et al. (2008), as well as by Nichols (2000) for some of the Maxey-Eakin valleys and other valleys in Nevada. Without knowing which valleys Maxey and Eakin actually used to obtain the natural discharge, application of a new analysis may be no more reliable than one using the Hardman 1936 map; however, at least for reconnaissance level computations, the

revised recharge coefficients based on PRISM (1961–1990) seem to be reasonable tools (DBS&A 2008a and b).

## Discussion

Review of the early bulletins reveals how the various elements of the Maxey-Eakin method may have evolved by about 1948–1949 as Bulletin 8 was prepared by Maxey and Eakin. A few years earlier, Maxey and Robinson (1947) had utilized existing precipitation gage data and estimated recharge percentages using nothing more than professional judgment to compute recharge in the Las Vegas area valleys. They relied partly on short-term

**Table 4** Recalculated precipitation zone areas and recharge for 21 original valleys

Maxey-Eakin Basin	Updated Area (1000 ha) from GIS for Hardman 1936 Precipitation Map							Original recharge estimate in acre-feet ( $10^6$ m <sup>3</sup> )	Updated recharge estimate in acre-feet ( $10^6$ m <sup>3</sup> )
	<5 (<0.13)	5–8 (0.13–0.2)	8–12 (0.2–0.31)	12–15 (0.31–0.38)	15–20 (0.38–0.51)	>20 (>0.51)	Total		
Las Vegas Valley	120.7	12.0	5.8	2.9	2.1	1.1	162.5	30,000 (37)	81,12 (10)
Pahrump Valley	46.0	6.8	12.0	4.2	2.1	1.3	81.8	23,000 (28)	9,859 (12)
Indian Springs Valley	52.7	2.1	5.7	0.3	0.0	0.0	63.8	4,700 (6)	1,072 (1.3)
White River Valley	9.4	18.5	73.4	35.0	1.8	0.5	165.7	40,000 (149)	32,033 (39)
Penoyer Valley	0.0	9.9	37.1	9.1	1.5	1.0	71.9	6,400 (8)	12,032 (15)
Railroad Valley	13.0	52.2	89.4	35.8	14.1	2.9	284.3	50,400 (62)	58,533 (72)
Ruby Valley	0.0	7.5	49.1	21.7	11.8	2.3	103.5	68,000 (84)	44,160 (54)
Antelope North + Goshute	0.0	27.2	50.1	10.0	0.2	0.0	127.5	10,400 (13)	7,859 (10)
Independence Valley	0.0	0.0	42.1	14.6	1.8	0.0	58.3	9,300 (11)	13,330 (16)
Buena Vista Valley	29.8	7.2	23.3	5.5	0.0	0.0	76.3	10,000 (12)	8,988 (11)
Paradise Valley	0.0	7.3	38.9	3.2	1.9	0.2	62.4	10,000 (12)	13,017 (16)
Clover Valley (Elko County)	0.0	7.9	48.0	11.8	3.4	1.3	84.1	20,700 (26)	19,150 (24)
Diamond Valley	4.1	4.3	44.4	13.6	4.2	0.6	77.6	16,000 (20)	22,434 (28)
Hot Creek	0.0	18.4	47.0	12.2	2.1	0.0	106.6	10,600 (20)	16,118 (20)
Spring Valley	5.8	24.6	68.2	32.4	3.6	2.1	172.9	75,000 (93)	46,221 (57)
Grass Valley	0.0	10.4	35.8	0.0	0.0	0.0	61.6	13,000 (16)	9,458 (12)
Big Smoky Valley	64.2	37.4	99.8	26.9	14.1	4.9	302.1	77,000 (95)	75,639 (93)
Fish Lake Valley	19.4	5.9	21.4	13.6	2.1	2.3	73.5	33,000 (41)	21,451 (26)
Kawich Valley	0.0	6.8	10.9	6.0	2.8	0.0	36.3	NA	8,347 (1)
Reveille Valley	NA	NA	NA	NA	NA	NA	NA	NA	NA

NA not available

records from snow gages placed by the USGS at high elevations to supplement the longer-term record of precipitation gages at lower elevations. It is evident from the Las Vegas area work that Maxey recognized the relationship between elevation, precipitation, and recharge by 1948. He then went on to work on studies of other valleys, including White River Valley, which had little precipitation data at high elevations from which to determine the volume of precipitation falling in the valley.

About that same time, perhaps by coincidence, Hardman (1948) published his map of state-wide annual precipitation, which provided a convenient means to quantify precipitation volumes in valleys with limited data. Loeltz et al. (1949), not Maxey or Eakin, appear to be the first to apply the Hardman precipitation map in their report on Paradise Valley, but they did not use the Maxey-Eakin recharge coefficients, most likely because they had not yet been fully developed. Robinson et al. (1949) also produced an unpublished report on Spring Valley that included Hardman precipitation. Robinson, Maxey's co-investigator in the Las Vegas area, may have introduced Maxey to the Hardman map when Maxey was working in the White River Valley.

In late 1949, Eakin (1950) was finalizing his Fish Lake Valley report (Bulletin 11), acknowledging the recently published Maxey and Eakin (1949) report. To compute recharge, Eakin used the recharge coefficients in Bulletin 8, but he computed total precipitation for the valley from two rain gages on the valley floor and extrapolated this to higher elevations using an

orographic relationship by Lee (1912) for the Sierra Nevada range in California. It appears that Eakin was either unaware of the Hardman map as late as December 1949 or learned of it just as Bulletin 11 was about to be finalized and decided not to change his report, in part because it was only a reconnaissance level report and the change may not have been significant. The fact that the recharge assessments in bulletins 8 and 11 were being published by Maxey and/or Eakin using different approaches for precipitation volume almost simultaneously suggests that the two authors may not have been in close communication. It is also noteworthy that later, Maxey recalled that for the derivation there were 21 valleys (Watson et al. 1976), while Eakin recalled only 12 valleys (J. Harrill, unpublished data, 2007). Perhaps owing to the fast pace of these reconnaissance investigations and the demand for publishing the results, as well as the fact that Maxey left Nevada in 1948, there may have been limited opportunities for the investigators to collaborate and develop a consensus on their approach. Nevertheless, based on Maxey's Las Vegas work, Maxey's early connection to Robinson, and Eakin's failure to utilize the Hardman map in his Fish Lake report, it appears likely that Maxey was the primary developer of the Maxey-Eakin recharge coefficients that were first published in Bulletin 8.

The trail that led to the actual derivation of the recharge coefficients seems to end here. Beyond the recharge percentages reported in the Las Vegas reports, there is no record of any trial

and error process, and no notes or reports showing how the recharge percentages came to be. There is no record to confirm which basins may have gone into the derivation. Without such records, it is entirely possible that the recharge coefficients were developed primarily by professional judgment. For example, if Maxey, relying on the specific precipitation ranges in the zones on Hardman's map, could assume that the lowest recharge rate would be 0% on valley floors where precipitation was less than 8 in/year and 25% where precipitation was more than 20 in/year (50.8 cm/year), then he could simply assign progressively increasing recharge percentages in between using the Hardman precipitation zones (e.g., 3, 7, and 15%). In fact, the progression was such that Wilson and Guan (2004) developed a smooth power function for the relationship between mean annual precipitation rate and recharge rate.

It seems reasonable that Maxey and Eakin could have initially developed the recharge percentages in this simple manner, using their best guess based on their experience. It also seems reasonable that they would have used these initial estimates with the Hardman precipitation map and compared the calculated preliminary recharge volumes to independently calculated natural discharge and adjusted some of the recharge percentages accordingly, but there is no record of this. That no one has yet been able to independently rederive the Maxey-Eakin recharge coefficients by regression analysis or other means, and that the 25% recharge coefficient was unchanged since the Las Vegas work, are further evidence suggesting that professional judgment may have played a dominant role in developing the recharge coefficients. If this is the case, then perhaps the Hardman 1936 map may not have been so critical in the derivation of the recharge coefficients, which may help explain why no one has yet reproduced the method.

Nevertheless, the reconnaissance series bulletins indicate that after publication of Bulletin 8 in late 1949, there seems to be more common application of the Maxey-Eakin method in other valleys in Nevada. This is likely because the method was not only expedient for reconnaissance purposes, but also seemed to have produced reasonable results. Most of the reconnaissance studies show calculations of recharge from precipitation using the Hardman 1936 map with the Maxey-Eakin coefficients and a separate computation of discharge by examining the various basin outflow components of the water budget. In the majority of those reports, the recharge is not simply set equal to the discharge; however, the values often are quite similar. The successful application of the Maxey-Eakin method by other scientists, who continued publication of results in subsequent bulletins and reconnaissance reports, likely would have progressively built confidence within the professional community that the Maxey-Eakin method was reasonable for their reconnaissance level investigations.

Years later, Avon and Durbin (1994) compared the Maxey-Eakin method to independent analyses of recharge by water budgets from 40 basins in Nevada and concluded that “[t]he Maxey-

Eakin method provides fairly reliable estimates of recharge to basins in Nevada.” However, for improved accuracy, D’Agness et al. (1997) noted, the Maxey-Eakin method “. . . should be modified to consider critical factors, such as rock type, permeability of weathered rock and soil, permeability of stream channel deposits, soil moisture at the time of precipitation and slope.” Distributed parameter watershed models are now available to account for many of these and other factors (e.g., SNL 2007; USGS 2008; DBS&A 2008a and b; Markstrom et al. 2015).

Berger et al. (2008) note that Maxey-Eakin coefficients are specifically tied to the Hardman 1936 precipitation map and no other, including the revised precipitation map by Hardman (1965) and PRISM datasets. Their opinion obviously stems from their understanding that the Hardman 1936 map was critical in the trial and error derivation of the original Maxey-Eakin coefficients. The implications of this are significant in two aspects. First, regardless of the degree of uncertainty in precipitation on the 1936 map for a particular basin, even if one today had extensive long-term records of measured precipitation gage data in lieu of the 1936 Hardman map, predictions of recharge by the Maxey-Eakin method with its original recharge coefficients may not be considered reliable by those authors. Second, it suggests that the Maxey-Eakin method can only be used in Nevada because the Hardman map covers only Nevada. To apply the method elsewhere would necessitate developing a completely new equation based on long-term precipitation and natural discharge for that area.

Nevertheless, the Maxey-Eakin method has also been widely applied to determine recharge in states other than Nevada and in other physiographic provinces, for example in New Mexico (Bartolino et al. 2010) and California (Davisson and Rose 2000; Reichard et al. 2003). The apparent acceptance of the results obtained by these scientists in applying the Maxey-Eakin recharge coefficients without the 1936 Hardman map suggests either that the recharge coefficients are not very sensitive to the geographic setting or that the Hardman 1936 map is not integral to the successful application of the Maxey-Eakin method to approximate recharge in the Southwestern United States.

## Summary and conclusions

The development of the Maxey-Eakin method as published cannot be scientifically reproduced. In addition, there are no unpublished notes or technical reports containing the method derivation that normally would include details about approach assumptions, equations, and tabulated results that a scientist reasonable familiar with hydrogeology could replicate.

There has been wide disagreement in the literature on the number of valleys used in the derivation of the Maxey-Eakin equation, ranging from 12 to 21. None of the prior tallies on the number or identities of the original valleys could be confirmed.



The Hardman 1936 precipitation map of Nevada is reported to be a key element in the development and application of the Maxey-Eakin method. The map was developed from sparse weather station records, mostly at low elevations, supplemented by precipitation estimated from topographic and vegetation maps. The Hardman 1936 average precipitation map likely has considerable uncertainty at the local watershed scale and, on average over the state, it likely reflects precipitation that is somewhat lower than the long-term mean.

Natural groundwater discharge volumes were reportedly used to derive the Maxey-Eakin recharge coefficients. The primary component of discharge was phreatophyte consumptive use. For the preliminary studies of recharge, Maxey and Eakin initially chose a constant evapotranspiration rate to apply to phreatophyte consumptive use where the water-table depth was less than 50 ft (15.24 m). However, different rates, tied to specific vegetation type and variable water-table depth, were subsequently used to compute discharge in the bulletins. The evapotranspiration rates were estimates obtained in part from early studies outside of Nevada and in part from professional judgment. In some of the presumed original Maxey-Eakin basins, there were other discharges to wells, springs, streams, and underflow out of the basin, with the latter especially difficult to quantify at the reconnaissance level.

Furthermore, some basins likely were not at long-term equilibrium, and not all discharge in the valleys presumed to be the original Maxey-Eakin valleys was generated by precipitation within that valley, owing to underflow entering from adjacent valleys. Thus, for an original Maxey-Eakin valley, the natural discharge values that were paired with volumes of recharge from the Hardman map likely contain significant uncertainty. Moreover, the discharge rates in the published bulletins almost certainly would not be the values used for deriving the recharge coefficients. Professional judgment on recharge percentages may have played a larger role than previously believed. If so, the 1936 Hardman precipitation may not have been so critical in the derivation of the recharge coefficients.

The Maxey-Eakin method has been widely used by practitioners, and has withstood extensive review. At a reconnaissance level at least, the method appears to produce reliable estimates of groundwater recharge. For most applications at the reconnaissance level, recharge computed using precipitation other than Hardman's 1936 map also produces reasonable estimates. Caution is urged when using the Maxey-Eakin method outside the Basin and Range physiographic province, and where increased confidence is required in the analysis to account for hydraulic properties of soils and geology, topographic slope, and aspect. For such studies, there are many other field methods and field data-based modeling tools available to compute recharge using site-specific data.

**Acknowledgements** The authors wish to acknowledge Greg Bushner and the Vidler Water Company. We'd also like to acknowledge the

helpful comments of Professor John L. Wilson, who reviewed a draft of the manuscript. We are also grateful for the careful and detailed comments of *Hydrogeology Journal's* reviewers. Dr. John Hawley generously provided additional reference materials and perspective. The Nevada Agricultural Experiment Station kindly granted permission to use the Nevada precipitation maps. We also acknowledge the assistance of Samuel Romero with graphics, the support of Deborah Salvato in preparation of the manuscript, Robyn Fay for editorial review, and other technical and financial support from Daniel B. Stephens & Associates, Inc.

## References

- Avon L and Durbin TJ (1994) Evaluation of the Maxey-Eakin methods for estimating recharge to ground-water basins in Nevada. AWRW Water Resour Bull 30(1), February 1994
- Bartolino JR, Anderholm SK, Myers NC (2010) Groundwater resources of the East Mountain area, Bernalillo, Sandoval, Santa Fe, and Tarrant counties, New Mexico, 2005. US Geol Surv Sci Invest Rep 2009-5204
- Berger DL, Halford KJ, Belcher WR, Lico MS (2008) Technical review of water-resources investigations of the Tule Desert, Lincoln County, southern Nevada. US Geol Surv Open-File Rep 2008-1354
- D'Agnesse FA, Faunt CC, Turner AK, Hill MK (1997) Hydrogeologic evaluation and numerical simulation of the Death Valley regional ground-water flow system. US Geol Surv Water Resour Invest Rep 96-4300
- Davisson ML, Rose TP (2000) Maxey-Eakin methods for estimating groundwater recharge in the Fenner watershed, southeastern California. UCRL-ID-139027, Lawrence Livermore National Laboratory, Livermore, CA
- DBS&A (Daniel B. Stephens & Associates, Inc.) (2008a) Addendum to mean annual recharge for the Tule Desert Hydrographic Basin, Lincoln County, Nevada. Prepared for the Lincoln County Water District and Vidler Water Company, Carson City, NV
- DBS&A (Daniel B. Stephens & Associates, Inc.) (2008b) Mean annual recharge for the Tule Desert Hydrographic Basin, Lincoln County, Nevada. Prepared for the Lincoln County Water District and Vidler Water Company, Carson City, NV
- Donovan DJ, Katzer T, Brothers K (2009) Review of ground-water recharge estimates in Nevada with an analysis of geologic control on the recharge process. Southern Nevada Water Authority, Las Vegas, NV
- Eakin TE (1950) Preliminary report on ground water in fish Lake Valley, Nevada and California. Water Resour Bull no. 11. State of Nevada Office of the State Engineer. Prepared in cooperation with the US Department of the Interior Geological Survey, Washington, DC
- Eakin TE, Maxey GB (1951a) Ground water in Ruby Valley, Elko and white pine counties, Nevada. In: State of Nevada Office of the State Engineer, Water Resour Bull no. 12, Contributions to the hydrology of eastern Nevada. Prepared cooperatively by the US Geological Survey, Reston, VA
- Eakin TE, Maxey GB (1951b) Ground water in clover and Independence valleys, Elko County, Nevada. In: State of Nevada Office of the State Engineer, Water Resour Bull no. 12, Contributions to the hydrology of eastern Nevada. Prepared cooperatively by the US Geological Survey, Reston, VA
- Eakin TE, Maxey GB, Robinson TW (1949) Ground water in Goshute-Antelope Valley, Elka County, Nevada. Water Resour Bull no. 12, State of Nevada Office of the State Engineer. Prepared cooperatively by the US Geological Survey, Reston, VA
- Eakin TE, Maxey GB, Robinson TW, Fredericks JC, Loeltz OJ (1951) Contributions to the hydrology of eastern Nevada. Water Resour Bull no. 12, State of Nevada Office of the State Engineer. Prepared cooperatively by the US Geological Survey, Reston, VA
- Epstein BJ (2004) Development of uncertainty analysis of empirical recharge prediction models for Nevada's desert basins. MSc Thesis, University of Nevada Reno, NV, 206 pp

- Epstein BJ, Pohl GM, Huntington J, Carroll RWH (2010) Development and uncertainty analysis of an empirical recharge prediction model for Nevada's desert basin. *J Nevada Water Resour Assoc* 5(1)
- Fiedler, AG, Nye SS (1933) Geology and ground-water resources of the Roswell Artesian Basin, New Mexico. US Geol Surv Water Suppl Pap 639
- Hardman G (1936) Nevada precipitation and acreages of land by rainfall zones. Agricultural Experiment Station report, University of Nevada, Reno, NV, 10 pp and map
- Hardman G (1948) The precipitation of Nevada. Nevada Agricultural Experiment Station, Department of Irrigation, Reno, NV
- Hardman G (1965) Nevada precipitation map. Report, Nevada Division of Conservation and Natural Resources, Reno, NV, 27 pp
- Jeton AE, Watkins SA, Lopes TJ, Huntington J (2005) Evaluation of precipitation estimates from PRISM for the 1961–90 and 1971–2000 data sets, Nevada. *US Geol Surv Sci Invest Rep* 2005-5291. [http://pubs.usgs.gov/sir/2005/5291/PDF/SIR2005\\_5291.pdf](http://pubs.usgs.gov/sir/2005/5291/PDF/SIR2005_5291.pdf). Accessed 2 February 2018
- Lee CH (1912) An intensive study of the water resources of a part of Owens Valley, California. *US Geol Surv Water Suppl Pap* 294
- Loeltz OJ, Phoenix DA, Robinson TW (1949) Ground water in Paradise Valley, Humboldt County, Nevada. *Water Resour Bull* no. 10, State of Nevada Office of the State Engineer. Prepared in cooperation with the US Department of the Interior Geological Survey, Washington, DC
- Lopes TJ, Evetts DM (2004) Ground-water pumpage and artificial recharge estimates for calendar year 2000 and average annual natural recharge and interbasin flow by hydrographic area, Nevada. *US Geol Surv Sci Invest Rep* 2004-5239
- Markstrom SL, Regan RS, Hay LE, Viger RJ, Webb RMT, Payn RA, LaFontaine JH (2015) PRMS-IV, the precipitation-runoff modeling system, version 4. *US Geol Surv Techniques and Methods*, book 6, chap B7, 158 pp. <https://doi.org/10.3133/tm6B7>. Accessed 22 September 2017
- Maxey GB, Eakin TE (1949) Ground water in White River Valley, White Pine, Nye, and Lincoln counties, Nevada. *Water Resour Bull* no. 8, State of Nevada Office of the State Engineer. Prepared in cooperation with the US Department of the Interior Geological Survey
- Maxey GB, Eakin TE (1950) Ground water in railroad, Hot Creek, Reveille, Kawich, and Penoyer valleys, Nye, Lincoln, and White Pine counties, Nevada. *Water Resour Bull* no. 12, State of Nevada Office of the State Engineer. Prepared cooperatively by the US Geological Survey, Washington, DC
- Maxey GB, Robinson TW (1947) Ground water in Las Vegas, Pahrump, and Indian Springs valley. *Water Resour Bull* no. 6, State of Nevada Office of the State Engineer. Prepared in cooperation with the US Department of the Interior Geological Survey, Washington, DC
- National Oceanic and Atmospheric Administration (NOAA) (2016) Climate division Palmer drought indices. Available online at <http://www.incdnoa.gov/pub/data/cirs/climdiv/>. Accessed 21 February 2018
- National Oceanic and Atmospheric Administration (NOAA) (2018) US Climate Division data plotting page: division boundaries and county relationships. <https://www.esrl.noaa.gov/psd/data/usclimdivs/boundaries.html>. Accessed 14 September 2017
- Nichols WD (2000) Regional ground-water evapotranspiration and ground-water budgets, Great Basin, Nevada. *US Geol Surv Prof Pap* 1628
- NV OSE (2018) Designated groundwater basins of Nevada. Nevada Office of the State Engineer, Division of Water Resources, Reno, NV. [http://water.nv.gov/mapping/maps/designated\\_basinmap.pdf](http://water.nv.gov/mapping/maps/designated_basinmap.pdf). Accessed February 2018
- PRISM Group, Northwest Alliance for Computational Science and Engineering, Oregon State University (PRISM) (2018) Datasets. <http://www.prism.oregonstate.edu/>. Accessed 14 July 2018
- Reichard EG, Land M, Crawford MT, Johnson T, Everett RR, Tulshan TV, Ponti DJ, Halford KL, Johnson TA, Paybins KS, Nishikawa T (2003) Geohydrology, geochemistry, and groundwater simulation optimization of the central and west coast basins, Los Angeles County, California. *US Geol Surv Water Resour Invest Rep* 03-4065
- Robinson TW (1953) Big Smoky Valley, Nevada in subsurface facilities of water management and patterns of supply-type area studies. *Phys. and Economic Foundation of Natural Resources Report* 4, US Congress, House Communications on Interior and Insular Affairs, Washington, DC, pp 132–146
- Robinson TW, Loeltz OJ, Phoenix DA (1949) Ground Water in Grass Valley and adjacent portions of the Humboldt River Valley, Pershing and Humboldt counties, Nevada. *US Geol Surv Open-File Rep.* 100 pp
- Rush FE, Schroer CV (1971) Water resources of Big Smoky Valley, Lander, Nye, and Esmeralda counties, Nevada. *Nevada Division Water Resour Bull* 41, 84 pp
- Sandia National Laboratories (SNL) (2007) Simulation of net infiltration for present-day and potential future climates. MDL-NBS-HS-000023 REV 01, Yucca Mountain Project, Tonopah, NV
- Thomas HE, Shamberger HA (1979) Forward to the George Burke Maxey memorial volume of contemporary hydrogeology, *J Hydrol* 43:ix–x
- US Geol Surv (2008) Documentation of computer program INFIL3.0: a distributed-parameter watershed model to estimate net infiltration below the root zone. *US Geol Surv Sci Invest Rep* 2008-5006, 98 pp
- Watson P, Sinclair P, Waggoner R (1976) Quantitative evaluation of a method for estimating recharge to the dessert basins of Nevada. *J Hydrol* 31:335–357
- White WN (1932) A method of estimating ground-water supplies based on discharge by plants and evaporation from soil, results of investigations in Escalante Valley, Utah. *US Geol Surv Water Suppl Pap* 659-a
- Wilson JL, Guan H (2004) Mountain-block hydrology and mountain-front recharge. In: Hogan JF, Phillips FM, Scanlon BR (eds) *Groundwater recharge in a desert environment: the southwestern United States*. American Geophysical Union, Washington, DC