HYDROLOGIC IMPLICATIONS OF GREATER GROUND-WATER RECHARGE TO LAS VEGAS VALLEY, NEVADA

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HYDROLOGIC IMPLICATIONS OF GREATER GROUND-WATER RECHARGE TO LAS VEGAS VALLEY, NEVADA[1]

David J. Donovan and Terry Katzer[2]

ABSTRACT: Published estimates of natural recharge in Las Vegas Valley range between 21,000 and 35,000 acre-feet per year. This study examined the underlying assumptions of previous investigations and evaluated the altitude-precipitation relationships. Period-of-record averages from high altitude precipitation gages established in the 1940s through the 1990s, were used to determine strong local altitude-precipitation relationships that indicate new total precipitation and natural recharge amounts and a new spatial distribution of that recharge. This investigation calculated about 51,000 acre-feet per year of natural recharge in the Las Vegas Hydrographic Basin, with an additional 6,000 acre-feet per year from areas tributary to Las Vegas Valley, for a total of 57,000 acre-feet per year. The total amount of natural recharge is greater than estimates from earlier investigations and is consistent with a companion study of natural discharge, which estimated 53,000 acre-feet per year of outflow. The hydrologic implications of greater recharge in Las Vegas Valley infer a more accurate ground-water budget and a better understanding of ground-water recharge that will be represented in a ground-water model. Thus model based ground-water management scenarios will more realistically access impacts to the ground-water system.
(KEY TERMS: ground-water hydrogeology; ground-water modeling; water management; natural recharge; Las Vegas Valley; Nevada; precipitation.)

INTRODUCTION

Las Vegas Valley (LVV) in southern Nevada (as shown in Figure 1) is a typical basin and range valley as described by Fenneman (1931). The elongated Valley is bounded by subparallel mountain ranges – the Spring Mountains to the west, the Sheep and Las Vegas Ranges to the north, and the McCullough Range to the east and south. The valley floor is hot and arid with a mean annual high temperature of 80°F and an average precipitation of 4.16 inches at the Las Vegas Weather Service Office (WSO) Airport Station [Desert Research Institute's (DRI) Western Regional Climatic Center (WRCC), 1998]. Most of the natural recharge occurs on the surrounding mountain ranges and most of the discharge occurs as evapotranspiration (ET) on the valley floor from the ground-water system. LVV is unusual for a Nevada valley because there is over 10,000 feet of topographic relief between the highest point in LVV, which is Mount Charleston [11,915 feet above mean sea level (asl)] in the Spring Mountains and the outlet of the valley in Las Vegas Wash (1,540 feet asl). This topographic relief results in very strong climatic differences between the highest and lowest points in LVV.

The goal of this investigation was to develop a set of algorithms that can be used to predict the distribution of natural recharge based on altitude and precipitation for each node of a ground-water model currently being developed. Other numerical ground-water modelers of LVV (Harrill, 1976; Morgan and Dettinger, 1994) distributed recharge so that predicted water levels would match measured water levels. To accomplish this goal, recent high-altitude precipitation data were used with long-term low-altitude data to develop an altitude-precipitation relationship. A linear regression was developed to express this relationship. During the data analysis, it became obvious that not only were there different relationships between mountain ranges, but where there were numerous data sites, such as in the Spring Mountains, there were unique relationships for different drainages. Thus, precipitation was calculated both as a function of altitude, and also by watershed to compensate for microclimates.

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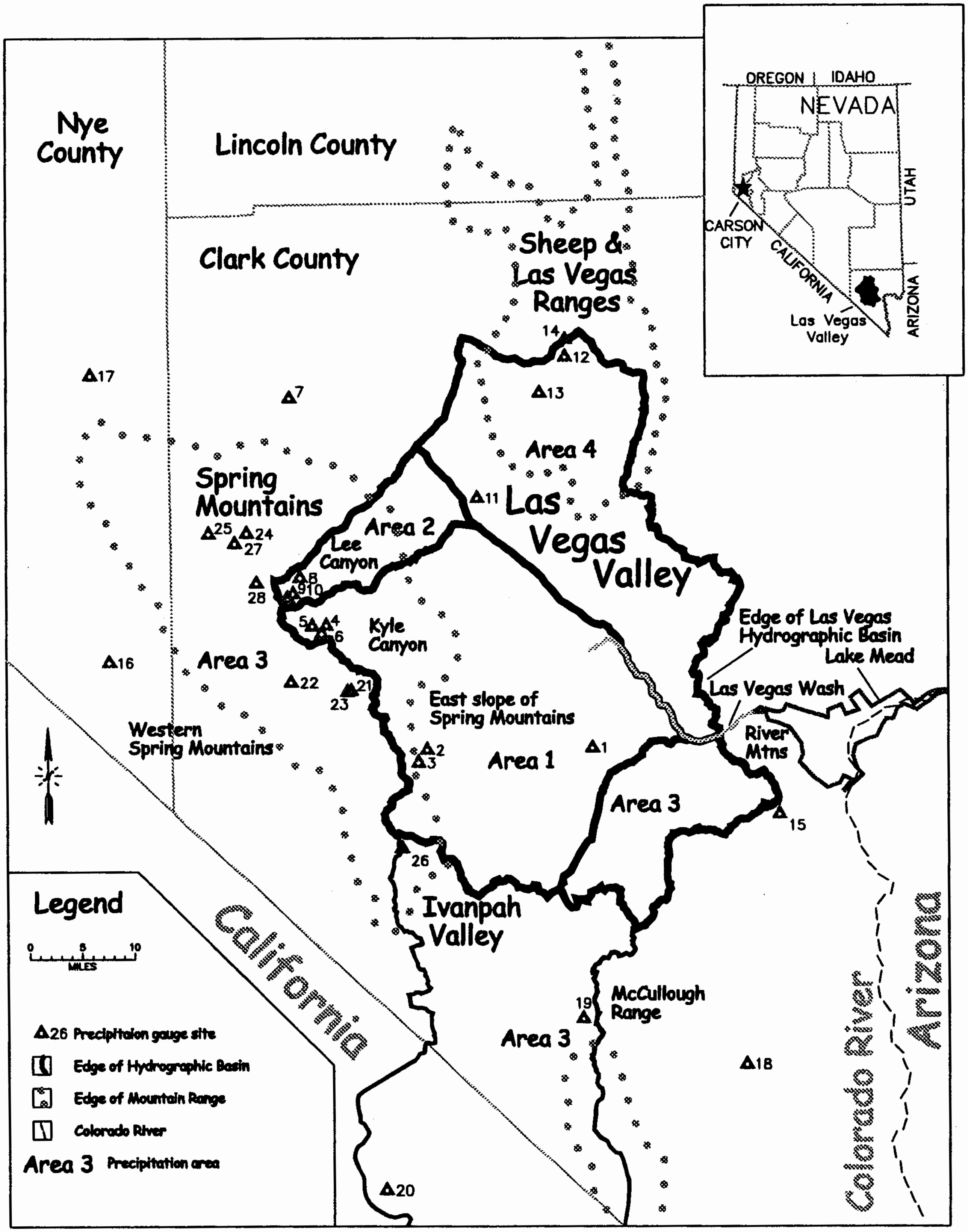

Figure 1. Location Map Showing Las Vegas and Ivanpah Valleys Precipitation Areas and Stations Used for This Analysis.

Once the new altitude-precipitation relationships were developed and applied, it became apparent that natural recharge volumes calculated in this study were higher than the original natural recharge first calculated by Maxey and Jameson (1948) and higher than the original natural discharge volumes first estimated by Malmberg (1965). Prior to ground-water development (circa 1900), the ground-water system in LVV was assumed to be in steady state (i.e., natural recharge is equal to natural discharge). It seemed prudent at this point to reevaluate the natural discharge and Dr. Dale Devitt, Professor of Soil and Water, Department of Environmental and Resource Sciences, University of Nevada, Reno (UNR), initiated a companion study of natural discharge in LVV. Results from his study (Devitt *et al.*, 2000) using the Penman Combination Prediction method [Malmberg, (1965) used the Blaney-Criddle method or the more simplistic regional application model] and water use factors from more recent ET studies in southern Nevada, showed the original estimate of ET was about 60 percent too low. This in turn meant the natural recharge was higher than previously reported. Additionally we estimated the subsurface outflow from the basin through a narrow section underlying Las Vegas Wash using a form of the Darcy flow equation and local transmissivity values. This analysis indicates about 6,000 afy of ground water exits the basin. Thus the purpose of this study was expanded to include an estimate of a new steady state water budget for LVV.

METHOD OF ANALYSIS

This investigation (1) analyzed all available precipitation data for LVV, (2) compared this data to existing precipitation maps, (3) developed local altitude-precipitation relationships, (4) described recharged efficiencies and their limitations, and (5) created original equations to calculate the amount of precipitation and recharge per cell for model use. These steps produced a new estimate of natural recharge much higher than previously thought.

New altitude-precipitation relationships were necessary because of observed differences between the average values of precipitation gage data at a given altitude and location and published estimates of the amount of precipitation at the same altitude and location. Since this investigation is associated with a hydrogeologic ground water model currently under development that uses current computer dependent algorithms, the methods employed in this analysis were selected to be compatible with Geographic Information System (GIS) software and hydrogeological modeling software to ease calculations. Hence, a numerical approximation technique was developed that would replicate the older technique of contouring precipitation manually. Then, after applying recharge efficiency factors (i.e., the percentage of the precipitation that becomes natural recharge), the natural recharge was calculated for each contoured zone and then summed. The assumptions of the numerical approximations are identical to older empirical relationships between altitude and precipitation and between precipitation and natural recharge efficiencies. The assumptions are that precipitation increases with altitude at a local rate and the recharge efficiencies are proportional to the precipitation and, thus, both precipitation and the natural recharge efficiencies increase with increasing altitude (Maxey and Eakin, 1949). If both precipitation and recharge efficiency are calculated by numerical approximations, the amount of recharge can be calculated per node in a hydrogeologic model. The numerical approximation method also removes digitizing errors associated with converting older, scale dependent, analog maps to digital form.

EXISTING PRECIPITATION DATA

The locations of precipitation gages used in this investigation are shown in Figure 1. The mean annual precipitation values with period-of-record lengths ranging from 8 to 69 years are summarized in Table 1. The most important stations are the high altitude locations because this is where the bulk of natural recharge occurs and the database has been improved with the addition of U.S. Geological Survey (USGS) storage gages installed in the mid-1980s. Medium altitude storage gages, installed by the Nevada Division of Water Resources (NDWR) in the early 1960s, now have 30 to 40 years of record. Low altitude precipitation data, some with periods-of-record of about 85 years, are available through clearing houses on the Internet. This investigation used the following website provided by the WRCC: (http://www.wrcc.dri.edu/summary/climsmnv.html).

The period-of-record averages for annual precipitation for all stations are plotted against altitude (Figure 2). The most striking feature of this graph is the wide spread of the high altitude data points. The adjusted r^2 (0.68) indicates only 68 percent of the variability can be explained with this regression. The grouping of the data points suggests that the relationship between altitude and precipitation may be unique for each range or canyon. The relative dryness of the Sheep Range with increasing altitude compared to the Spring Mountains was observed by previous

TABLE 1. Characteristics of Precipitation Stations Used in This Analysis.

Area	Agency*	Site No.	Period**	Latitude	Longitude	Altitude (feet)	Precipitation (inches)	Record Begin	Record End
Kyle Canyon, East Slope Spring Mountains (Area 1)									
Las Vegas / McCarran	NWS	1	D	36 04 56	115 10 01	2,162	4.16	1949	1998
Red Rock S.P. / Spr Mtn. Rnh.	NWS	2	D	36 05 00	115 27 00	3,780	12.21	1977	1998
Spring Mountain Ranch	NDWR	3	A	36 03 55	115 27 55	4,000	11.17	1966	1996
Kyle Canyon	NDWR	4	A	36 15 38	115 37 03	7,500	20.39	1961	1966
Kyle Canyon	NDF	5	M	36 15 36	115 38 30	7,606	28.04	1981	1995
Kyle Canyon	USGS	6	S	36 14 57	115 37 33	7,760	26.27	1985	1996
Lee Canyon (Area 2)									
Indian Springs	NWS	7	D	36 34 52	115 40 30	3,136	3.07	1948	1964
Lee Canyon	NDWR	8	A	36 19 43	115 39 40	8,400	22.72	1961	1996
Lee Canyon	USGS	9	S	36 18 22	115 40 25	8,510	23.34	1985	1996
Lee Canyon	NWS	10	M	36 18 00	115 41 00	9,000	21.96	1945	1952
Western Spring Mountains, McCullough Range, Ivanpah Valley (Area 3)									
Boulder City	NWS	15	D	35 59 00	114 51 00	2,525	5.73	1931	1998
Pahrump	NWS	16	D	36 12 45	115 59 24	2,670	4.76	1948	1998
Desert Rock	NWS	17	D	36 37 00	116 01 00	3,330	6.28	1984	1998
Searchlight	NWS	18	D	35 38 00	114 55 00	3,540	7.79	1914	1998
McCullough Pass	NDWR	19	A	35 42 06	115 11 35	3,768	6.28	1967	1996
Mountain Pass	NWS	20	D	35 28 00	115 32 00	4,730	8.66	1955	1998
Roberts Ranch	NDWR	21	A	36 10 04	115 34 36	6,000	13.98	1961	1996
Upper Williams Ranch	NDWR	22	A	36 10 52	115 40 44	6,000	14.60	1962	1996
Roberts Ranch	NWS	23	M	36 10 00	115 35 00	6,100	13.95	1945	1952
Cold Creek	NDWR	24	A	36 23 30	115 45 06	7,400	17.10	1961	1996
Wheeler Pass	NDWR	25	A	36 23 30	115 49 00	7,683	15.00	1964	1996
Potosi Peak	USGS	26	S	35 56 41	115 29 46	8,080	16.90	1985	1996
Trough Spring	USGS	27	S	36 22 40	115 46 21	8,240	17.63	1985	1996
Adams Ranch	NDWR	28	A	36 19 18	115 44 10	9,050	20.41	1967	1996
Sheep and Las Vegas Ranges (Area 4)									
Desert Game Range/Corn Creek	NWS	11	D	36 26 12	115 21 21	3,025	4.32	1948	1998
Hidden Forest	NWS	12	M	36 38 00	115 12 00	7,550	12.58	1945	1952
Sheep Peak	USGS	13	S	36 34 60	115 14 43	9,600	14.37	1985	1996
Hayford Peak	USGS	14	S	36 39 29	115 11 58	9,840	15.71	1985	1996

*Proper names of agencies: National Weather Service (NWS), U.S. Geological Survey (USGS), Nevada Division of Water Resources (NDWR), Nevada Division of Forestry (NDF).
**Periods of measurement: Daily (D), Monthly (M), Semi-Annual (S), Annual (A).

precipitation investigations (Maxey and Jameson, 1948; Quiring, 1965). Additionally, Maxey and Jameson (1948) noted the relative dryness of the west slope of the Spring Mountains compared to the east slope. Table 1 lists the precipitation stations that were used to define the four altitude-precipitation relationships (areas are shown on Table 4).

EXISTING PRECIPITATION MAPS

The Hardman map [published in 1936 (Hardman, 1936), revised in 1965 (Hardman, 1965), and modified in 1972 by NDWR (State Engineer's Office, Nevada Division of Water Resources, Department of Conservation and Natural Resources, June 1972, and subsequent Map S-3, Water for Nevada, Special Report, Hydrologic Atlas)] covers the entire state of Nevada

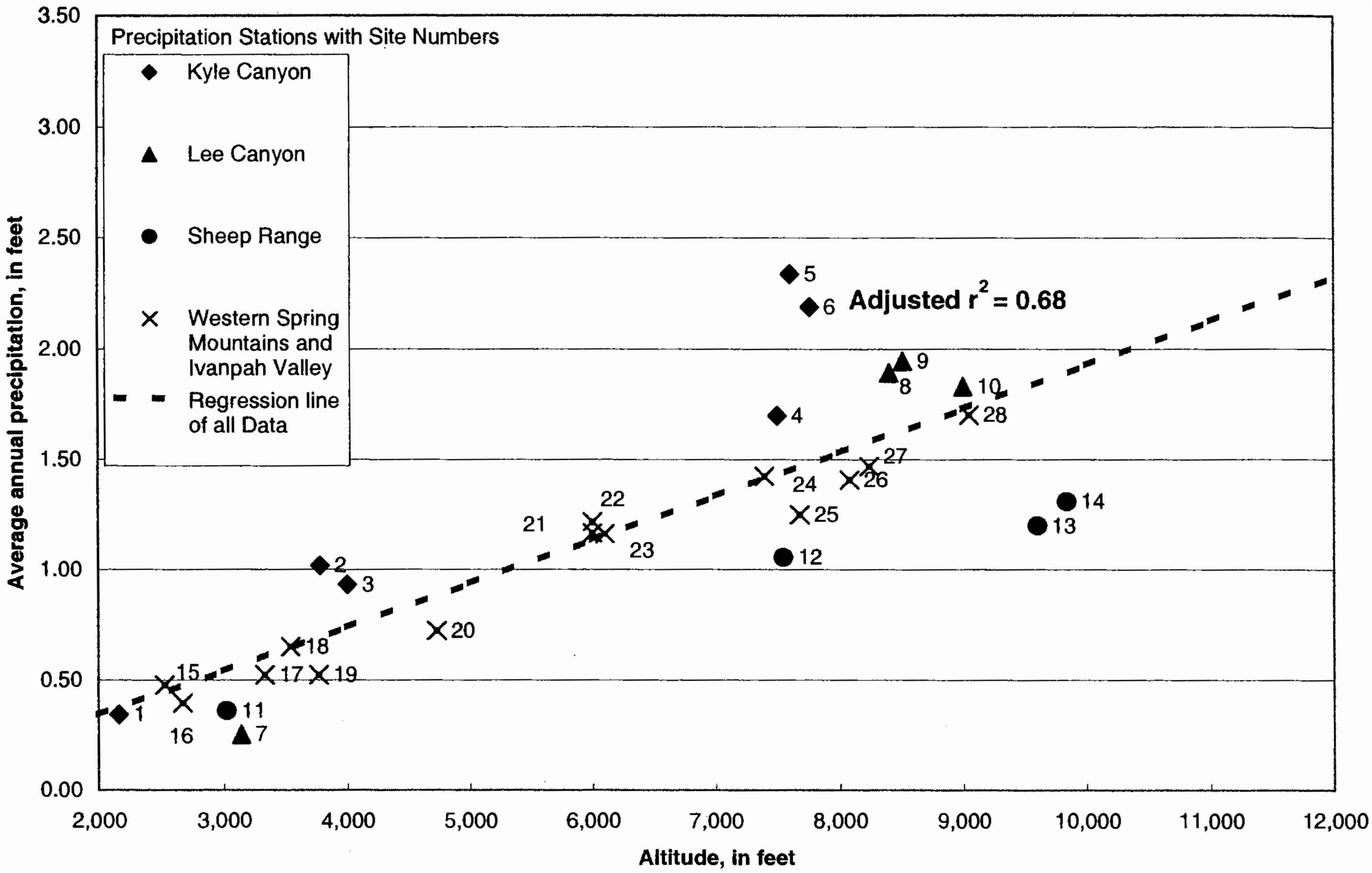

Figure 2. Plot of Altitude Versus Precipitation.

and has precipitation contours of 4, 8, 12, 15 or 16, and 20 inches. A limitation of the Hardman map is the maximum contour interval of only 20 inches so the map underrepresents precipitation in mountain ranges with significant acreage above 9,000 feet (asl) because the actual precipitation is much greater in the higher parts of the mountain ranges.

Maxey and Jameson (1948), although later in time than the original Hardman work, did not reference the Hardman map nor did they use a precipitation map. They had virtually no precipitation data and estimated average precipitation values for three altitude zones in the Spring Mountains and two altitude zones in the Sheep Range.

The Parameter-altitude Regressions on Independent Slopes Model (PRISM) precipitation map developed by the Oregon Climatic Service (Daly *et al.*, 1994, 1997), has contours of approximately 2 inches, and is referred to here as the PRISM map. In the Spring Mountains, the PRISM map shows a maximum precipitation of 21 inches, similar to the Hardman map, so both maps underestimate high altitude precipitation. PRISM is more detailed but overestimates precipitation at lower altitudes which is the primary difference between the maps. Thus, the existing precipitation maps and distributions were deemed inadequate for this study, particularly so because the recent high-altitude precipitation stations show a distribution that is more representative of the individual area.

LOCAL ALTITUDE-PRECIPITATION RELATIONSHIPS

The precipitation distributions described above (Maxey and Jameson, 1948, Hardman map (Hardman, 1936), PRISM map (Daly *et al.*, 1994, 1997)] are compared in Figure 3 for Kyle Canyon, a large high altitude area in the Spring Mountains that is a major area for natural recharge to LVV. Figure 3 also includes the local altitude-precipitation relationship for Kyle Canyon developed for this study that shows a maximum predicted value of 39 inches on the highest point in the canyon and Spring Mountains.

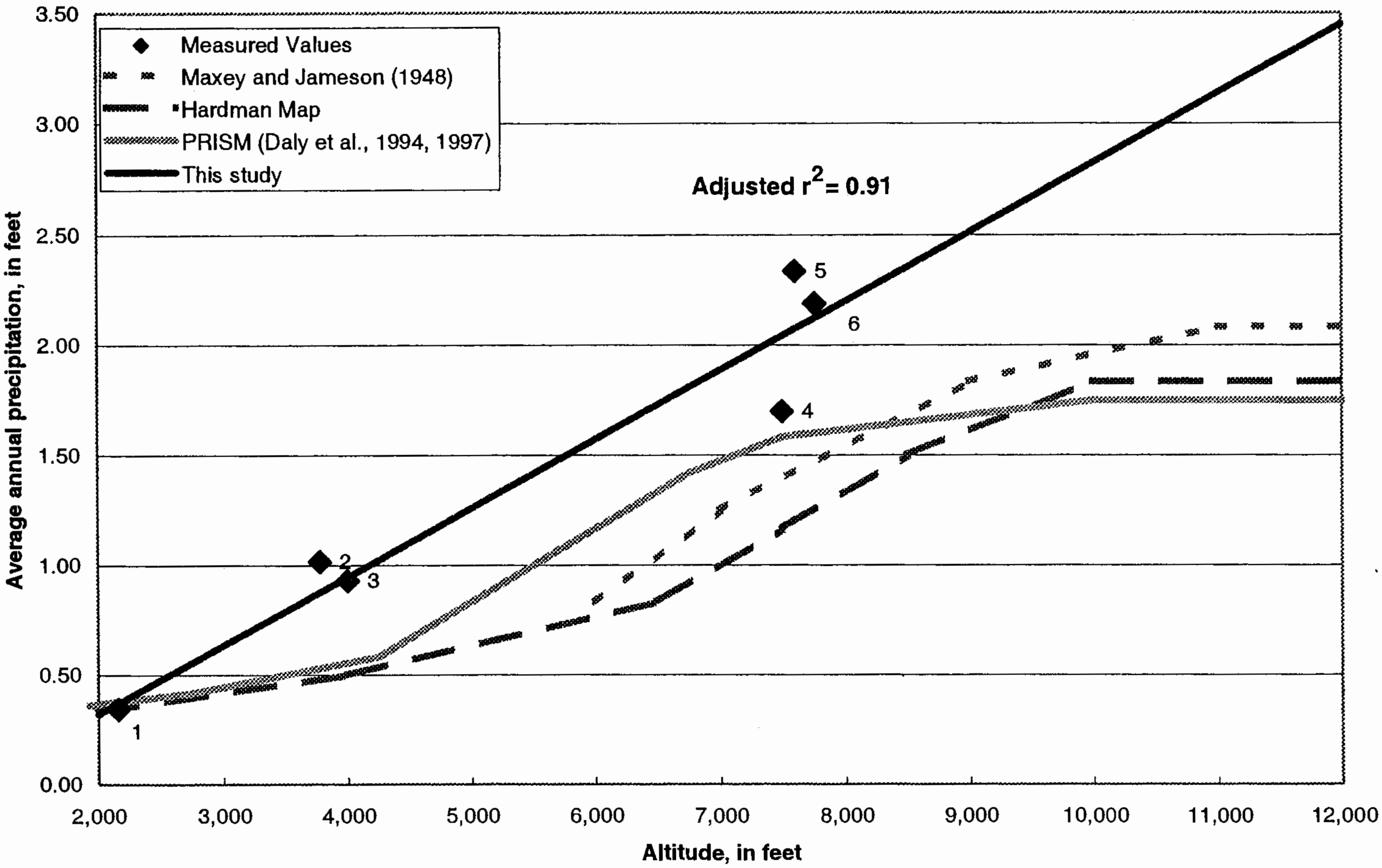

Figure 3. Measured Values and Approximation Methods for Kyle Canyon.

Six precipitation gages are used to define the Kyle Canyon altitude-precipitation relationship but only three are above 7,000 feet (asl). Two of the gages, Nos. 5 and 6, have only 12 and 11 years of record, respectively. Nevertheless, even with these deficiencies the adjusted $r^2 = 0.91$ indicates a high correlation between altitude and precipitation in the altitude range of 2,000 to 8,000 feet (asl). Based on this correlation, the relationship was assumed to be linear to the maximum altitude in the drainage area, about 12,000 feet (asl).

LVV was subdivided into four geographic areas (Figure 1), observed to have significant variations in precipitation. The groupings of the data and the locations of the sites where data were collected determined the four geographic areas: (1) East slope of the Central Spring Mountains including, Kyle and Red Rock Canyons and Cottonwood Valley; (2) Lee Canyon; (3) Western slope of the Spring Mountains, the McCullough Range, River Mountains, and Ivanpah Valley; and (4) Sheep and Las Vegas Ranges. By subdividing the precipitation data into these areas (listed in Table 1) the coefficients of determination (r^2) for the altitude-precipitation relationships (Figures 4 and 5) increased (from an adjusted r^2 of 0.68 for all data) to an adjusted $r^2 = 0.91$, 0.97, 0.95, and 0.98, respectively.

Using the altitude-precipitation methods described above defines a precipitation distribution that is locally different from previous investigators' distributions, and has a larger maximum value in the highest part of the Spring Mountains. The total amount of precipitation for LVV (708,000 afy) is compared with other precipitation maps in Table 2 (Hardman, PRISM) and is about is about 20 percent higher than values calculated from processing these maps through GIS.

These two precipitation maps either underestimate (Hardman) or overestimate (PRISM) the spatial extent of the mountain ranges and minimize the variation between and within mountain ranges. Because the Hardman map is regional and generalized from a 1:2,000,000 scale topographic map, accurate local information is lacking in detail. The map documents general precipitation trends but not the

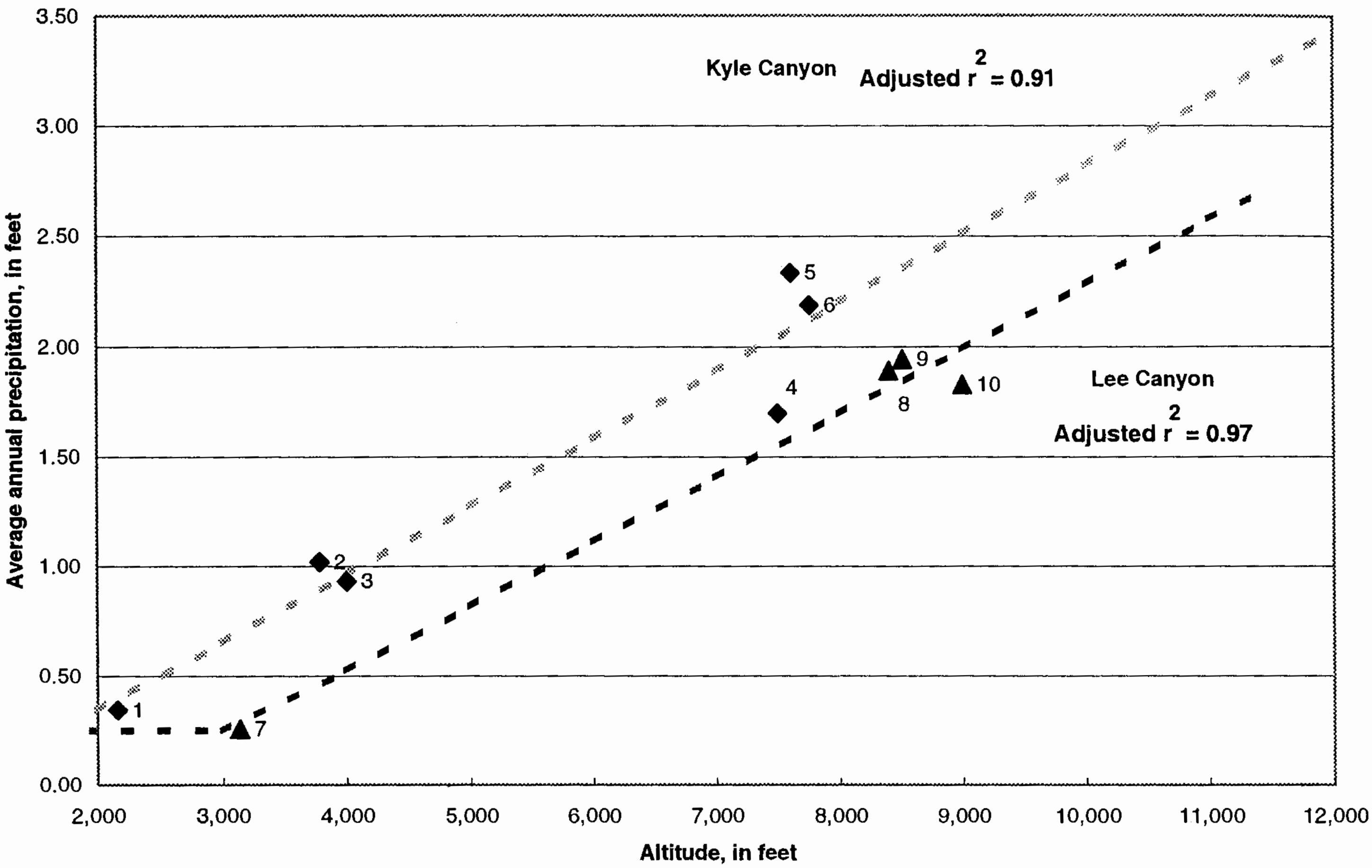

Figure 4. Altitude-Precipitation Relationships for Kyle and Lee Canyons.

strong localized altitude-precipitation relationships observed in LVV.

TABLE 2. Comparison of Total Precipitation From Published Precipitation Maps for Las Vegas Valley.

Investigator(s)	Date	Precipitation Estimate (acre-feet/year)
Hardman	1936*	561,0001
PRISM (Daly *et,al,* 1994, 1997)	1997	613,000
Donovan and Katzer	**This Study**	**708,000**

*This number was calculated from the digitized version of the 1965 revision of this map as published in the 1972 Nevada State Water Plan.

The PRISM map (Daly *et al.,* 1994, 1997) is very easy to process with GIS and is based on sound methodology. However, the horizontal elevation control is about 13,000 feet compared to about 75 feet used for this analysis. In the Spring Mountains the topographic relief, in 13,000 feet of distance, is typically about 3,500 feet, and the total topographic relief in LVV is over 10,000 feet. This amount of relief, combined with strong localized altitude-precipitation relationships, produced the variation between measured and predicted precipitation values and the differences between our methods and the PRISM and Hardman maps in the total amount of precipitation.

NATURAL RECHARGE EFFICIENCIES

The Maxey-Eakin (1949:40) recharge method has been used throughout Nevada by the NDWR and USGS to estimate perennial yields of hydrographic basins. Briefly, the method estimates (based on the Hardman map), the average annual volume of precipitation for altitude zones in any given drainage basin.

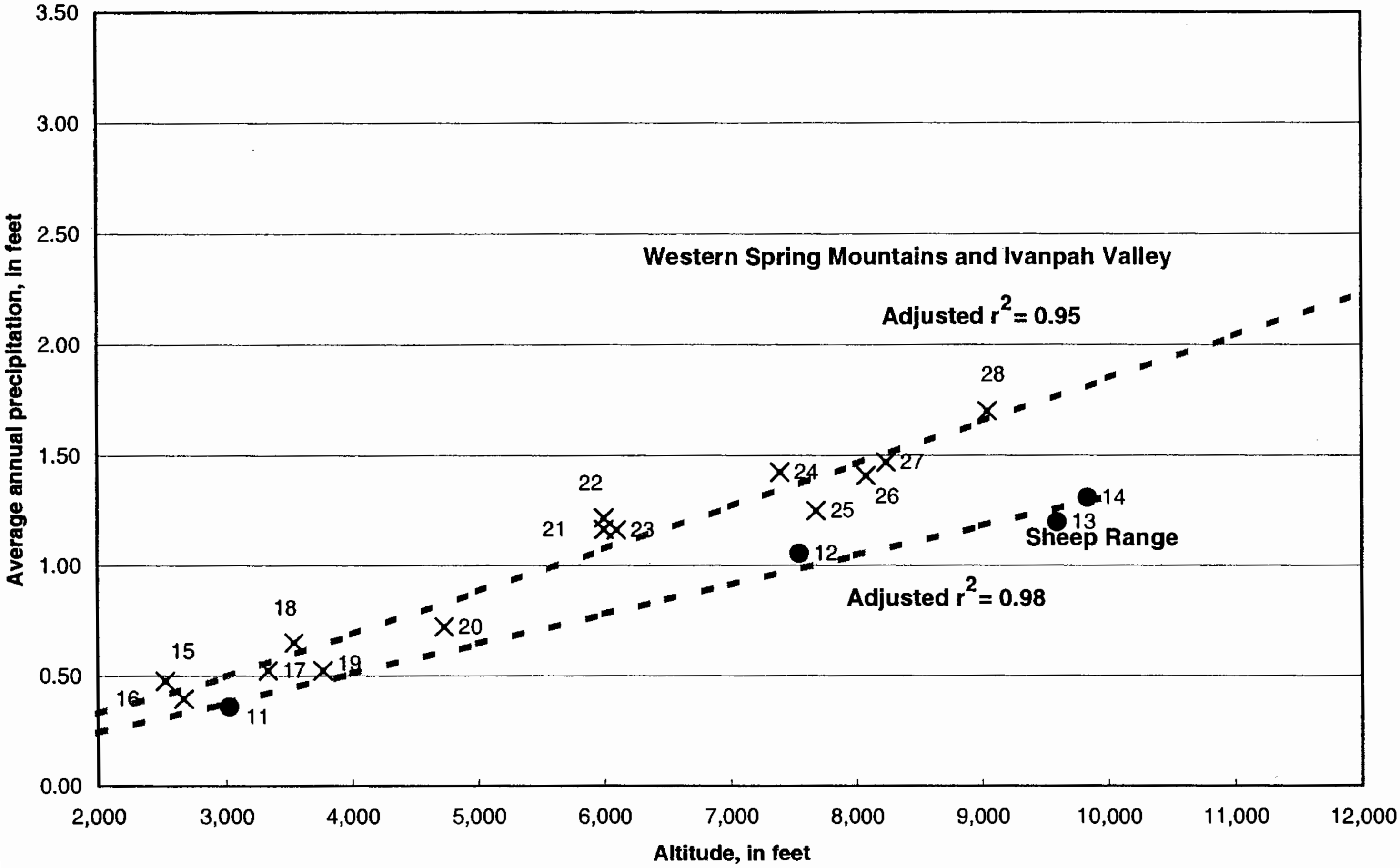

Figure 5. Altitude Precipitation Relationship in Western Spring Mountains, Ivanpah Valley, and Sheep Range.

Ground-water recharge is calculated as a percentage (also called recharge efficiency) of the precipitation. The method is nonunique and was developed by estimating ground-water discharge from numerous basins and balancing the recharge by trial-and-error to equal the discharge. For this investigation we could have used recharge efficiencies different from those finally settled on by Maxey and Eakin (1949); but, again, because the method is nonunique and natural recharge for LVV nearly equals the discharge, there was no reason to vary the percentages. In the Maxey-Eakin (1949) method, natural recharge begins at 8 inches of precipitation, has 1000-foot altitude intervals, and three recharge efficiencies in areas where the precipitation is less than 20 inches.

The recharge efficiencies used by Maxey and Jameson (1948) are clearly predecessor to the Maxey-Eakin efficiencies (Maxey and Eakin, 1949:41), but differ because Maxey and Jameson (1948) believed natural recharge does not occur below 10 inches of precipitation. They also used 2,000 feet altitude intervals instead of 1,000 and used a more liberal (20 percent) recharge efficiency in areas where the precipitation is less than 20 inches. Both methods assume 25 percent recharge efficiency in areas where precipitation is greater than 20 inches.

The recharge efficiencies of Maxey and Jameson (1948), Maxey and Eakin (1949), and this study are listed in Table 3 and apply to LVV or Nevada in general.

MATHEMATICAL APPROXIMATIONS

A linear regression equation was developed (using period-of-record values) for altitude versus precipitation for each of the subdivided areas. The resulting equations were then used to calculate the precipitation based on altitude for each area and are as follows:

TABLE 3. Comparison of Recharge Efficiencies Used to Estimate Recharge for Las Vegas.

Investigators: **Dates:**	Maxey and Jameson[1] 1948	Maxey and Eakin[2] 1949	**Donovan and Katzer[3]** **1999**
Precipitation Zones (inches)	**Efficiency**	**Efficiency**	**Efficiency**
< 8	0	0	**0**
8-10	0	0.03	**0.03**
10-12	0.20	0.03	**0.03**
12-15	0.20	0.07	**0.07**
15-20	0.25	0.15	**0.15**
20-24	0.25	0.25	**0.20**
24-30	0.25	0.25	**0.25**
30-36	0.25	0.25	**0.25**
> 36	0.25	0.25	**0.25**

[1]Maxey and Jameson (1948:108) used two altitude zones for the Spring Mountains, 6,000 to 8,000 feet with a 20 percent recharge efficiency, and the area above 8,000 feet with a recharge efficiency of 25 percent; in the Sheep range they applied a 20 percent recharge efficiency for the entire area above 6,500 feet.

[2]These are the standard recharge efficiencies defined by Eakin *et al.* (1951:80-81). USGS investigators deviated from these values for a variety of reasons about 37 percent of the time during their investigations in Nevada (Avon and Durbin, 1994:102). These efficiencies are based on Hardman's precipitation map (1936).

[3]This study produces a slight modification of the standard Maxey-Eakin recharge efficiencies caused by precipitation zone breakpoints.

(1) Kyle Canyon, East Central Spring Mountains, (the wettest area analyzed):

$$P = 0.000309(A) - 0.2716 \quad (1)$$

(2) Lee Canyon:

$$P = 0.000293(A) - 0.6470 \quad (2)$$

(3) Western Spring Mountains, Ivanpah Valley, and McCullough Range:

$$P = 0.000193(A) - 0.0839 \quad (3)$$

(4) Sheep and Las Vegas Ranges (the driest area analyzed):

$$P = 0.000134(A) - 0.0257 \quad (4)$$

where P = precipitation in feet per year and A = altitude above mean sea level, in feet.

These equations provide a rapid means to determine precipitation anywhere in the LVV drainage area. To calculate natural recharge, the same recharge efficiency (listed in Table 3) is used throughout any given precipitation interval. This method to estimate natural recharge is traditional, can be easily used with published maps, and if the maps exist in digital form, can be easily calculated.

New tools exist for this type of analysis. DEMs are available with sampling intervals of 30 meters (100 feet) or less from satellite imagery and USGS 1:2,000,000 to 1:24,000 scale quadrangle sheets (USGS, 1998). These DEMs are commonly used with GIS computer software, modeling computer software (hydrologic, hydrogeologic, geologic, and atmospheric), and satellite image analysis computer software.

These techniques do not improve the quality of the numerical recharge estimates used in hydrogeologic calculations. The quality can only be improved by increasing the number of good observations, whereas digital data only allows faster calculations.

The standard Maxey-Eakin efficiencies could have been used for this study because the natural recharge was calculated using area-altitude tables generated from GIS software. The precipitation value, however, at a given altitude was calculated from an equation and it can be paired with another equation that is a mathematical approximation of the Maxey-Eakin efficiencies. This allowed the estimates of recharge to be made quickly with minimal potential calculation error, whether the recharge is calculated using tables or calculated cell-by-cell for the ground-water model. When calculated cell-by-cell for the ground-water model, each cell of known altitude and area has a unique calculated precipitation, recharge efficiency, and natural recharge values.

The recharge efficiencies were approximated by a nonlinear regression of the average value of precipitation per Maxey-Eakin precipitation interval versus the recharge efficiencies for each interval (Figure 5). The natural recharge efficiency equation can be mathematically expressed as:

$$r_e = 0.05(P)^{2.75} \tag{5}$$

Except where the precipitation is less than 8 inches (0.67 feet), where $r_e = 0$ and is greater than 20 inches (1.67 feet), and where $r_e = 0.25$. The amount of recharge for each precipitation value is:

$$r_i = (P)(r_e) \tag{6}$$

and the total amount of natural recharge is:

$$R = \Sigma(r_i)(A_i) \tag{7}$$

where r_e = natural recharge efficiency, P = precipitation in feet per year, r_i = recharge in feet per year, R = total natural recharge in acre-feet per year, and A_i = area in acres.

The mathematical approximation of the Maxey-Eakin efficiencies calculates about 3 percent less natural recharge than if the traditional methods and the Maxey-Eakin efficiencies (Table 3) are used. The mathematical approximation approach slightly overestimates natural recharge at lower precipitation values and slightly underestimates natural recharge at higher precipitation values. Additionally the mathematical treatment allows for rapid input in the ground-water model and potentially eliminates calculation errors.

GROUND-WATER RECHARGE

Only a small percentage of the precipitation in any valley becomes natural recharge. Estimates of this natural recharge efficiency percentage for LVV vary by author (Table 3). If Maxey and Jameson's (1948) recharge efficiencies are used with the area-altitude-precipitation tables for this study, the total ground-water recharge is about 65,000 afy, or about double the published amounts. This estimate was eliminated as too large, because the discharge is significantly less. If either the standard Maxey-Eakin efficiencies or the mathematical approximation developed for this study are used with the area-altitude-precipitation tables generated for this study, the total amount of recharge estimated is about 51,000 afy – within the confines of the Las Vegas Valley Hydrographic Basin as defined by Rush (1968). This is an area smaller than that described by Maxey and Jameson (1948) and Malmberg (1965), but identical to the area described by Harrill (1976) and Morgan and Dettinger (1994). Table 4 summarizes this analysis.

The form of the Maxey-Eakin efficiency technique was rewritten as an equation for use in conjunction with the precipitation estimation technique; however, the underlying assumptions are identical. These efficiencies were used so the results calculated from the new precipitation estimates could be compared to previous investigations. The true rate of natural recharge is, of course, dependent upon a large number of factors including, but limited to vegetative cover, lithology of the soil or rock, wind speeds, and insolation. The conditions for natural recharge in LVV are probably close to optimal to retain the maximum amount of recharge – the recharge occurs at high altitude in predominately carbonate terrain. Thus the Maxey-Eakin efficiencies may actually be conservative. Investigation of the true recharge efficiencies would be a fruitful area for future researchers but beyond the scope of this study.

Within the boundary defined by Rush (1968), approximately 51,000 afy is considered the best estimate of natural recharge (compared to the discharge at 47,000 afy), although this technique may overestimate the natural recharge in two areas – La Madre Mountain and the western slope of the Sheep Range. La Madre Mountain is a spur of the Spring Mountains transverse to the main axis of the range between Red Rock and Kyle Canyons. The distal part of this spur may not receive as much precipitation as would be indicated by elevation because, according to Piper (1969), precipitation decreases on the leeward side of mountain blocks as the distance from the mountain crest increases (a rain shadow effect). Although part of the western slope of the Sheep Range is included in the Las Vegas Valley Hydrographic Basin boundary of Rush (1968), Winograd and Thordarson (1975:C89-90) suggested that ground-water flow from this area is to the west, away from LVV, and this study assumed the ground-water flow is to LVV.

Alternatively the natural recharge may be higher because this investigation assumed a maximum recharge efficiency of 25 percent (similar to the Maxey-Eakin method), and this assumption may be unwarranted. Additionally, the regression line developed for Kyle Canyon (Figure 4) underpredicts the precipitation at the two highest altitude stations and, therefore, precipitation at or above this altitude may be higher than predicted in this investigation.

Ivanpah Valley is topographically higher than, and ground-water flow is tributary to, LVV (Glancy, 1968:30). The altitude-precipitation relationship for this area is similar to the west side of the Spring Mountains, and when the Maxey-Eakin efficiencies are applied to Ivanpah Valley it yields about 6,000 afy of ground-water recharge. This brings the total natural recharge for LVV to about 57,000 afy.

A recent geochemical investigation using stable and radioactive isotopes (Pohlmann *et al.,* 1998) of

TABLE 4. Natural Recharge Estimate for Las Vegas Valley Hydrographic Basin as Defined by Rush (1968).

Elevation Range		Precipitation		Recharge	Area	Total Volume	Total Recharge
Lower	Upper	Inches	Feet	Efficiency	(acres)	(acre-feet)	(acre-feet)
Kyle Canyon, East Slope Spring Mountains (Area 1)							
1,000	2,000	4	0.33	0.00	29,062	9,590	0
2,000	3,000	6	0.50	0.00	171,478	85,892	0
3,000	4,000	10	0.81	0.03	116,812	94,605	2,649
4,000	5,000	13	1.12	0.07	54,627	61,121	4,162
5,000	6,000	17	1.43	0.13	37,255	53,196	7.084
6,000	7,000	21	1.74	0.25	23,821	41,374	10,343
7,000	8,000	25	2.05	0.25	13,418	27,451	6,863
8,000	9,000	28	2.35	0.25	6.015	14,166	3,541
9,000	10,000	32	2.66	0.25	3.693	9,839	2,460
10,000	11,000	36	2.97	0.25	1.564	4,651	1,163
11,000	12,000	39	3.28	0.25	219	718	180
		Subtotal (Area 1)			**457,964**	**402,603**	**38,444**
Lee Canyon (Area 2)							
2,000	3,000	4	0.33	0.00	5,817	1,920	0
3,000	4,000	5	0.38	0.00	19,086	7,225	0
4,000	5,000	8	0.67	0.02	12,703	8,531	143
5,000	6,000	12	0.96	0.05	10,215	9,853	446
6,000	7,000	15	1.26	0.09	8,338	10,486	985
7,000	8,000	19	1.55	0.17	7,814	12,117	2,024
8,000	9,000	22	1.84	0.25	5,765	10,628	2,657
9,000	10,000	26	2.14	0.25	3,309	7,071	1,768
10,000	11,000	29	2.43	0.25	1,170	2,842	711
11,000	12,000	33	2.72	0.25	139	380	95
		Subtotal (Area 2)			**74,358**	**71,052**	**8,828**
McCullough Range* (Area 3)							
1,000	2,000	4	0.33	0.00	21,972	7,251	0
2,000	3,000	5	0.40	0.00	63,731	25,404	0
3,000	4,000	7	0.59	0.00	27,456	16,243	0
4,000	5,000	9	0.78	0.03	2,679	2,102	54
5,000	6,000	12	0.98	0.05	4	4	0
		Subtotal (Area 3)			**115,841**	**51,004**	**54**
Sheep and Las Vegas Ranges (Area 4)							
1,000	2,000	3	0.25	0.00	35,148	8,787	0
2,000	3,000	4	0.31	0.00	89,218	27,592	0
3,000	4,000	5	0.44	0.00	56,317	24,963	0
4,000	5,000	7	0.58	0.00	45,679	26,369	0
5,000	6,000	9	0.71	0.02	42,091	29,938	587
6,000	7,000	10	0.85	0.03	42,212	35,680	1,124
7,000	8,000	12	0.98	0.05	15,095	14,782	698
8,000	9,000	13	1.11	0.07	11,723	13,051	876
9,000	10,000	15	1.25	0.09	1,918	2,392	220
		Subtotal (Area 4)			**339,401**	**183,553**	**3,504**
Grand Total					**987,564**	**708,211**	**50,830**

*Excludes Ivanpah Valley.

water from springs in the Lake Mead area east of Las Vegas Valley concluded that the recharge sources of one-third of the springs are local and low elevation due to relatively heavy stable isotopic signatures. In the hydrographic basins investigated by Pohlmann *et al.* (1998), the highest peak in the region (Muddy Peak) is less than 5,500 feet (asl) and most of the ranges are less than 3000 feet (asl). This altitude range would produce very little natural recharge from a standard Maxey-Eakin analysis using the Hardman map because the precipitation in most of this area is estimated to be less than 8 inches. The precipitation gage records indicate slightly higher precipitation values than predicted from the Hardman map, indicating potentially minor recharge. Pohlmann *et al.* (1998) introduce the possibility that natural recharge may occur at lower precipitation ranges and much lower altitude ranges than was previously thought.

Following this logic, the mathematical approximation of the Maxey-Eakin efficiency curve described above [$r_e = 0.05(P)^{2.75}$] was extended to 0 rather than being truncated at 8 inches (0.67 feet). This produced an efficiency of about 1.0 percent at 6 inches of precipitation, 0.10 percent at 3 inches, and 0.01 percent at 1 inch, and generated an estimated 3,000 afy of additional natural recharge. Using these efficiencies and including Ivanpah Valley, the combined natural recharge for LVV could be as large as 60,000 afy, which is much higher than the estimated discharge. The following tabulation summarizes the components of the ground-water budget for LVV:

INFLOW (this study)

Ground Water	**AFY**
Recharge	51,000
Inflow (Ivanpah Valley)	6,000
Total	**57,000**

OUTFLOW

Evapotranspiration (Devitt *et al.*, 2000)	**AFY**
Phreatophytes	40,000
Bare soil evaporation	7,000
Ground-Water Outflow (this study)	6,000
Total	**53,000**
Imbalance	**4,000**

The imbalance of 4,000 afy is considered well within the accuracy of the estimating techniques. For budget purposes an average of 55,000 afy of ground-water inflow and outflow is assumed.

Natural recharge can be estimated using nonreactive (conservative) chemical ions or stable isotopes (water fingerprinting). These methods compare the ratio of the chemical ion (or isotope) at a site of interest with the original value of the source water. The total quantity of the source water must be known to determine the amount of water at the site of interest, or if the amount at the site of interest is known, the total amount at the source can be calculated. Dettinger (1989) (Chloride ion) and Thomas *et al.* (1996) (stable isotopes of Deuterium, and Oxygen 18) estimated natural recharge based on these techniques.

The total amount of recharge and the percentage of the total natural recharge from the three major mountain ranges surrounding LVV (Spring Mountains, Sheep Range, and McCullough Mountains) and from Ivanpah Valley is compared in Table 5 as estimated by various investigators. Dettinger (1989:67) reported a Maxey-Eakin analysis by Harrill. The Maxey-Eakin analysis was mentioned (Harrill 1976: 50) but the results were not reported by mountain range in his model documentation.

We believe the hydrologic implications of defining greater recharge for LVV means a better understanding of the ground-water system (and in particular the ground-water budget), that when replicated in the ground-water model it will increase our confidence in the utility of the model to access impacts to the ground-water system.

DISTRIBUTION OF NATURAL RECHARGE

Documentation of the two published ground-water models of LVV (Harrill, 1976; Morgan and Dettinger, 1994) includes maps of the location and amount of recharge as used within the ground-water model by major area within the LVV. These maps allow the distribution of natural recharge estimated by these ground-water models to be evaluated spatially. The distributions (i.e., location, total amounts of natural recharge, and the percentage of total amount of recharge contributed from each part of the mountainous region surrounding the alluvial part of the valley) of this investigation and the published ground-water models are compared in Table 6. The total amount of natural recharge estimated in this investigation is larger, but the percent of total of natural recharge from each geographic area is similar to the distribution in the published models.

In these previous ground-water models only the alluvial part of the valley was modeled, the recharge was added along the edges of the model and the amounts and locations of natural recharge were changed to achieve a best fit of predicted versus actual water levels (Harrill, 1976:49-50). This is a

TABLE 5. Comparison of Natural Recharge Estimates for the LVV Ground-Water System.

Investigator(s)	Basis of Estimate[1]	Date	Spring Mountains afy[2]	Spring Mountains Percent[3]	Sheep and Las Vegas Ranges afy[2]	Sheep and Las Vegas Ranges Percent[3]	Ivanpah Valley and McCullough Range afy[2]	Ivanpah Valley and McCullough Range Percent[3]	Totals (rounded) afy[2]
Maxey and Jameson[4]	P	1948	27,200	79	7,200	21	*	*	34,000
Malmberg	D	1965	19,700	94	1,300	6	100	< 1	21,000
Harrill[5]	P	1976	16,300	56	13,000	44	*	*	29,000
Harrill	D	1976	24,100	82	2,300	8	3000	10	29,000
Dettinger	G	1989	17,000	61	11,000	39	*	*	28,000
Morgan and Dettinger	D	1994	27,700	84	2,900	8	2,500	8	33,000
Thomas *et al.*	G	1996	29,000	92	2,500	8	*	*	32,000
Las Vegas Valley Only									
Donovan and Katzer	**P**	**1999**	**47,300**	**93**	**3,500**	**7**	**100**	**< 1**	**51,000**
Las Vegas Plus Ivanpah Valley									
Donovan and Katzer	**P**	**1999**	**47,300**	**84**	**3,500**	**6**	**5,800**	**10**	**57,000**

*No value reported.
[1]P = Precipitation; D = Darcy; and G = conservative ion or stable isotope.
[2]afy = acre-feet per year.
[3]Percent of investigator(s)' total.
[4]Calculated from original precipitation and recharge efficiencies of Maxey and Jameson (1948:107-107).
[5]Reported by Dettinger (1989).

TABLE 6. Comparison of Natural Recharge Estimates by Major Drainage.

Investigator(s): Date: Drainage:	Harrill 1976 Recharge afy	Harrill 1976 Percent of Total	Morgan and Dettinger 1994 Recharge afy	Morgan and Dettinger 1994 Percent of Total	Donovan and Katzer 1999 Recharge* afy	Donovan and Katzer 1999 Percent of Total
Spring Mountains						
Lee and Kyle Canyon	17,000	58	18,700	57	**34,000**	**60**
Red Rock Canyon	7,100	24	9,000	27	**12,700**	**23**
(Sub-Total)**	24,100	82	27,700	84	**47,300**	**83**
Sheep and Las Vegas Ranges						
Las Vegas Range (Gass Peak)	680	2	400	1	**300**	**< 1**
Sheep Range Proper	1,600	6	2,500	8	**3,200**	**6**
(Sub-Total)	2,280	8	2,900	9	**3,500**	**6**
Southern Las Vegas Valley						
Ivanpah Valley and Sloan Hills	2,500	8	1,800	5	**6,400**	**11**
McCullough Range Total	460	2	700	2	**100**	**< 1**
(Sub-Total)**	2,960	10	2,500	7	**6,500**	**11**
Grand Total	29,340	100	33,100	100	**56,700**	**100**

*All values rounded to nearest 100.
**Adjusted to reflect areas as described in model documentation (Harrill, 1976:51; Morgan and Dettinger 1994:83).

common abstraction (not an actual analysis of the natural recharge) but rather an investigation of aquifer dynamics.

The amounts and locations of natural recharge estimated in this investigation are a result of using the Maxey-Eakin efficiency curve approximations with the area-altitude-precipitation tables created for this study. It is, consequently, a precipitation-recharge investigation, not an investigation of aquifer dynamics. Therefore, the similarity between the way natural recharge is distributed in earlier models and in this study is significant and lends support to the validity of this approach.

DISCUSSION

Although the relationship between altitude and precipitation varies by geographic area, the relationship between precipitation and recharge efficiency was consistently applied.

Estimates of natural recharge rely on a number of variables that are themselves estimated because they cannot be directly measured. Consequently, it is common and necessary when estimating a basin budget, to derive a companion study of natural discharge that is estimated from an independent set of variables. Therefore, this investigation most carefully evaluated studies that included estimates for both natural recharge and natural discharge. To evaluate natural recharge estimates both the total amount of natural recharge and the way it is spatially distributed are important (Tables 5 and 6) because the natural hydrologic system should be replicated as close as possible to increase confidence in understanding the ground-water system.

If 57,000 afy (with Ivanpah Valley) is the approximate value of natural recharge, this creates a large imbalance in the water budget using Malmberg's (1965) natural discharge estimate of 24,000 afy. Results of a new phreatophyte discharge study (Devitt *et al.*, 2000) based on Malmberg's (1965) reconstruction of predevelopment conditions indicate the consumption by phreatophytes and bare-soil evaporation in LVV was about 47,000 afy prior to ground-water development. Additive to the phreatophyte and bare-soil discharges is about 6,000 afy of ground-water outflow exiting LVV in the vicinity of Las Vegas Wash, yielding a total discharge of 53,000 afy. The resulting imbalance of 4,000 afy in the water budget is considered well within the accuracy of the estimating techniques. As indicated previously, an average value of 55,000 afy best represents the ground-water inflow and outflow.

Evaluation of the older methods of natural recharge approximation reveal that most of the methods would produce larger estimates if the area-altitude-precipitation tables created for this investigation (Table 3) were used in conjunction with these methods.

The large-scale precipitation maps of Hardman (Hardman, 1965) and PRISM (Daly *et al.*, 1994, 1997) that cover the entire state of Nevada tend to minimize the local large spatial variation in the altitude-precipitation relationships observed in this investigation. These maps tend to underestimate (compared to the gage records) the amount of precipitation in the Spring Mountains, and Kyle Canyon in particular (Figure 2). This investigation, although precipitation based, concluded that most of the natural recharge is from the Spring Mountains.

Because the natural recharge estimated in this investigation has a percentage distribution similar to the earlier models, it is anticipated that the natural recharge can be placed on the mountain blocks. In the new hydrogeologic model of LVV currently under development natural recharge was placed where it actually occurs rather than added to the edge of the alluvium, as was done in earlier models. Preliminary model calibration runs indicate this technique is acceptable.

Because the Maxey-Eakin efficiencies and altitude-precipitation relationships were approximated in a mathematical form as part of this investigation, the technique can be applied on a cell-by-cell basis. This produces about 3 percent (50,800 versus 49,300 afy) less total natural recharge in the ground-water model than the traditional tabular method described previously, primarily because of the coarseness of the cells (1320 feet) compared to resolution of the DEMs (75 feet) used to calculate acreages in the area-altitude-precipitation table produced from GIS software. The reduction in recharge primarily occurs in the Spring Mountains.

SUMMARY

The total amount of precipitation for LVV (708,000 afy) estimated by this technique falls at the high end of the range of values calculated from processing the published maps through GIS software. The location and amount of the precipitation is based on gaged values. The increase in natural recharge is primarily the result of an increase in the estimate of precipitation at high altitude in Kyle Canyon and the east slope of the Spring Mountains. This investigation determined local altitude-precipitation relationships by dividing

LVV into geographic areas then regressing measured precipitation data against altitude. Efficiency factors based on the Maxey-Eakin efficiencies were then applied to estimate natural recharge. The natural recharge estimated in this investigation may be as large as 60,000 afy of which 6,000 afy is tributary from Ivanpah Valley and about 3,000 afy from low altitude recharge. The value selected to best represent natural recharge is 55,000 afy, the average between ground-water inflow and outflow and does not include the low altitude recharge. This value is 75 to 250 percent higher than previously published natural recharge estimates. The hydrologic implications of greater recharge leads to better understanding of the ground-water system that will allow a futher refinement of the new hydrogeological model being developed for LVV, which means a better estimate of ground-water levels for steady and nonsteady state conditions.

Even though the new natural recharge estimate is considerably larger than previously believed, this does not increase the total amount of water available for use because LVV has been overdrafted for decades and the total use of ground water, about 76,000 afy (Coache, 1998:1), is still much larger than the natural recharge estimate.

The spatial distributions of the natural recharge in this investigation are also consistent with the previous hydrologic models and conservative ion and stable isotope analyses. Unlike earlier models, the natural recharge will be distributed on the mountain blocks, where it actually occurs, rather than being distributed around the edges of the alluvial part of the aquifer-system.

The new water budget indicates about 57,000 afy of inflow to LVV and 53,000 afy (47,000 afy ET, plus 6,000 afy ground-water outflow) of natural discharge. The imbalance of 4,000 afy is within the accuracy of the estimating techniques.

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HYDROLOGIC IMPLICATIONS OF GREATER GROUND-WATER RECHARGE TO LAS VEGAS VALLEY, NEVADA

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