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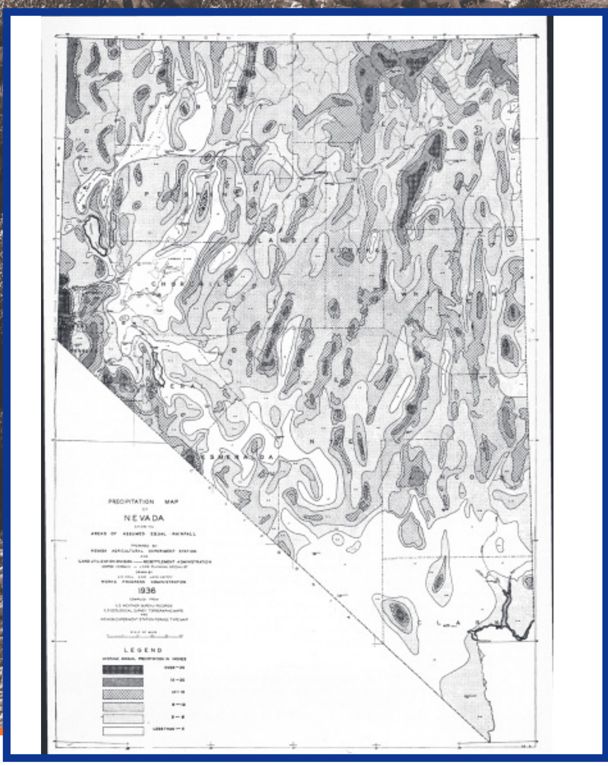

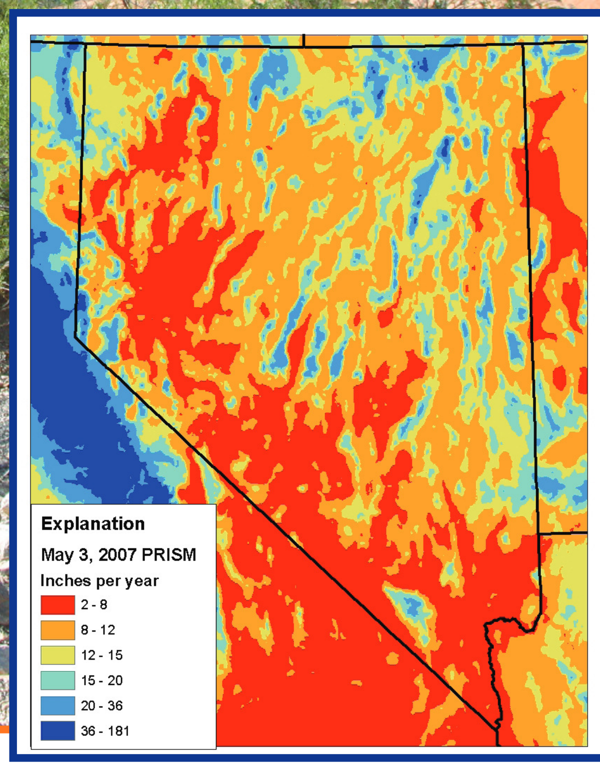

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PREFACE

Water resource evaluation in the west, especially in the Great Basin, starts with estimations of surface water runoff, ground-water recharge and evapotranspiration. In Nevada, the Department of Conservation and Natural Resources, in conjunction with U.S. Geological Survey began reconnaissance level studies in the 1940s. This was the first attempt at estimating a water budget for Nevada's basin and range valleys, the first attempt at quantifying the amount of water available for use.

These first studies were conducted by a small number of dedicated geologist and hydrologists, covered a vast remote area and were completed in a relative short period of time. Over the 1940s to 70s over two hundred valleys were investigated in areas with very limited data. Precipitation data were sparse as were spring flow, stream flow, and ground-water level measurements. Evaporation and plant transpiration rates were based on historical estimated literature values, not rates measured in the specific study valleys. After all, these were reconnaissance level studies conducted in the mid twentieth century.

The Maxey-Eakin technique arose from some of the earliest studies that utilized the Hardman Precipitation Maps for estimating ground-water recharge. As these reconnaissance level studies continued over the next twenty years, the Maxey-Eakin technique was revised by investigators as necessary to address valley-specific conditions; while still utilizing the basic premise of the Maxey-Eakin technique which is that the greater the altitude, the greater the percentage of precipitation that becomes ground-water recharge.

As water resource studies continued after the reconnaissance studies, more sophisticated measuring devices were developed for evapotranspiration (and valley specific measurements were collected), more precipitation stations (many at high altitudes) were installed, and the computing capabilities exploded with digital elevations and aerial imagery. However, in spite of this additional data, when preparing a water budget, one must estimate the ground-water recharge. That brings the investigator back to altitude – precipitation relationships and in many studies this means a variation of the Maxey-Eakin technique.

This report is an attempt to document the historical evolution of estimating ground-water recharge over the past 60 years in Nevada's Basin and Range valleys. The authors wish to stress that this paper is just a history designed, hopefully, to document the various techniques and results of studies to define the water budgets in these Nevada valleys, and to provide a reference for hydrologists working in Nevada ground-water basins. There is no intent to imply a "right" method or a ground-water recharge estimate, just an attempt to document some of the results of numerous hours of study in the human endeavor to understand Nevada's Basin and Range hydrology.

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ABSTRACT

The U.S. Geological Survey in cooperation with the State of Nevada conducted the first ground-water recharge study in Nevada in the 1940s. The study focused on Las Vegas Valley and the program was later expanded to include the entire state. Most of the studies conducted under this cooperative program were reconnaissance in nature, which gave the investigators scant time to compile an in-depth hydrogeologic database. During this time the traditional Maxey-Eakin method was developed. The published geologic maps provided the geologic framework that controls the movement of ground water and an existing state-wide precipitation map was used to estimate the volume of precipitation available for ground-water recharge and surface-water runoff. Evapotranspiration studies in areas other than Nevada - some in the Great Basin - provided the first estimates of water use by phreatophytes. In many valleys investigators used local precipitation data rather than the state-wide map to estimate precipitation. As the cooperative program moved into the late 1970s and beyond investigators began using different techniques and databases to estimate ground-water recharge.

The fundamental assumption of hydrologic budgets is that ground-water recharge must equal ground-water discharge, taking into consideration changes in ground-water storage and outflow. Because ground-water discharge occurs on valley floors in the near-surface hydrologic environment, most of the physical processes governing evapotranspiration can be instrumented with micrometeorological equipment to determine the ground-water loss; this type of data collection began in Nevada in the 1970s and provides an estimate of discharge that, by definition, should equal recharge.

In general this effort resulted in higher estimations of evapotranspiration rates than originally used in most of the reconnaissance studies. A higher ground-water use rate by phreatophytes means the ground-water recharge must also be higher than originally estimated. Thus, ground-water budgets are considered by some investigators to actually be greater than originally estimated in the early studies.

The transition from the 60-year-old Maxey-Eakin method of estimating ground-water budgets has been accelerating over the past 20 years with the improvement of equipment and methods of measuring evapotranspiration and the analyses of other long-term hydrologic data. This includes investigations by the U.S. Geological Survey, the Desert Research Institute (part of the University of Nevada System of Higher Education), and the Las Vegas Valley Water District/Southern Nevada Water Authority. The use of hydrologic models is becoming more and more prevalent by the U.S. Geological Survey and other entities. These models rely on meteorological data, updated precipitation maps, satellite images, geological data, and other data that can be represented in a ‘Geographic Information System’.

The section on geologic control of ground-water recharge in Spring Valley emphasizes the role of permeability of the rocks that water moves through to reach ground-water aquifers. The analysis depends, in part, on defining the amount of surface-water runoff from the recharge area in the mountain block.

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INTRODUCTION

Nevada is located within the Basin and Range structural province (Fenneman, 1931; Fenneman and Johnson, 1946) and encompasses portions of three hydrologic provinces; the Great Basin, the Colorado River, and the Snake River Plain (Rush, 1968). The state was further subdivided into 253 distinct hydrographic basins (Rush, 1968), and has since been divided into 256 hydrographic areas and sub areas. Many basins are connected by surface drainage, such as provided by a few major river systems and numerous ephemeral washes. Additionally, ground water in numerous basins, particularly in central, eastern, and southern parts of the state, is in hydraulic continuity with adjacent basins through underlying permeable carbonate rocks (Harrill and Prudic, 1998).

In 1943 O. E. Meinzer, then Director of the U.S. Geological Survey (USGS), Ground-Water Branch, authorized the first of the cooperative water-resource investigations with the State of Nevada (Shamberger, 1991). Dr. Meinzer assigned George B. Maxey, an assistant geologist at the time, to conduct the first study in Las Vegas Valley. George Maxey continued a close association with all aspects of Nevada hydrogeology for the remainder of his life and is referenced throughout this study in regard to ground-water recharge.

In subsequent years, the USGS conducted water-resource studies in all of Nevada's basins in cooperation with the Nevada Department of Conservation and Natural Resources (NDCNR). Within that department are the State Engineer's office and the Nevada Division of Water Resources (NDWR). The NDWR allocates and regulates the ground- and surface-water resources of the state and has relied on the technical expertise of the USGS to estimate these resources. Most of these early studies were done at a reconnaissance level, some with greater in-depth evaluations depending on the state's priority at the time. During the past 30 years there have been completely funded federal water-resource investigations authorized by the U.S. Congress for the USGS and the Desert Research Institute (DRI). Additionally, some federal agencies provide direct funding for the USGS and DRI. There are numerous other entities cooperating with the USGS and DRI including counties, cities, and water districts that have contributed funding for water-resource studies. In addition, some entities perform their own water-resource evaluations and estimate ground-water recharge, the focus of this study.

This report provides a summary of multiple analyses that have evolved from previous reconnaissance studies and presents an analysis of the impact that lithologies of different permeabilities have on the distribution of ground-water recharge.

Purpose and Scope

The purpose of this study is to document the historical and traditional ground-water recharge methodologies developed by the USGS in Nevada and used for administrative purposes by NDWR. Historically, NDWR has used estimates of ground-water discharge as the basis for the available water supply, i.e., the perennial yield. However, in many basins where there is insufficient information to accurately determine the amount of ground-water discharge, the available resource is based on estimated recharge. The primary recharge method utilized by the state through the 1990s was commonly referred to as the Maxey-Eakin method. More recently the state has adopted a variation of the Maxey-Eakin method combined with an updated precipitation map. Additionally, the purpose of this study is to briefly discuss some recent USGS ground-water recharge studies by Harrill and Prudic (1998), Nichols (2000a, b, and c), Berger (2000a and b), Hevesi and others (2002; 2003), Belcher (2004), Flint and others (2004), and a University of Nevada Reno study by Epstein (2004).

These publications are progressively more computationally intensive, and each introduces features that will likely be incorporated into future recharge estimates. This body of work shows the transition from the traditional reconnaissance method of estimating ground-water recharge to more computer- intensive methods.

The scope of the current paper is to compare the traditional application of the Maxey-Eakin method by the USGS and DRI to the modified methodology developed by the Las Vegas Valley Water District (LVVWD) and Southern Nevada Water Authority (SNWA) and applications to selected basins in eastern and southern Nevada. A recent analysis by SNWA is also presented to quantify the control on ground-water recharge imposed by the type of geology in one basin in eastern Nevada.

HYDROLOGIC PROCESSES

Water that falls as rain or forms from melting snow in a mountain block is subjected to three hydrologic processes: evapotranspiration (ET), mountain front runoff, and ground-water recharge. The ET process includes sublimation directly from snow and evaporation from open water bodies and bare soil as well as transpiration by plants. Mountain front runoff is surface water that exits the source areas as streamflow (which includes springflow). Any remaining water is considered ground-water recharge, and is the residual in the following equation:

$$\text{Precipitation} - (\text{ET} + \text{Mountain Front Runoff}) = \text{Ground-Water Recharge} \qquad (1)$$

This equation infers that all water is accounted for, but in actuality there is always an unknown amount present in the vadose zone that varies with time. Water in the vadose zone is either transferred by ET to the atmosphere or contributes ultimately to ground-water recharge with an unknown minor amount always considered as specific retention. Thus the vadose zone plays an important role in the hydrologic processes by acting as a holding tank for phreatophyte (plants that send their roots to the water table) zone by storing precipitation until it either ETs back to the atmosphere or infiltrates past the effective depth from which phreatophytes can withdraw water, thereby ultimately reaching the water table. There is a constant interchange of water between the water table available to phreatophytes (maximum about 50 ft below land surface) and the vadose zone. Throughout the growing season, phreatophytes depend on the vadose zone for their water supply. As this supply becomes depleted, the plants switch to using ground water (Thomas, J. T. written communication 8/18/08). During wet years, most of the ET demand may be supplied by precipitation (includes surface-water run on) and the ground-water table, in response to ground-water recharge, rises throughout a valley. This analysis ignores anthropogenic use. During dry years when the vadose zone has minimal water, the phreatophytes depend more on ground water and the water table declines in response to this increased demand.

The details of this process are a traditional (Meinzer 1927, Robinson, 1947) and active area of research (Thomas, written communication 8/18/08, based on current research, and Devitt, in review, 2008). The best areas of current research are interdisciplinary studies that integrate hydrology, and agricultural engineering from older literature with more recent soil physical, isotopic, meterological, and wildland ecology studies.

Ground-water inflow to some valleys can occur as interbasin flow, but that water originated in adjacent valleys as ground-water recharge resulting from precipitation. Examples of interbasin ground-water flow are documented by Eakin (1966) for the White River Flow System (WRFS) and by Prudic and others (1995) for the Death Valley Flow System (DVFS). These two vast flow systems consist of a series of valleys that are hydraulically connected at depth through a complex aquifer system of Paleozoic carbonate rocks. Other valleys in the state are part of smaller regional flow systems, and many valleys are considered single ground-water systems. Some of the valleys in these regional systems are closed topographically so there is no surface-water outflow. However, many valleys are connected by through-flowing perennial rivers such as the Truckee, Carson, Walker, and Humboldt river systems of western and northern Nevada and the Meadow Valley Wash and Muddy River in southeastern Nevada. There are also numerous valleys that are connected by ephemeral drainages such as the White River system in central and southern Nevada.

Ground-Water Recharge

Ground-water recharge is controlled by precipitation, evapotranspiration, surface-water runoff. These three interrelated hydrologic processes have numerous controlling parameters and a wide range of variability. The main parameters governing these processes are as follows:

- Precipitation storm track, type, temperature, intensity, amount, and altitude/area distribution
- Evapotranspiration solar radiation, temperature, humidity, wind, aspect, land cover (plant type and density) and available moisture
- Surface-water runoff slope, depth and type of soil, lithology and earth structure, sediment size, land cover, and density of drainage pathways

In addition to these three processes, ground-water recharge is also controlled by the hydrogeological setting of the recharge area, which includes the permeability of the soil and/or rock, depth of soil, aspect, slope, vegetation, and temperature.

Because of the wide variability in these parameters from one mountain range to another and from one drainage to another within the same range, precipitation, ET, runoff, and ground-water recharge are difficult to determine. The water-budget component with the largest volume is precipitation, followed by ET, which occurs wherever precipitation occurs.

Surface-water flow in ephemeral or perennial streams in any given valley provides some amount of ground-water recharge as the drainages cross alluvial fans and even valley floors depending on the volume and frequency of flow, depth to ground water, and the character of the sediments. Ground-water recharge also results from irrigation of landscapes and agricultural land, which is commonly termed secondary recharge.

Thus ground water, which started as surface water, reappears through specific springflow orifices or as diffuse springflow and is considered once again to be surface water. This surface water is subject to ET during its transient time in the valley and also, depending on other hydrogeologic parameters, may re-infiltrate the channel bed to the ground-water system in the mountain block and under the alluvial fans. Springflow that does not reach a channel in sufficient volume to create runoff is probably lost to ET with some portion re-infiltrating to the ground-water system once more becoming ground-water recharge.

Natural Ground-Water Discharge

Natural ground water is discharged in hydrographic basins by two processes. The first that occurs in time is through ET in the main recharge area in the mountain blocks, which accounts for much of the precipitation, but is not considered in the ground-water recharge process. ET by phreatophytes in the valley lowland is, however, quite common in most of the basins in Nevada, although there are numerous basins in southern Nevada where the depth to ground water precludes the existence of phreatophytes. Typical ET on the valley floors or lowlands includes these elements: large areas with low discharge rates from phreatophytes; bare soil; open water, spring (paludal) and riparian (stream); and agricultural areas that may be small in size but have rates similar to the Potential Evapotranspiration (PET), which is generally considered the maximum rate for an open water body.

There are numerous springs in virtually all the mountain blocks in the state with many of the springs located along mountain front faults. Generally the discharge from these springs is small, but there are exceptions. Ground-water discharge from springs is considerable in some areas, particularly from carbonate rocks on valley floors in the eastern and southern part of the state. These springs are generally considered regional because the discharge is large and the water temperature is elevated above the ambient air temperature at the spring, which usually indicates recharge from more than one valley is contributing to the spring, but of course there are exceptions.

The second natural discharge process is termed ground-water outflow and occurs when there is a hydraulic gradient from one valley to another and there are no hydrogeologic barriers that prevent ground-water flow. Outflow generally occurs through permeable rock aquifers underlying alluvial ground-water systems. This is quite common in the basins of central, eastern, and southern Nevada where ground-water is hydraulically connected over a very large area through Paleozoic carbonate rocks. (Harrill and others 1988) Ground-water outflow can also occur through alluvium in valleys that are connected by perennial or ephemeral drainages.

Alteration of the hydrologic system by artificial discharge by wells and other anthropogenic activities is also relatively common and a factor in the consideration of whether a water budget is a steady state, transient or current conditions budget. The usual goal of a Maxey-Eakin estimate is a steady state water budget. A complete water budget also includes a description of the volumes and locations of the artificial discharge through time.

METHODOLOGIES FOR ESTIMATING GROUND-WATER RECHARGE

The multiple methods of estimating ground-water recharge that have been utilized can be categorized as either "Direct" or "Non Direct" methods.

Direct

One direct way to measure the amount of ground-water recharge in any area is to install lysimeters (large tanks filled with native soil) in the unsaturated zone to measure the water content of the soil column as it changes with depth and time resulting from natural or artificial precipitation events. Lysimeters, according to Meinzer (1942, p. 406), have been in use since 1796. Another way to gather data is to install a meter or device that will measure the vertical flux as water infiltrates into the soil or rock and moves down past the root zone and the effective depth where evaporation occurs. These data will define the depth where ET becomes ineffective and ground-water recharge occurs. A major criticism of the devices used to date is that they require disturbing the soil column. If the devices are operated long term, however, the soils will stabilize. The principal disadvantage of all methods that collect point data, is that a large number of installations are needed to reduce the variability of spatial analysis and they must be maintained and operated over long periods of time, such as is done for surface-water gaging stations, ground-water level networks, and precipitation stations.

Non Direct

Many investigators have discussed the numerous and varied techniques used to estimate ground-water recharge in Nevada, including the empirical Maxey-Eakin method featured in this paper. For instance, Watson and others (1976), Avon and Durbin (1994), and Belcher and Elliot (2001) list most of these techniques including those that depend on geochemistry. Since 2001, a number of additional, primarily modeling, techniques have been proposed, some of which are cited in the later portion of this report. This paper concentrates on altitude-precipitation relationships and recharge efficiencies because they directly use precipitation data.

MAXEY–EAKIN METHOD

The first reference to the development of the 'Maxey-Eakin' method of estimating ground-water recharge in Nevada is by Maxey and Eakin (1949, p.40) who evaluated 13 valleys to determine their recharge efficiencies. Later, Eakin and others (1951, p. 151), indicated that preliminary recharge studies in 15 valleys in east central Nevada were used to develop the recharge percentages. Undoubtedly recharge-discharge work was going on in other valleys. The work to develop the recharge efficiencies in the 13 or 15 valleys is unpublished and not referenced by Eakin and others (1951). Watson and others (1976, p. 240), based on a personal communication with Maxey, state that an additional 8 valleys were also used to develop the recharge percentages (Watson and others 1976, p. 240, Table II). Eakin refutes this (oral communication, 2006) and is explicit in his restatement that only 13 valleys were used to develop the recharge percentages. It is only of historical interest because by 1949, the method had been developed and no additional refinements were made even though additional valleys were studied.

The earliest hydrogeologic investigations in Nevada (Meinzer 1923, Bixby and Hardman, 1928), emphasized the physical features of typical Nevada valleys and the likelihood that most ground-water recharge (deep percolation) physically occurs near the bedrock-alluvial interface termed the "intake zone" in Meinzer (1923) with the water coming from higher altitudes. Hardman and Mason (1949, p. 11) indicated that the areas that receive greater than 20 inches of precipitation define the recharge areas. Based on these ideas, the Maxey-Eakin technique (Maxey and Eakin, 1949) appears to be a reasonable non-unique set of coefficients linked to the precipitation rate and physical conditions of a typical Nevada valley including form and timing of the precipitation, type of exposed bedrock, thickness of soil cover, runoff and deep percolation (recharge).

Historical Development in Las Vegas Valley

Maxey and Jameson (1948) are credited with the first ground-water recharge estimates made in the State and specifically in Las Vegas Valley. Their study was based in part on a ground-water recharge estimation technique that Jameson was familiar with in the Roswell Basin in New Mexico based on a relationship between altitude and precipitation (Hugh Shamberger, former State Engineer and Director of the NDCNR, oral communication, ca 1983). Eakin and others (1951, p.80) reference the Roswell study by Fiedler and Nye (1933, Figure 33, p. 246) who developed an altitude-precipitation relationship and used it to estimate the total amount of precipitation for the Roswell Basin in New Mexico stating: "Less than 25 percent of the precipitation plus run-off from tributary streams that flow across the area is ground-water recharge." They specifically indicated that they could not estimate the percentage of precipitation that becomes ground-water recharge without additional data.

The basis for this approach and the Maxey-Eakin (1949) method that followed is this: because precipitation increases with altitude, so should ground-water recharge, based on the logical assumption that higher rates of precipitation and lower ET and temperature at higher altitudes should result in higher volumes of recharge.

The method utilizes the relationship between precipitation amount and ground-water recharge, not the relationship between precipitation and altitude. Altitude is only critical to estimate the spatial distribution of precipitation.

Maxey and Jameson (1948) in their work in Las Vegas Valley used the few local, low altitude precipitation stations available and one reasonably high altitude station in Kyle Canyon. They divided the mountain ranges surrounding the valley into altitude-precipitation zones; three in the Spring Mountains and two in the Sheep Range. They determined the area in each zone and using their altitude-precipitation relationship determined the volume of precipitation. The amount of ground-water recharge was estimated by multiplying the volume of precipitation in each altitude zone by the recharge efficiency, which is the percentage of precipitation that becomes recharge. The development of the recharge efficiencies they used is undocumented. Even though they did not specifically map the ET areas, they did estimate the discharge from areas of shallow ground water, on the valley floor. The fate of ground-water discharge from wells and springs was attributed to ET.

Development of Precipitation Maps

Bixby and Hardman (1928, p. 8) first documented an increase in precipitation with altitude in Nevada. They based their conclusions, in part, on two studies. The first by L. H. Taylor (1902) who estimated an increase of 12.8 inches of precipitation per 1,000 ft of altitude rise in the Truckee River Basin, of northwestern Nevada and eastern California. The other work is by W. O. Clark and C. W. Riddell (1920) who estimated an increase of 4.5 inches of precipitation per 1,000 ft of rise in the Steptoe Valley drainage of eastern Nevada. Bixby and Hardman (1928, p. 12) also concluded: "It is this concentration of the total rainfall in comparatively small areas that makes possible a relatively large amount of underground storage in a region of extremely scanty precipitation."

To estimate the volume of precipitation, the USGS primarily used precipitation maps developed by Hardman 1936, 1949, 1962 and 1965, in respectively Hardman (1936), Hardman and Mason (1949), Lamke and Moore (1965) and Hardman (1965). As best as can be determined, there were 70 precipitation stations available to Hardman (1936); their locations are shown on figure 1. The maximum station length for these stations in 1936 is 50 years, and the minimum is two years. However, it is quite probable Hardman used: an *ad hoc* precipitation network, his knowledge of water use rates by natural vegetation, and his analyses of precipitation based on his pioneering dendrochronlogy to supplement data from existing official precipitation stations. Hardman (1948) states that there were 107 sites. The later maps were modified to reflect new topography, and in some geographical areas the amount of precipitation changed considerably. In subsequent studies, USGS Scientists George Maxey and Thomas Eakin refined ground-water discharge estimates to estimate recharge with the assumption that the ground-water systems they studied were in a steady state where recharge equals discharge.

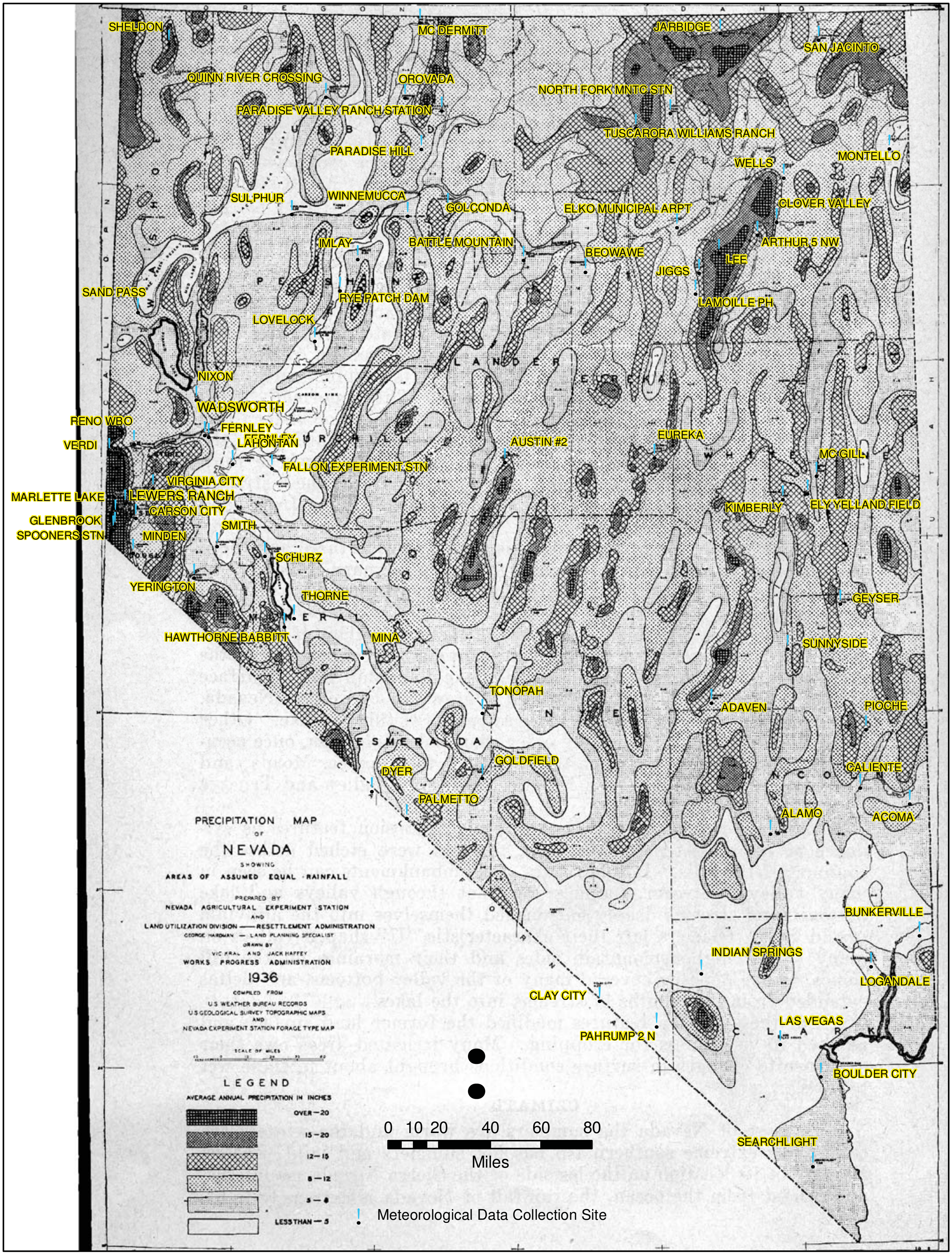

Figure 1. Hardman (1936) precipitation map and records available prior to 1936, from the files of the National Climate Data Center (NCDC) daily records

The Hardman (1965) map is similar to the 1936 map except the precipitation zones are lowered by approximately 1,000 ft along with the corresponding recharge efficiencies; i.e., the 12- to 15-inch precipitation zone starts at 6,000 feet altitude instead of 7,000 feet altitude. Thus, the 1965 precipitation map shows more precipitation than the 1936 precipitation map. For example, in Las Vegas Valley (entire drainage area), it amounts to about 40 percent more precipitation, and in Spring Valley (entire drainage area) precipitation is about 70 percent greater. The 1965 map is more locally detailed, and is clearly influenced by altitude; and the altitude – precipitation relationship varies spatially, however, precipitation contours do not precisely correlate with altitude contour lines in any area. There are only 63 precipitation stations (including Zorra Vista and Downeville) shown on the map; the fate of Hardman's (1948) additional 44 stations is unknown.

SNWA (2007, Table 5-4, p. 5-17) provided a Geographic Information System (GIS) comparison and description of the differences in precipitation between the Hardman (1962) map, and the reconnaissance studies in Cave, Dry Lake, and Delamar Valleys in east-central Nevada. These studies were performed by Eakin (1962, and 1963a) who used a slightly different version of the 1962 map. The original size of the map is 8.5" by 11" and is in Bulletin 30 (Lamke and Moore, 1965, figure 1 p. 5), with a date of November 1962 specified on the figure. Using GIS processing, the 1962 and 1965 maps were rectified and visually compared and are very similar. Apparently the Hardman 1965 map is the end version of several modifications to the 1936 map.

Normal GIS processing is a combination of software and operator choices and hence uncertainties are introduced by scaling, rectification (warping of image to conform to a specified coordinate system), and conversion to vector data. As a result, the exact locations of the intended positions of the contours are not certain and can vary between analyses. These differences are minimized and the errors in the analyses are easier to identify if large contiguous areas are analyzed. To provide examples, we developed a preliminary assessment of the differences between the Hardman (1936 and 1965) maps in Las Vegas and Spring Valley, the results of which are shown in table 1. Due to the GIS considerations it is likely that these numbers will be refined in subsequent analyses; however, they are considered to be of the correct magnitude.

Table 1. Precipitation and recharge comparison of the Hardman (1936,1965) precipitation maps in acre-feet/year

	Precipitation		Recharge	
Area	Hardman (1936)	Hardman (1965)	Hardman (1936)	Hardman (1965)
Spring Valley Northern Schell Creek Range[1]	237,800	240,600	13,300	15,800
Las Vegas Valley Spring Mountains	237,400	250,300	6,600	7,400

1. Schell Creek Range north of Cleve Creek in Spring Valley.

The mountain ranges in the example shown in table 1 show a consistent and non-uniform relationship between the two maps with nearly a 20 percent increase in recharge in the northern Schell Creek Range north of Cleve Creek in Spring Valley and about a 10 percent increase in the Spring Mountains in Las Vegas Valley.

The nonlinear relationship between total volume of precipitation and total estimate of recharge is caused by the inherent nonlinear relationship of the Maxey-Eakin coefficients. There is an inbuilt preference (large percentages) for the relatively small portions of an individual; valley with greater rates of precipitation. These are usually the mountain blocks which are only a small percentage of the total area of the valley. The inbuilt preference exists in the standard coefficients of Maxey-Eakin, reproduced in table 2, and all subsequent analysis. The same percentages are also used in reports that explicitly use Hardman's later precipitation maps, including Harrill (1968) and Rush (1971).

Maxey-Eakin Precipitation Zones

The standard Maxey-Eakin precipitation zones based on the Hardman map (1936), and the corresponding precipitation amounts and recharge efficiencies are listed in table 2. The recharge efficiencies are the estimated amount of precipitation in the various precipitation zones that becomes ground-water recharge.

Table 2. "Standard" Maxey-Eakin assumptions used to estimate precipitation and ground-water recharge[1].

Precipitation zone (in)	Altitude zone (ft)	Average annual precipitation (ft)	Recharge efficiency (%)
More than 20	More than 9,000	1.75	25
15 to 20	8,000 to 9,000	1.46	15
12 to 15	7,000 to 8,000	1.12	7
8 to 12	6,000 to 7,000	0.83	3
Less than 8	Less than 6,000	Variable	Negligible

1. Eakin (1966).

Development of Recharge Efficiencies

Meinzer (1932, p. 103) indicated that ground-water recharge studies began in the seventeenth century, and one of the most common methods developed since then applies a percentage (i.e., the recharge efficiency) to the precipitation, and the resultant value equals the annual ground-water recharge. Meinzer further indicates this method of estimating ground-water recharge by applying percentages to the amount of precipitation: "…is of little value, however, except to give an idea of maximum possibilities, unless there is a reliable basis for the percentage that is assumed." The only *reliable basis* referred to must be a direct measurement of either recharge or discharge. Ground-water discharge is easier to measure than ground-water recharge; therefore, the measurement of discharge provides a reasonable basis for estimating ground-water recharge.

All of the actual and potential valleys used to develop recharge efficiencies are listed in table 3.

Table 3. Valleys used by Maxey-Eakin to develop the range of recharge efficiencies.

Hydrologic basin number	**Hydrologic valley**	**Hydrologic basin number**	**Hydrologic valley**
Original valleys referenced by Maxey and Eakin[1]		Additional valleys not referenced by Maxey and Eakin, but referenced by Maxey[2]	
157	Kawich	69	Paradise
161	Indian Spring	117	Fish Lake
162	Pahrump	129	Buena Vista
170	Penoyer	137	Big Smokey N.
173A	Reveille	138	Grass
173B	Railroad	153	Diamond
176	Ruby	156	Hot Creek
184	Spring	177	Clover
186	Antelope N.	--	--
187	Goshute	--	--
188	Independence	--	--
207	White River	--	--
212	Las Vegas	--	--

1. Maxey and Jameson, 1948; Maxey and Eakin, 1949; Eakin and others, 1951.
2. Watson and others (1976, p. 240).

Subsequent USGS studies most commonly cite Eakin and others (1951, p. 79-81) as the origin of the Maxey –Eakin technique where it states:

> "…the recharge (efficiencies) percentages agree reasonably well with those obtained in Las Vegas Valley, Nevada and the Roswell Basin, New Mexico, particularly for the zones of higher precipitation" Eakin and others (1951, p. 80).

Therefore only these two basins are known to be predecessor basins to the development of the Maxey-Eakin method.

The recharge percentages, in the words of Eakin and others (1951): "…were balanced by trial and error against the estimates of discharge by natural losses in the 13 valleys" Eakin and others (1951, p. 26). Thus, to estimate ground-water discharge, phreatophyte areas were mapped and water-use rates applied based on the work of Blaney and others (1930 and 1938), Gatewood and others (1950), Lee (1912), White (1932), Young and Blaney (1942), and more recently Robinson (1970). Once ET was estimated, an iterative process applied recharge factors to precipitation volumes by precipitation zones until balance was achieved, or nearly so, with ground-water discharge. The technique was designed to be applied rapidly at a reconnaissance level and therefore no attempt was made to give weight to other factors and processes, particularly geologic controls that influence ground-water recharge.

Maxey and others, (1966) commented on the use and applicability of the Maxey – Eakin methodology and indicated:

> "…It is recognized that this method is highly approximate – even values for precipitation are largely estimated, the estimates being used based on only a few records at widely spaced stations. However, the method is as acceptable as any available to arrive at a minimum estimate of perennial ground-water recharge and allows for some rational basis of judgment as to the order of magnitude of water that may be available for development. Precipitation zones were delineated by Hardman (1965) and percentage of precipitation recharged was determined empirically by the Survey in a number of valleys in northern Nevada" Maxey and others, (1966, p. 16).

This quote reiterates the basic assumptions of the methodology. In the report, the standard coefficients were tied to the precipitation rate, however, altitude is also reported, with 8 inches of precipitation occurring at the 5000-ft elevation contour. The reference to Hardman (1965) refers to an increase in the accuracy of the 1936 map by the inclusion of new topographic data produced by the USGS Topographic Division. In general, the new topography increased the precipitation in mountainous areas given as examples and discussed previously.

Altitude Threshold for Recharge

One major assumption common to all Maxey-Eakin studies is that ground-water recharge does not take place with less than 8 inches of precipitation. Numerous studies have, however, shown this not to be the case, such as Claassen (1983), Osterkamp and others (1994), Pohlmann and others (1998), Savard (1998), Dixon and Katzer (2002) and most recently Paces and others (2002). Eakin and others recognized this potential for low-altitude recharge, as stated in their study of Goshute-Antelope Valley: "The ground water is recharged largely by surface flow from the mountain canyons that percolate into the valley fill in the alluvial-fan areas at the edge of the mountains" Eakin and others (1951, p. 26). This implies that recharge efficiencies estimate the amount of potential ground-water recharge in the mountain block based on the distribution of precipitation with altitude even though the actual recharge may take place at lower altitudes as the channels cross the alluvial fans down gradient from the mountain front. Apparently the authors are saying that very little of the recharge occurs in the higher altitudes even though the precipitation is greater; in this case mountain-front runoff relegated to drainage channels provides the bulk of the recharge, at least in Goshute and Antelope Valleys.

Many years later, Eakin stated:

> "The distribution of water runoff from the mountains also permits some inferences to the distribution and manner of recharge to the ground-water system. For mountainous areas of otherwise similar characteristics, proportionally large runoff suggests little recharge by deep infiltration in

> the bedrock in the mountains and small runoff suggests proportionally large recharge by deep infiltration in the bedrock. Also, substantial runoff from the mountains suggests that recharge by infiltration from streamflow on the valley fill may be significant" Eakin (1966, p. 260).

Again recognizing the total ground-water recharge is accounted for, regardless of where it takes place, because the recharge efficiencies have accounted for it. This assumption probably leads to an underestimate of recharge because not all the water that flows in the drainages as surface-water runoff has its source on the mountain block, but occurs as overland runoff resulting from precipitation directly on alluvial fans. Whether this is accounted for in the Maxey-Eakin method is unclear. More recent analyses (Berger, 2000a, 2000b and this report) explicitly describe the assumed distribution of the recharge.

Technical Evaluations of Maxey-Eakin Method

The Maxey-Eakin method has been used in nearly every valley in Nevada; there are two technical evaluations of the method's reliability. The first, a study by Watson and others (1976), utilized multiple and simple linear regressions to analyze the Maxey-Eakin method and to develop new predictive equations for ground-water recharge. They concluded that neither their equations nor those of Maxey-Eakin reliably predict ground-water recharge, but that both can be used for a first approximation of recharge. A second study nearly 20 years later by Avon and Durbin (1994) examined the question of Maxey-Eakin reliability with the benefit of additional hydrologic data and interpretations for many of the valleys. They compared ground-water recharge estimates using the Maxey-Eakin method with recharge estimates that were independently derived using other methods such as geochemistry and water balance. Avon and Durbin (1994, p. 110) concluded: "…the Maxey-Eakin method provides fairly reliable estimates of recharge to ground-water basins in Nevada…"

Most of the NDWR's Bulletin and Reconnaissance water-resource evaluations are summarized in Scott and others (1971). The largest number of such studies occurred in the 1960s, as indicated by a later summary (Lopes and Evetts, 2004), and shown on figure 2.

In water-resource evaluations of Nevada basins conducted in the 1940s through the 1970s, USGS investigators deviated about 37 percent of the time from the standard Maxey-Eakin method (Avon and Durbin, 1994). Several USGS investigators developed altitude-precipitation relationships independent of the Hardman map, of which Maxey and Jameson (1948) is the earliest example. The investigators also changed the Hardman precipitation zones to adjust precipitation based on local climate in the valley of interest. Avon and Durbin (1994) considered this change to be within the definition of a standard Maxey-Eakin estimate as do Lopes and Evetts in a recent summary (2004). In a few valleys, the Maxey-Eakin recharge efficiencies were modified; Avon and Durbin (1994) list 15 such studies.

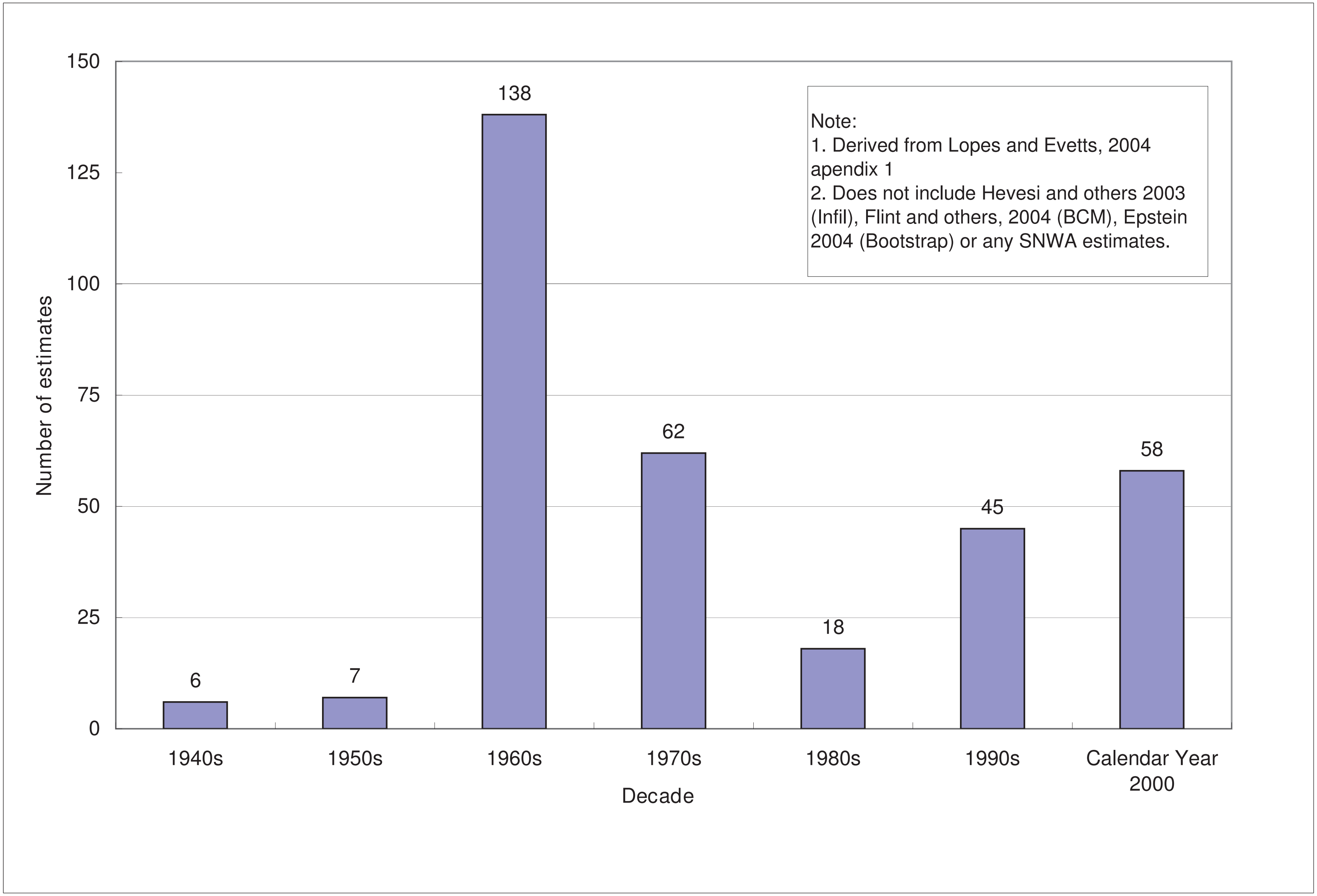

Figure 2. Number of USGS recharge estimates by decade of publication year, ending in 2000

The standard Maxey-Eakin efficiencies listed by Eakin and others (1951) for the various precipitation zones are listed in table 2 and also table 4 for comparison to those calculated by Watson and others (1976) and Avon and Durbin (1994). The results of the multiple regression analyses by Watson and others (1976) and Avon and Durbin (1994) are also listed in table 4.

Table 4. Comparison of recharge efficiencies and results of multiple linear regressions by Eakin, Watson and others, and Avon and Durbin.

Precipitation zone, in inches	Recharge efficiencies, in percent			95 percent confidence interval range	
	Eakin and others[1]	Watson and others[2]	Avon and Durbin[3]	Watson and others[2]	Avon and Durbin[3]
More than 20	25	24	20.3	± 15	± 10.4
15-20	15	19	20.4	± 16	± 10.0
12-15	7	1[4]	-3.5	± 6	± 5.5
8-12	3	4	6.7	± 2	± 2.5
Less than 8	0	0	1.1	± 1	± 1.4

1. Eakin and others (1951).
2. Watson and others (1976).
3. Avon and Durbin (1994).
4. A mark or negative sign exists on all known copies of the report. Avon and Durbin (1994) reported this value as minus one.

Epstein (2004) provided a three-part study: (1) a review of historic recharge methods, (2) a statistical uncertainty analysis using the "bootstrap brute force" (or "bootstrap") statistical methodology (Efron and Tibshirani, 1998), and (3) new estimates of ground-water recharge for all the valleys in Nevada. The author concluded that the original Maxey-Eakin estimates were reasonable but likely conservative.

Despite Epstein's extensive statistical analysis, the recharge estimates are less certain because of three deficits. First, the new estimates were based on the August 1998 version of the PRISM (Parameter Regression on Independent Slopes Model) (Daly and others, 1994) precipitation map, which contains known data errors. The PRISM method to estimate precipitation is a linear approximation of altitude and precipitation and a sound methodology; however, the underlying basic data have never been reported, limiting analysis by others (Jeton and others, 2005). A recent (6/16/06) version of the 800 meter 1970 – 2000 PRISM precipitation maps appears to resolve the data issues discussed in Jeton and others (2005) and to be more representative of the precipitation than previous versions. Personal communication with Justin Huntington (2006, 2007) hydrologist formally with DRI, currently with NDWR and George Taylor (Climatologist, PRISM Group, oral communication, 2006) confirm the correction of the input data for the new version of the PRISM map These errors were identified by Justin Huntington (written communication, January 2006) who found two precipitation data sets (1961-1990 and 1971-2000) used by PRISM contained mislocated precipitation stations and some stations that should have been included were not. Nevertheless, the precipitation zones used by Epstein (2004) are shown in table 5 along with his recharge coefficients. The second deficit is that only new recharge estimates were provided, and the third is that the report explicitly acknowledged that basin-specific discharge analysis is required for a better estimate of natural recharge.

Table 5. Coefficients for 1998 version of the PRISM map developed by Epstein (2004) using multiple linear regressions and the bootstrap statistical method to estimate recharge.

Precipitation Zone (inches per year)	Coefficient (recharge percentage)
0 to less than 10	0.019
10 to less than 20	0.049
20 to less than 30	0.195
Greater than 30	0.629

RECENT USGS MODIFICATIONS OF MAXEY-EAKIN METHODOLOGY

The following described investigations are modifications to the Maxey-Eakin method, although they still rely on these basic assumptions: basins are in steady state, and precipitation increases with increasing altitude, as does attributed ground-water recharge. These studies are referred to here as the Harrill and Prudic, Nichols, Berger, and Death Valley studies.

Harrill and Prudic (1998)

The first variation of the Maxey-Eakin method was based on a technique used in the southwest alluvial basins in Arizona (Anderson and others, 1992, p. B33-B34) that related annual precipitation to previously determined ground-water recharge. The technique is the development of a log-log relationship between the recharge and the effective precipitation volumes. Harrill and Prudic (1998) utilized this technique and correlated Maxey-Eakin estimates of recharge with annual precipitation greater than 8 inches to develop the following equation:

$$\text{Log } Q_r = -1.74 + 1.10 \log P_{P>8}, \tag{2}$$

where

Q_r is recharge, in acre-feet/year; and

$P_{P>8}$ is the total annual volume of precipitation, in acre-feet/year, where average annual precipitation exceeds 8 inches.

Although dependent on the Maxey-Eakin method, this relation does represent a variation in the way recharge is calculated, in that the total natural recharge volume is calculated directly from the total effective precipitation volume. This equation was used to analyze the results of the estimates that existed to date and may never have been used as the sole method of estimation.

Nichols (2000a, 2000b, and 2000c)

The studies by Nichols (2000a, 2000b, 2000c) represent a significant scientific advancement in estimating ground-water budgets. In the late 1980s, an investigation was initiated and continued into the 1990s to collect micrometeorologic data to measure the amount of ET by phreatophytes in Owens Valley, the Amargosa Desert, Railroad Valley, Smith Creek Valley, and the Smoke Creek Desert. ET was then correlated with vegetative cover as determined from LANDSAT (satellite) data and the depth to ground-water (Nichols, 1994; Nichols and others, 1997; Nichols, 2000a; and Nichols, 2000b). Ground-water discharge was then determined by applying the appropriate use rate to the phreatophytes in 16 valleys in north-central and eastern Nevada, shown in figure 3 in yellow. This geographic area is shown as 19 valleys due to subdivisions of HA 155 (Little Smokey) and HA186 (Antelope). The author used the PRISM precipitation model of Daly and others (1994) to distribute precipitation throughout the 16 valleys.

Nichols (2000c, p. C19-C23) first modified a PRISM precipitation map (May, 1997 version) for his study area to show one-inch precipitation zones (Smith and others, 2000), and then he combined zones and solved for the recharge coefficients with an iterative procedure that used multiple linear regression to match his estimated discharge. The iterative process is similar to the 'trial and error' process used by Maxey-Eakin (1949) and Eakin and others (1951) to determine the recharge percentages. The equation developed by Nichols is (2000c, p. C21, equation 1):

$$Y = b_0 + \sum_{n=1}^{5} b_i X_i + E_i \qquad (3)$$

where

Y is estimated recharge, in acre-feet, based on the estimated discharge, in acre-feet;
X_i is the independent variable, in this case precipitation volume in acre-feet,
In each of the five precipitation zones;
b_i is the coefficient for each independent variable;
b_0 is the intercept, in acre-feet, on the Y axis; and
E_i is the error, in acre-feet, in the estimated discharge, for the entire estimate

Using multiple linear regressions to balance recharge and discharge was also performed by Watson and others (1976) Avon and Durbin (1994) and Epstein (2004) in their studies. The recharge coefficients of Nichols (2000c, table C12, p. C24) are listed in table 6.

Table 6. Recharge coefficients used to estimate recharge in Nichols 2000c.

Precipitation Zone (Inches)	Recharge Coefficients
8 to < 12	0.008
12 to < 16	0.130
16 to < 20	0.144
20 to < 34	0.158
= > 34	0.626

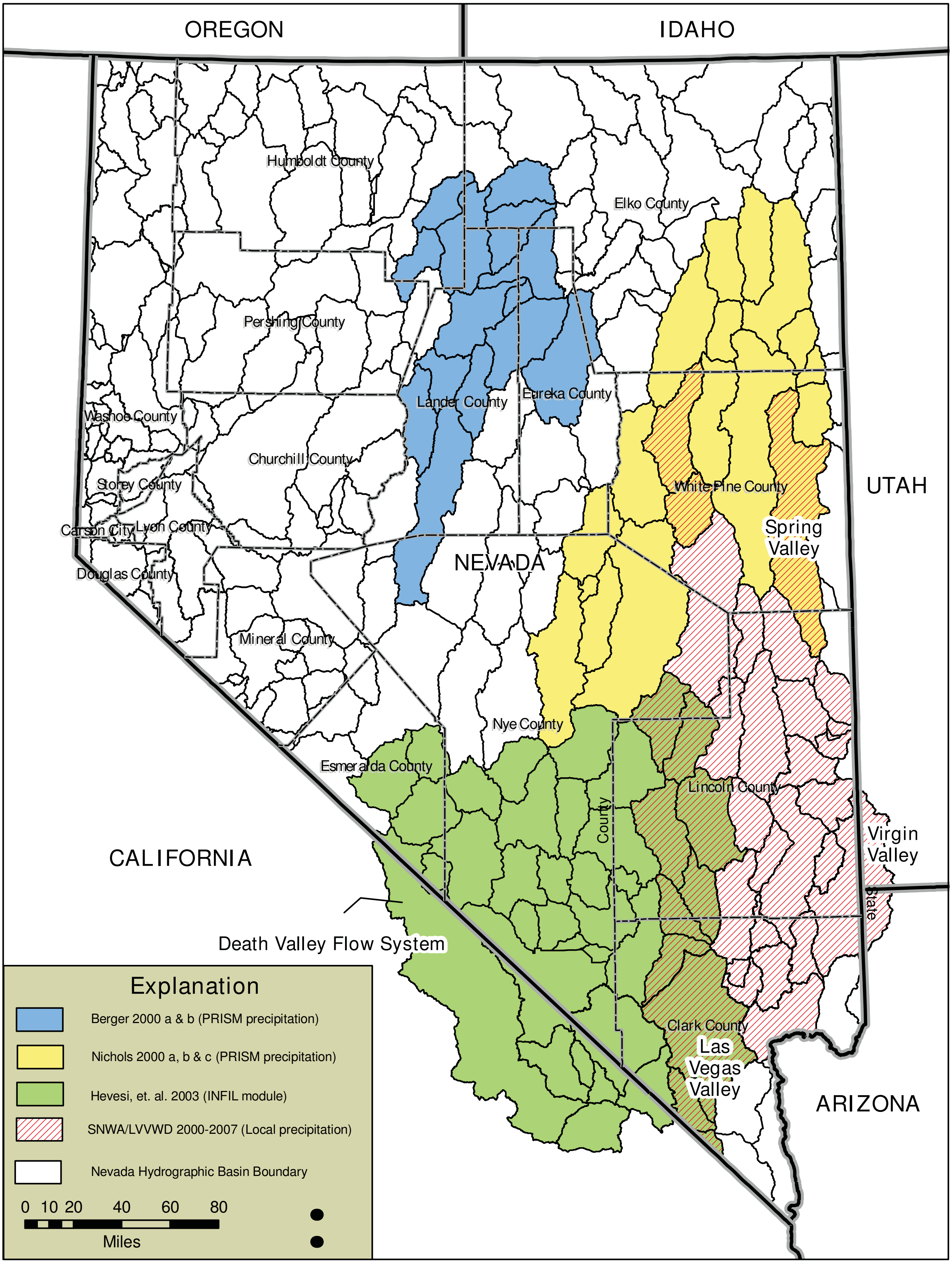

Figure 3. Areas of application of selected natural recharge methodologies

This method significantly increased previously estimated ground-water budgets for 14 of the 16 valleys studied by Nichols (2000c, table C13, p. C25), shown in figure 3. As a check of method, the estimated discharge was compared against the recharge calculated using the equation "predicted recharge" yielding a correlation coefficient (r^2) value of 0.975 and an adjusted r^2 of 0.909. Because the difference is usually positive it was assumed to be additional interbasin flow. The difference between these two values is shown in table 7.

Table 7. Estimated total ground-water discharge and calculated recharge by Nichols[1] in acre-feet, used in developing recharge coefficients.

Basin No.	Basin Name	Total discharge used for input into regression analysis	Calculated recharge using new coefficients	Difference
150	Little Fish Lake	9,600	9,674	74
154	Newark	52,000	49,189	-2,811
155	Little Smokey[2]	11,500	12,753	1,253
156	Hot Creek	5,800	5,806	6
173B	Railroad (north)	67,000	61,234	-5,766
174	Jakes	17,600	38,259	20,659
175	Long	38,000	47,826	9,826
176	Ruby	148,000	145,795	-2,205
177	Clover	59,100	58,872	-228
178	Butte	70,500	69,122	-1,378
179	Steptoe	129,500	131,716	2,216
184	Spring	94,000	103,777	9,777
185	Tippett	11,900	12,430	530
186	Antelope	16,000	16,872	872
187	Goshute	41,000	41,026	26
188	Independence	50,200	50,142	-58

1. Nichols (2000c, p. C23, columns D, E, and I).
2. Includes part of Antelope Valley.

The PRISM map has been significantly revised multiple times and we have not evaluated the precipitation data set used by PRISM for Nichols' studies so it is not known if the map he used for the 16 valleys is correct or not (see previous discussion of PRISM), but we do know the high-altitude precipitation stations installed by the USGS in 1984 were not used by PRISM for the 1961-1990 data set. Presumably, if the corrected precipitation map (posted July 16, 2006) had a greater volume of precipitation, Nichols would have derived smaller recharge coefficients, and if the volume was less, the recharge coefficients would be proportionately larger. However, as long as the volume of precipitation was great enough to satisfy the ET component in all of the valleys Nichols worked in, the error in the precipitation map is inconsequential. In some of the valleys Nichols studied there is significant ground-water outflow and these values may be questionable depending on the magnitude of the potential error. Therefore, while it is unfortunate that the precipitation map may not be totally accurate, this probably does not impact Nichols' ET results which were derived independently of the PRISM map.

Early studies of ET by Lee (1912), Blaney and others (1930, 1938), White (1932), and later studies by Gatewood and others (1950) and Robinson (1970) were based generally on ET-tank rather than large in-situ field experiments, Nichols (2000a) summarized these studies by saying: "None of these studies developed methods that can be applied systematically to estimate ground-water evapotranspiration by phreatophytes" Nichols (2000, p. A3). This is of concern because Maxey and Eakin (1949) developed their recharge estimates based on ground-water discharge by phreatophytes and bare soil. The differences in experimental procedures may be one reason why recent ET studies have generally defined higher ET rates than the earlier studies. Nevertheless, USGS investigators from the 1940s through the 1970s utilized these early studies and estimated ET from ground-water in nearly all the basins in Nevada. These results are published in the NDWR Reconnaissance and Bulletin Series and most of the studies are cited in Avon and Durbin (1994), Lopes and Evetts (2004), Belcher (2004), and Epstein (2004) and this report.

Nichols (2000a) provided equations for estimating ET as a function of depth to water and density of phreatophytes growing under natural conditions. In addition, site-specific examples and the implications for the natural recharge estimates were described (Nichols, 2000b). This issue is important because it is constantly in flux due to natural climate variability, local anthropogenic alterations, and most recently climate change considerations. The ET rates as published in Nichols' work are reasonable but are locally and temporally variable. The results of Nichols' hydrologic evaluation of the 16 valleys in central and northeastern Nevada are compared to earlier USGS studies in table 8.

Table 8. Comparison of areas, precipitation, ground-water recharge, and ground-water ET for the valleys investigated by Nichols (2000c) with estimates by the USGS from the Reconnaissance Series, in acres and acre-feet/year.

		Reconnaissance Studies[2,1]				Nichols			
Basin No.	Basin Name	Area (Acres)	Precip[3,2] (AF)	Recharge (AF/YR)	GW ET	Area (Acres)	Precip[3,2] (AF)	Recharge (AF/YR)	GW ET
150	Little Fish Lake	278,260	226,750	11,000	10,000	276,483	236,430	9,700	9,700
154	Newark	512,000	410,490	17,500	16,000	509,283	515,471	49,000	60,500
155	Little Smokey[2]	743,840	432,930	5,400	1,900	740,576	523,359	13,000	6,000
156	Hot Creek	657,990	397,340	7,000	4,600	658,500	424,067	5,800	5,000
173B	Railroad (north)	1,376,800	996,000	46,000	80,000	1,369,671	1,089,249	61,000	85,000
174	Jakes	270,080	250,000	17,000	0	270,498	289,477	38,500	600
175	Long	416,000	343,940	10,300	2,200	419,844	452,367	48,000	11,000
176	Ruby Valley	639,900	682,550	68,000	67,600	638,935	867,225	146,000	167,000
177	Clover	288,100	287,870	20,700	19,000	292,115	363,328	59,000	84,500
178	Butte	635,400	563,300	19,000	19,900	652,362	700,905	69,000	44,500
179	Steptoe	1,265,000	1,328,310	85,000	70,000	1,245,618	1,344,191	132,000	128,000
184	Spring	1,084,900	962,790	75,000	70,000	1,067,010	1,141,444	104,000	90,000
185	Tippett	233,000	164,500	6,900	0	221,574	211,905	12,500	2,900
186	Antelope	252,600	175,200	4,700	100	255,680	246,551	17,000	4,000
187	Goshute	610,560	440,000	10,400[1,3]	10,075	612,168	592,875	41,000	42,500
188	Independence	336,000	296,280	9,300	9,500	360,670	394,414	50,000	47,000

1. As listed in Scott and others, 1971, tables 2 and 3.
2. Precipitation.
3. Includes recharge estimate for northern Antelope Valley.

For 12 of the 16 valleys, Nichols (2000) estimate of ET rate was greater than the amount of ET listed in the Reconnaissance Series by a factor of 2.9. There was virtually no change in one valley and the increase was very large in three small valleys. The increase in ET is roughly equal to the computed increase in ground-water recharge, where Nichols' (2000) estimate for 14 of the valleys averaged 2.8 times the amount of ground-water recharge listed in the Reconnaissance Series.

Berger (2000a, 2000b)

The third set of investigations was conducted by Berger (2000a, 2000b) working in the 14 hydrographic basins that make up the middle part of the Humboldt River Basin in north-central Nevada, shown in figure 3. Berger (2000a, 2000b) developed water budgets for three distinct geomorphic landforms in each basin: the mountain block, piedmont, and valley floor. When the water budget (or mass balance) approach is used, ground-water recharge and surface-water runoff equal the total amount of water yield from the mountain block. This approach with some variation has been used in other Nevada basins by Arteaga and Durbin (1978), Arteaga and Nichols (1984), Katzer and others (1984), and Maurer and Berger (1997).

For the distribution of precipitation, Berger (2000a, 2000b) used the PRISM (1997 simulation results) map described above (with potential database errors discussed previously) for the distribution of precipitation to compare with the estimate derived by the water budget approach. ET in the mountain block was determined from the difference of annual precipitation and water yield (residual). ET in the piedmont-slope area was determined by applying the Penman-Monteith equation to available climate data (Monteith, 1965). Ground-water ET was determined using the work of Nichols (2000a, 2000b).

Surface-water runoff was estimated using a relationship between precipitation and water yield (Berger 2000b. p. 9) and was determined using the following equations:

$$ROmb - 0.0000228(Pm)^{3.96} \quad (4)$$

$$\text{Water yield } (W) = 0.00273(Pm)^{2.56} \quad (5)$$

where
ROmb is the estimated average runoff from the mountain block in inches per year; and
Pm is the average annual precipitation in the mountain block in inches per year; and

Volumes were then determined by multiplying the area of the mountain block in acres and dividing by 12 to yield a result in acre-feet per year.

The results from this technique significantly increased all components of the water budget over previous estimates using the Maxey-Eakin method and both are listed in table 9. In general, recharge increased by about 45 percent but was offset by an increase in discharge of approximately 30 percent in some valleys. The hydrologic components defined by Berger (2000a, 2000b) are difficult to compare by individual valleys with previous USGS estimates because some early investigators grouped many of the valleys together. In addition the ground-water budgets do not necessarily balance in either the Reconnaissance Series or Berger's reports because ground-water inflows and outflows are not listed. One factor that is not considered in many of the these more detailed studies is the potential for phreatophyte stands to increase or decrease in size from the time the original reconnaissance studies were done. These potential changes could be caused by either natural processes or anthropogenic activities.

Table 9. Comparison of areas, precipitation, and ground-water recharge for valleys investigated by Berger (2000a, 2000b) with estimates by USGS from the Reconnaissance Series (rounded to nearest 1,000 above 1,000, nearest 100 below 1,000).

		Reconnaissance Studies[1]				Berger[2]			
Basin No.	**Basin Name**	**Area (acres)**	**Precip[3] (AF)**	**Recharge (AF/YR)**	**GW ET**	**Area (acres)**	**Precip[3] (AF)**	**Recharge (AF/YR)**	**GW ET**
53	Pine	641,000	660,000	50,000	15,000	645,000	688,000	66,000	45,000
54	Crescent	481,000	430,000	13,000	12,000	482,000	446,000	18,000	
55	Carico Lake	241,000	160,000	4,000	4,000	242,000	239,000	20,000	7,000
56	Upper Reese River	728,000	700,000	37,000	37,000	727,000	803,000	91,000	45,000
57	Antelope	289,000	260,000	11,000	500	290,000	279,000	21,000	5,000
58	Middle Reese River	204,000	170,000	7,000	3,000	204,000	186,000	13,000	7,000
59	Lower Reese River	376,000	280,000	14,000	22,000	382,000	341,000	19,000	55,000
60	Whirlwind	60,000	45,000	1,700		63,000	55,000	4,000	15,000
61	Boulder Flat	348,000	240,000	17,000	30,000	347,000	308,000	19,000	120,000
	Rock Creek	284,000	240,000	9,000	3,000	288,000	256,000	17,000	11,000
	Willow Creek	259,000	250,000	15,000		264,000	280,000	28,000	20,000
64	Clovers Area	461,000	300,000	9,000		462,000	401,000	18,000	81,000
65	Pumpernickel	191,000	130,000	3,400	72,000	196,000	169,000	9,000	29,000
66	Kelly Cr. Area	193,000	130,000	4,000		193,000	181,000	13,000	25,000

1. As listed in Scott and others (1971, tables 2 and 3).
2. Average values for the years 1989 and 1995 were calculated by the authors based on Berger (2000a, table 6 p.15-18) values probably do not represent average of maximum or minimum. Budgets are not balanced because ground-water inflows or outflows are not listed.
3. Precipitation.

Studies of the Death Valley Flow System (DVFS)

A number of studies have been published on various aspects related to the DVFS, (figure 3). See for example the USGS publications website: (http://regmod.wr.usgs.gov/publications.htm). Germane to this study are the works of D'Agnese and others (1997), Belcher and Elliot (2001), Hevesi and others (2002, 2003), and Belcher (2004).

As part of the development of ground-water models for the DVFS, D'Agnese and others (1997, p. 52) developed a GIS matrix to estimate recharge. It was composed of four variables: (1) altitude, (2) slope-aspect, (3) rock or soil type, (4) vegetation, and used an unpublished precipitation map. This study was not utilized or developed by any subsequent authors.

Later studies describe the development of a model, termed Infil (Hevesi and others 2002, 2003), which incorporates several variables: (1) daily precipitation values from a network of precipitation stations, (2) infiltration rates based on the hydraulic properties of the various soils and rock types in the study area, and (3) local-regional climatic data to determine ET. These and other factors are incorporated into the model in order to estimate ground-water recharge. Belcher (2004, p. 118) states:

> "Model uncertainty remained high for many model inputs such as bedrock permeability, soil thickness, root density as a function of depth, stream-channel properties, spatial distribution of climate by month (computed from daily records), and potential evapotranspiration coefficients."

This model can be classified as a water-balance based regional modeling approach. The recharge efficiencies are locally modified by all the factors and are reported as a range by the authors. The estimates of ground-water recharge from this model are compared to the estimates from the Reconnaissance Series in table 10.

Table 10. Summary of historic recharge estimation results in the Death Valley region and model area in acre-feet/year[1,5].

HA No.	Valley Name	Source of recharge estimate	Method[2]	sq mi	Recharge (AF/YR)	Hevesi and others (2003)[5]
142	Alkali Spring Valley	Scott and others, 1971	ME	320	100	142
143	Clayton Valley	Rush, 1968	ME	555	1,500	1,051
144	Lida Valley	D'Agnese and others, 1997	GFM	537	474	610
145	Stonewall Flat	Rush, 1968	ME	378	100	1,241
146	Sarcobatus Flat	Malmberg and Eakin, 1962	ME	819	1,200	2,466
147	Gold Flat	Rush, 1971	ME	681	3,800	4,205
148	Cactus Flat	Rush, 1971	ME	395	600	1,410
157	Kawich Valley	Rush, 1971	ME	359	3,500	3,688
158	Emigrant Valley1	D'Agnese and others, 1997	GFM	770	12,999	N/A
158A	Emigrant Valley (Groom Lake)	Rush, 1971	ME	661	3,200	5,739
158B	Emigrant Valley (Papoose Lake)	Rush, 1971	ME	109	4	368
159	Yucca Flat	Rush, 1971	ME	300	700	1,557
160	Frenchman Flat	Rush, 1971	ME	457	100	1,903
161	Indian Springs Valley	Rush, 1971	ME	668	10,000	4,591
162	Pahrump Valley	Avon and Durbin, 1994	ME	989	26,000	11,759
162	Pahrump Valley	Harrill, 1986	GFM	989	37,000	
163	Mesquite Valley	Glancy, 1968	ME	438	1,500	3,470
163	Mesquite Valley	Dettinger, 1989	CL	438	1,600	
164A	Ivanpah Valley (north)	Scott and others, 1971	ME	244	1,500	1,399
164B	Ivanpah Valley (south)	Harrill and others, 1988	ME	508	500	1,569
165	Jean Lake Valley	Glancy, 1968	ME	98	100	73
166	Hidden Valley (south)	Scott and others, 1971	ME	33	10	23
168	Three Lakes Valley (north)	Rush, 1971	ME	301	2,000	1,490
169A	Tikapoo Valley (north)	Scott and others, 1971	ME	616	2,600	3,971
169B	Tikapoo Valley (south)	Scott and others, 1971	ME	370	3,400	2,295
170	Penoyer Valley	Avon and Durbin, 1994	ME	692	4,300	5,160
170	Penoyer Valley	Dettinger, 1989	CL	692	3,200	
170	Penoyer Valley	Van Denburgh and Rush, 1974	WB	692	3,800	
171	Coal Valley	Eakin, 1963	ME	456	2,000	3,322
172	Garden Valley	Eakin, 1963	ME	456	10,000	N/A
172 and 171	Garden and Coal Valleys	Kirk and Campana, 1990	D	912	11,000	6,645
173A	Railroad Valley (south)	Avon and Durbin, 1994	ME	593	5,500	4,135
173A	Railroad Valley (south)	Dettinger, 1989	CL	593	4,900	N/A
209	Pahranagat Valley	Eakin, 1963	ME	767	1,800	4,046
209	Pahranagat Valley	Kirk and Campana, 1990	D	767	1,500	
211	Three Lakes Valley (south)	Rush, 1971	ME	302	6,000	1,298
212	Las Vegas Valley	Avon and Durbin, 1994	ME	1,488	30,000	15,147
212	Las Vegas Valley	Dettinger, 1989	CL	1,488	28,000	
212	Las Vegas Valley	Harrill, 1976	GFM	1,488	30,000	
225	Mercury Valley	Rush, 1971	ME	111	250	359
226	Rock Valley	Rush, 1971	ME	84	30	352
225 and 226	Mercury and Rock Valleys	D'Agnese and others, 1997	GFM	195	385	N/A
227	Fortymile Canyon2	D'Agnese and others, 1997	GFM	514	681	N/A
227A	Fortymile Canyon (Jackass Flats)	Rush, 1971	ME	283	900	1,583
227B	Fortymile Canyon (Buckboard Mesa)	Rush, 1971	ME	231	1,400	1,959
228	Oasis Valley	Rush, 1971	ME	470	1,000	2,209
229	Crater Flat	Rush, 1971	ME	183	220	268
230	Amargosa Desert	Walker and Eakin, 1963	ME	1,330	1,500	2,139
240	Chicago Valley	Harrill and others, 1988	ME	108	50	569
241	California Valley	Harrill and others, 1988	ME	134	241[3]	775
240 and 241	California and Chicago Valleys	D'Agnese and others, 1997	GFM	243	296	N/A
242	Lower Amargosa Valley	D'Agnese and others, 1997	GFM	463	89	767
243	Death Valley	Miller, 1977	ME	3,675	8,000	16,891
244	Valjean Valley	Harrill and others, 1988	ME	418	400	671
245	Shadow Valley	Harrill and others, 1988	ME	391	1,200	1,731
NA	Death Valley regional model area	D'Agnese and others, 2002	GFM	17,486	79,000	101,300

1. Selected columns from Hevesi and others (2003, table.1, p.10-12). See footnote 5
2. ME (Maxey-Eakin estimate), D (Deuterium mass balance), CL (Chloride Mass Balance), GFM (Ground Water Flow model).
3. Reported as 241 acre-feet/year (814 m^3/d) in at least two locations by Hevesi and others (2003); however, Harrill and others (1988) report 200 acre-feet/year as the volume.
4. Total as listed in Hevesi and others (2003, table 23), Calculation used an average of previous values in Las Vegas, Mesquite, Pahranagat, Pahrump, Penoyer, and Railroad (South) Valleys.
5. Hevesi and others (2003, table 23 p. 160-161).

Hevesi and others (2003) present five model estimates of recharge for each valley. Belcher (2004) reports that model 1 was utilized in the Death Valley model. These estimates (Hevesi and others, 2003, part of table 23, p. 160-161) are listed in table 10 where they are compared to earlier USGS estimates.

This estimate (Hevesi and others 2003, table 23) includes a 28 percent increase in ground-water recharge for the entire Death Valley area compared to the Reconnaissance Studies. Table 10 also includes valleys reported in Hevesi and others (2003, table 23) outside of the DVFS area. The Las Vegas Valley estimate includes the drainage area of Las Vegas Valley (Hevesi and others, 2003, figure 4) and is significantly lower than all previous estimates. The estimate for all of Pahrump Valley is also significantly lower. In general, the results of the Hevesi (2003) studies show the recharge estimates increased in smaller valleys and decreased in larger valleys.

Death Valley has long been recognized as the terminus of a regional flow system with discharge confined to a few areas (Belcher, 2004, fig D-3, p.144), in particular Ash Meadows (Rush 1971). Publications of the Death Valley Flow Model Group (Belcher, 2004) also describe additional areas of discharge.

Belcher (2004, table F18, p. 330) indicates that the total recharge, 89,845 acre-feet/year (303,415 m^3/d) as simulated in the Death Valley ground-water flow model is slightly lower than that described in the Infil model of 101,300 acre-feet/year (342,000 m^3/d) and the total ET is 107,052 acre-feet/year (361,523 m^3/d). Inflow and outflow occur along the model boundary margins; hence the total inflow and outflow balance is approximately 133,000 acre-feet/year (448,000 m^3/d). Discharge, recharge, and total water budget for the Death Valley model are listed in table 11.

Table 11. Discharge, recharge and total budget for Death Valley model, in acre-feet/year.

Area	Observed Value[1]	Simulated Value
Discharge		
Sarcobatus Flat ET	13,225	8,131
Grapevine Canyon Springs	1,032	961
Penoyer Valley ET	3,800	2,381
Oasis Valley ET	6,014	7,050
Indian Springs area	663	236
Ash Meadows ET	17,877	18,983
Franklin Well area ET	341	189
Franklin Lake ET	1,042	2,277
Death Valley area springs and ET	38,001	55,083
Stewart Valley area ET	1,001	1,242
Pahrump Valley area ET and springs	9,594	6,666
Tecopa Basin area ET	6,237	1,127
Shoshone Valley area ET	2,077	1,072
Chicago Valley area ET	433	1,611
Total ET Discharge	**101,338**	**107,008**[4]
Recharge		
Entire Modeled Area	101,271[2]	89,845
Total Water Budget[3]		
Total Out		132,814
Difference (Total In – Total Out)		-159

1. Presumably the reported value by other workers, however independent estimate not cited in the table.
2. Correctly attributed to Hevesi and others (2003), in Belcher (2004, table F18).
3. Complete steady state budgets including boundary inflows and exit flows and partial valley recharge, last two reported values of Belcher (2004, table F18, p. 331)
4. Difference of 44 afy noted between this value and equivalent number in Belcher (2004, table F18).

STATE-WIDE STUDIES

In a related study for the Basin and Range Carbonate-Rock Aquifer System (BARCAS), Flint and Flint (2007) used a recharge calculation method named Basin Characterization Model (BCM) by Flint and others (2004), who estimated the recharge for all basins in Nevada. The model is simpler than the Infil model. Flint and Flint (2007, p. 6) list monthly precipitation, monthly minimum and maximum air temperature, monthly potential evaporation, soil-water storage capacity, and saturated hydraulic conductivity of the bedrock and alluvium as input parameters. The model calculates runoff, recharge from runoff, and in-place recharge. The method also relies on a version of the PRISM map that includes the errors discussed previously. Other investigations of discharge summarized in the draft version of the BARCAS summary report (Welsh and Bright, 2007) provide additional estimates of discharge; however, minimal efforts to balance recharge and discharge estimates for a single basin or flow system were made.

Epstein (2004) and Flint and others (2004), described large areas and used the PRISM precipitation map(s) as input data. They both provide: (1) a statistically determined range of uncertainty, and (2) a modeling approach to assess potential future conditions such as climate change. Both studies directly cite climate change as a reason for the development of the technique. Epstein's study (2004) is purely empirical, whereas those of Flint and Flint (2007) are in part based on hydrologic processes. If previous history is an indication, subsequent more detailed studies will provide new estimates of recharge and discharge.

HISTORY OF LVVWD/SNWA ESTIMATES

This section describes studies by LVVWD/SNWA to estimate ground-water recharge in Las Vegas Valley, lower Virgin River Valley, the White River and Meadow Valley Wash flow systems, and Spring Valley, all in eastern and southern Nevada (shown on figure 3). In all valleys featured the hydrologic data bases, precipitation, surface-water runoff, ground-water levels, and ground-water discharge by ET and outflow, were utilized to estimate ground-water recharge and the water resources budget. The Maxey-Eakin coefficients were applied to new precipitation-altitude relationships and matched against new estimates of ground-water discharge. The exception to this is the recent work by SNWA (2007 and 2008) who developed new recharge coefficients based on the PRISM precipitation map and new estimates of ET.

Precipitation data were used to develop altitude-precipitation relationships; surface-water runoff at gaging stations and miscellaneous streamflow measurements were used to estimate mountain front runoff; ground-water levels were used to estimate ground-water outflow, or interbasin flow; and measurements of ground-water discharge through ET and outflow were used to estimate the amount of potential ground-water recharge and the perennial yield. Entire periods of record were utilized with the exceptions of using only the most recent ground-water levels and estimates of ET.

A general problem with using the Maxey-Eakin recharge coefficients is that they were originally developed based on the Hardman precipitation maps, so in order to use the coefficients it is critical to update ground-water discharge (and interbasin flow) estimates. So new Maxey-Eakin recharge coefficients will only be as good as the discharge estimates. The hydrologic rule is that inflow equals outflow, with consideration of storage. It should be acceptable to use the Maxey-Eakin recharge coefficients if the resultant recharge equals the discharge estimates for the valley after the coefficients are applied to the new precipitation estimates. If this is not the case then one must develop new recharge coefficients. It is an error in judgment to increase recharge estimates by using a new map that has higher precipitation values unless the updated discharge matches the new recharge estimates.

In the following sections, the results are summarized rather than reproduced. The reader is referred to original publications for the details of a given data set.

The recharge estimates described utilize the Maxey-Eakin recharge efficiencies, but apply them not to the Hardman maps (1936, 1965), but to new altitude–precipitation relationships based on the complete period of record of select precipitation stations. It is important to note that the new estimates of recharge equal the new estimates of discharge.

In addition to the history of LVVWD and SNWA presented here, there are two new studies. One that is reported in the earlier section entitled "Development of precipitation maps," involves an analysis of the difference in precipitation volumes from the same areas using the Hardman 1936 and 1965 maps. This analysis was done using GIS, and the results are listed in table 1. The other study shows the effect that rocks of differing permeability have on ground-water recharge and is described in a later section entitled "Analysis of the effects of geologic controls in Spring Valley on ground-water recharge."

Precipitation Maps and Natural Recharge Methodology

LVVWD/SNWA investigators (Donovan and Katzer, 2000; LVVWD, 2001; Dixon and Katzer, 2002 (Virgin Valley Water District); Katzer and Donovan, 2003; SNWA, 2003; and SNWA, 2006) have always used all of the available in-valley precipitation data and data from all precipitation stations adjacent to any given valley or group of valleys in a study area to develop altitude-precipitation relationships. These data sets include the high-altitude precipitation stations that were not included in the PRISM data sets prior to 2006. This may be the appropriate scale for basin analysis, especially in Nevada with its Basin and Range topography as it allows detailed analysis of the characteristics of the individual stations, such as the time intervals (days, months, and years) of poorer data quality. However, this basin analysis does not produce a regional precipitation map with a common time period for all stations. Because of the generally low density of data sites, and typically high relief in Nevada, single data points have a strong control on precipitation interpretations, as noted previously by many authors including the creators of PRISM.

> "Comprehensive data sets are more likely to include stations in remote or otherwise 'difficult' locations that challenge the interpolation system when omitted, but help produce the best spatial climate data set when present"
> Daly (2006, p. 717).

A wide range of altitudes, or more properly, a mix of valley floor, range front, and ridge precipitation sites, is also desired, therefore, multiple networks are typically used in natural recharge analyses.

The 30-year precipitation average or 'climate normals' used by National Oceanic and Atmospheric Administration and by PRISM is arbitrary and reflects the availability of the data at the time of the development of the first climate normals (Guttman and Quayle 1996). Epstein (2004, p. 7) reports that the oldest climate record station in Nevada originated at Winnemucca in 1891. Currently, the Western Regional Climate Center (WRCC) in Reno Nevada now reports a discontinuous record from the present back to 1877. The argument for using all of the available data is to average out the wet years and dry years as much as possible. Using an arbitrary 30-year period, such as used by PRISM, is difficult to justify for use in estimating ground-water recharge when the movement of ground water in local and regional flow systems is measured in decades, hundred, or perhaps even thousands of years. In fact, according to Smith and others (2007) and Font, (1995) there are some basins that still contain Pleistocene water. In some ground-water systems, recharge that occurs on alluvial fans from surface-water runoff is clearly more modern water compared to deeper parts of the same system.

A recent summary by Lopes and Evetts (2004, Appendix 1) consisted of 357 entries of USGS recharge estimates for Nevada including 19 hydrographic areas without natural recharge estimates and 3 with unknown dates of publication. In this summary, the precipitation map is listed separately from the recharge method. Lopes and Evetts (2004, Appendix 1) reported that 33 Maxey-Eakin method estimates directly used the 1936 Hardman map and a majority, 166, used published and unpublished precipitation estimates provided by Hardman. If the definition of the Maxey-Eakin method were restricted to the use of a Hardman map, it would automatically exclude all valleys partly or entirely outside the State. If the same set of recharge coefficients is used, the difference between recharge estimates in space and time is the result of the precipitation map. Lopes and Evetts (2004) also list 13 USGS recharge estimates that explicitly developed altitude-precipitation relationships published in 1966 and 81 that were published subsequently. Of the 338 (357 less 19) estimates listed, 226 were described as Maxey-Eakin method estimates and they used multiple precipitation maps.

With the advent of large models with multiple results, the number of recharge (but not discharge) estimates has greatly increased. The 357 entries in the Lopes and Evetts (2004 apx. 1) table do not include Hevesi and others (2003), Flint and others, (2004), Flint and Flint (2007), Epstein (2004), Welch and others (2008), Lundmark (2007), or any SNWA estimate. The methodologies used are new, not valley-specific and would probably exceed several thousand if completely enumerated. It is expected that the number of available estimates will greatly increase in the future due to improvements in computer capabilities. The validity of the recharge estimates is, however, ultimately determined by discharge estimates and observed hydrologic changes in response to development. It is also expected that precipitation maps will continue to change, possibly over large areas due to the low density of available precipitation data.

More recent analyses of recharge are more complex and use additional computational power. Many of these more recent methodologies rely on the PRISM precipitation maps. Because of the topographic complexity of Nevada and sparse data, the precipitation maps produced by the PRISM group are sensitive to data availability and quality (Daly and others, 2005, 2006 and 2007). In particular, Daly and others (2006, p. 717) specifically describe the PRISM method and the effect of data density and resolution limitations of the model in the Spring Mountains adjacent to Las Vegas Valley as an example.

New Altitude-Precipitation Data Applied to Las Vegas Valley

In the mid to late 1990s LVVWD was in the process of developing a ground-water model for Las Vegas Valley with algorithms that would predict the spatial distribution of recharge (Donovan and Katzer, 2000). The report used all the precipitation data available in and adjacent to the Las Vegas area, which includes numerous high-altitude precipitation stations unavailable to Hardman in1936 or 1965, and some data potentially not utilized in the then-current version of the PRISM map. It became obvious to these investigators that combining all of the precipitation stations together in a single altitude-precipitation relationship (Donovan and Katzer, 2000, p. 1137, figure 2) did not produce a relationship that could be used with confidence in the drainage area for the valley, including a tributary valley to the south.

Thus, they turned to examining the microclimate of the various drainages based on the location of the precipitation stations and found four separate altitude-precipitation relationships with "adjusted r^2" (Helsel and Hirsch 2002, p. 313) greater than 0.90. The data for the published altitude-precipitation relationships are in Donovan and Katzer (2000, table 1, p. 1136) The resulting volume of precipitation for the valley was about 25 percent greater than the volume of precipitation determined using the Hardman map, footnoted as from the 1972 Nevada State Water Plan.

The investigators calculated the ground-water recharge using these new altitude-precipitation relationships together with the standard Maxey-Eakin recharge efficiencies to estimate recharge. This recharge equals about seven percent of the in-valley precipitation, resulting in in-valley recharge about 50 percent greater than reported by Maxey and Jameson (1948) and about twice as much as estimated by Malmberg (1965) and others (table 12). The reason for this increase in the precipitation and recharge estimates is straightforward; the precipitation database has been expanded temporally and spatially to include several high altitude precipitation stations which were not included in the earlier calculations. Also, the Hardman map interpretation is based on a 1:2,000,000 scale topographic map, which obviously is lacking in detail at the local level (figure 1).

Table 12. Comparison of ground-water recharge estimates for the Las Vegas Valley ground-water system.

Investigator(s)	Ground-Water recharge, in acre-feet/year
Maxey and Jameson[1]	34,000
Malmberg[2]	21,000
Harrill[3]	29,000
Morgan and Dettinger[4]	33,000
Donovan and Katzer[5]	51,000

1. Initial complete water resource assessment (Maxey and Jameson, 1948).
2. Additional hydrologic data collection and analytical assessments (Malmberg, 1965).
3. Initial modeling using nearly modern methods (Harrill, 1976).
4. MODFLOW model up to 1985. (Morgan and Dettinger 1994).
5. Recharge analysis as part of a modeling and water resource description project (Donovan and Katzer, 2000).

This new estimated recharge is significantly larger than previously estimated by all other studies (table 12). A follow-up ET study by Devitt and others (2002) found the discharge to be closer to 39,700 acre-feet/year. This updated ET value (Devitt and others, 2002), plus a revised estimate of ground-water outflow from the basin (12,000 af/yr) is within nine percent of the estimated ground-water recharge.

Thus Donovan and Katzer (2000, p.1140) assumed the main reason that the Maxey-Eakin recharge efficiencies were considered appropriate is that the estimated recharge nearly equals the estimated discharge. If the estimated increase in ET is nearly equal to the estimated increase in recharge due to greater precipitation, then the proportionality of the recharge efficiencies does not change. At the same time this may be fortuitous, because only one valley was investigated and if more data were available it may be that different recharge coefficients are needed in any given valley to match the long-term ground-water discharge rate.

In the case of Las Vegas Valley there is a well-documented difference in the altitude-precipitation relationships for each of the surrounding mountain ranges. Maxey and Jameson (1948) reported this and used a set of coefficients different from the final coefficients published a year later (Maxey and Eakin, 1949). Donovan and Katzer (2000, p. 1137) pointed out that neither the standard coefficients nor the Hardman (1936) precipitation map were used by Maxey and Jameson (1948). Applying the Maxey-Eakin standard coefficients to the Las Vegas Valley, and using the Hardman (1936) precipitation map yields an estimate of ground-water recharge of about 9,000 af/y; whereas if the Hardman (1965) map is used, the estimate of ground-water recharge equals about 13,000 af/y. Comparing these values to the ground-water discharge estimated by either Malmberg (1965, p.82 [24,000 af/y]) or Devitt and others (2002) results in a large imbalance (minimum of 11,000 af/y and a maximum of 42,700 af/y) in the ground-water budget and it illustrates the inadequacy of using the earlier precipitation map.

Even though recharge is assumed to increase with increased precipitation, there is insufficient data available to accurately apportion the recharge based on precipitation to any of the mountain blocks in Nevada at this time. In addition to climatic factors, there are many other parameters that control recharge such as geology (including soil and rock hydrologic characteristics and earth structures), which are directly related to permeability, slope, vegetative cover, and aspect. These parameters are extremely variable spatially. Alternatively, if the distribution of recharge in a mountain block is not required, one can simply calculate the percentage of precipitation that is discharged by ET and/or ground-water outflow (plus surface-water outflow, if appropriate) and assume that this equals the total resource available, not just the ground-water recharge. Complexity arises in valleys that have perennial streams. Generally, the data do not exist to separate mountain-block runoff into rejected recharge and surface water that may exceed the estimated ground-water recharge. Estimated ground-water outflow also adds a degree of uncertainty to any water-resource budget.

Lower Virgin River Valley

As part of a similar extensive revision of the hydrogeology of the lower Virgin Valley, natural discharge and recharge were reevaluated. The revised ET values supported the use of a new altitude-precipitation relationship and the continued application of the standard Maxey-Eakin efficiencies (Dixon and Katzer, 2002). Glancy and VanDenburgh (1969, table 9) reported the in situ basin recharge 9,500 af/y for HA 222 and 2,100 af/y for HA 221. Dixon and Katzer (2002) used the results of a three-year study (only two years of valid data) by Devitt and others (1998) to measure ET along the Virgin River corridor and estimated the recharge based on an updated precipitation network with an altitude-precipitation relationship (adjusted $r^2 = 0.95$) supplied by SNWA. The precipitation data and analyses are reported in Dixon and Katzer (2002, p. 33). As in Las Vegas Valley, the new estimate of ET was about 40 percent greater than originally estimated (Glancy and Van Denburgh, 1969). The reason for a higher use rate is due in part to an increase in the expansion of the phreatophytes between the studies. By developing a total water-resources budget that includes surface water, Dixon and Katzer (2002, table 13, p. 74) closed their budget (table 13) with reasonable certainty, but clearly there are some large unknowns.

Table 13. Water resource budget estimate for the lower Virgin River basin[1].

Inflow Components		Acre-feet/year[2]	Source
Virgin River at Littlefield, Arizona		180,000[3]	Gage record
Ground-water recharge:			
That bypasses Littlefield gage[4]		32,000	Estimated
That occurs downstream of Littlefield gage[5]		23,000	Estimated
Ephemeral flow direct to river[6]		8,000	Estimated
	Total	**243,000**	
Outflow Components			
Evapotranspiration[7]		70,000	Measured/estimated
Pumpage		12,000	Measured/estimated
River to Lake Mead		132,000	Estimated
Ground-water		29,000	Estimated by residual
	Total	**243,000**	

1. Dixon and Katzer (2002, table 13, p. 74).
2. Values rounded to the nearest 1000.
3. Includes about 30,000 af/y of ground-water flow (Dixon and Katzer, 2002, table 6) and the 3-4 cfs of bypassed surface water.
4. Ground-water recharge section.
5. Dixon and Katzer (2002, table 4).
6. Includes only ephemeral flow to the river downstream of the Littlefield gage, all flow upstream of the gage is included in the gage record.
7. Includes only ET downstream from the Littlefield gage from both phreatophytes and agriculture.

White River Flow System and Adjacent Areas

Once the new altitude-precipitation relationships were developed and validated, the Maxey-Eakin recharge efficiencies were applied to estimate recharge in other valleys, and the results were then compared to the most recent estimate of ground-water discharge by ET. The resultant altitude-precipitation relationships for these valleys are shown in table 14 and figure 4. Because the new altitude-precipitation relationships yield more precipitation than the previously-used Hardman maps (1936, 1965), more recharge is estimated using the same Maxey-Eakin efficiencies. In general the new recharge estimates are approximately balanced by the most recent estimates of ET, which have generally increased, plus an estimate of ground-water outflow, where appropriate. In the study of the White River and Meadow Valley Wash flow systems (in eastern and southern Nevada respectively), four altitude-precipitation relationships were used with adjusted r^2 values of 0.78, 0.85, 0.92, and 0.96 (LVVWD 2001, table 4-1 and p. 4-7 – 4-15).

In a study Tikaboo and Three Lakes Valleys (southern Nevada) two altitude-precipitation relationships were developed with adjusted r^2 values of 0.92 and 0.97. There are about 12 valleys within these two studies (LVVWD, 2001; SNWA, 2003) where the depth to ground water is so great that it precludes the establishment of phreatophytes; this creates uncertainty in these budgets because the single mechanism of ground-water discharge is ground-water outflow. Thus the assumption is that if the combination of an altitude-precipitation relationship and the Maxey-Eakin coefficients is valid for those valleys that have ground-water discharge by phreatophytes, then the technique is valid in all valleys.

Table 14. Location and number of altitude-precipitation relationships and correlation coefficients as determined by LVVWD/SNWA investigators.

Valley	Adjusted r^2	Reference
Las Vegas (four relationships)	0.91, 0.97[a], 0.95, and 0.98	Donovan and Katzer (2000, p. 1139, F-4, and p. 1140, F-5)
Lower Virgin River (one relationship)	0.95[b]	Dixon and Katzer (2002, p. 33, F-7)
White River and Meadow Valley Flow Systems (four relationships)	0.78[c], 0.92[d], 0.85, and 0.96	LVVWD(2001, p. 4-9, F-4-2, p. 4-10, F-4-3/4, and p.4-11, F-4-5)
Tikaboo and Three Lakes Valleys (two relationships)	0.92[d] and 0.97[a]	SNWA (2003, p. 29, F-6)
Spring Valley (one relationship)	0.91[e]	Katzer and Donovan (2003, p. 42, F-10 and SNWA p.3-13 F. 3-4)

a. Same relationship, slight modification for Tikaboo and Three Lakes Valley.
b. D. J. Donovan (written commun. to M. Johnson., 1999).
c. Used to reduce precipitation in recharge estimates in selected valleys.
d. Same relationship, Adjusted r^2 developed by comparison with data presented in SNWA (2003, p. 26) is 0.98
e Expanded and revised data set resulted in a different altitude-precipitation relationship with an adjusted r^2 of 0.82 .

In the WRFS the natural recharge was estimated using a modified Maxey-Eakin method (SNWA, 2007, p. 5-6 to 5-19). The recharge was estimated for the entire White River flow system using: (1) a total of seven (p. 5-6), three mathematical and four site specific, interbasin flow budget constraints, (2) revised estimates of ground-water discharge by ET (p. 4-10), (3) direct use of a PRISM map, excluding valley floor and ground-water discharge areas (p. 5-1), and (4) an equation to calculate recharge directly from the GIS precipitation map grid (p. 5-5). That equation is as follows:

$$R = 0.00026\ (P-8)^{3.0515} \quad (6)$$

where
R is recharge, in acre-feet/year and,
P is precipitation in inches.

Efficiency coefficients (recharge coefficients) were derived from the recharge equation in the following form:

$$E = (0.00026\ (P-8)^{3.0515})/P, \quad (7)$$

where
E is the percent of precipitation that becomes ground-water recharge and,
P is precipitation in inches.

The SNWA (2007) recharge coefficients are compared to the Maxey-Eakin coefficients in table 15.

Table 15. Recharge coefficients[1], in percent, for the May 3, 2007 PRISM map.

Precipitation Zone (inches)	Maxey-Eakin Method	SNWA 2007 Method
More than 20	25	45
15 to 20	15	15
12 to 15	7	4
8 to 12	3	0.4
Less than 8	0	0

1. SNWA 2007, table 5-1, p. 5-11.

Because the SNWA (2007) coefficients are larger than the Maxey-Eakin coefficients at greater rates of precipitation and smaller at lower rates of precipitation, the recharge values are similar to LVVWD (2001) at higher altitudes and more northerly valleys and generally larger in the middle latitudes and less in the southern part as shown in table 16. The total estimated recharge for the WRFS is 158,224 acre-feet/year, approximately 33 percent higher than the Reconnaissance and Bulletin Series estimates and 30 percent lower than LVVWD (2001). This difference between SNWA (2007) and LVVWD (2001) may also be due to more recent ET analyses used by SNWA (2007).

Table 16. Comparison of recharge estimation results for the White River flow system, in acre-feet/year[1].

Valley Name	SNWA (2007)	Flint and Flint (2007)	BCM[2] (2004)	BCM[3] (2004)	LVVWD (2001)[4]	Nichols (2000)[4]	Eakin (1966) and Rush (1968)[4]
Long Valley	19,928	25,000	16,289	13,536	23,000	48,000	10,000
Jakes Valley	12,288	16,000	10,974	8,310	24,000	38,500	17,000
White River Valley	41,065	35,000	34,925	30,759	62,000	--	38,000
Cave Valley	14,659	11,000	10,264	9,380	20,000	--	14,000
Garden Valley	24,818	--	17,947	15,559	19,000	--	10,000
Coal Valley	3,857	--	3,839	3,110	7,000	--	2,000
Pahroc Valley	4,507	--	4,432	48,322	8,000	--	2,200
Dry Lake Valley	15,667	--	10,627	11,298	13,000	--	5,000
Pahranagat Valley	5,507	--	7,043	7,186	7,000	--	1,800
Delamar Valley	6,401	--	7,764	6,404	5,000	--	1,000
Kane Springs Valley	4,189	--	5,421	6,328	7,000	--	2,600
Coyote Spring Valley	2,128	--	5,184	5,954	4,000	--	2,600
Muddy River Springs Valley	38	--	12	207	200	--	Minor
Hidden Valley	42	--	188	570	300	--	400
Garnet Valley	96	--	294	1,000	300	--	400
California Valley	0	--	23	652	300	--	<100
Lower Moapa Valley	33	--	--	147	1,000	--	<50
Black Mountain Area	0	--	54	1,470	400	--	<100
Total	**155,244**	**--**	**135,307**	**126,700**	**201,500**	--	**104,650**

1. SNWA (2007, table 5-2, p. 5-12); balanced by discharge.
2. Basin Characterization Model, Mean Value, Flint and others (2004).
3. Basin Characterization Model, Time Series Value, Flint and others (2004).
4. Balanced by discharge.

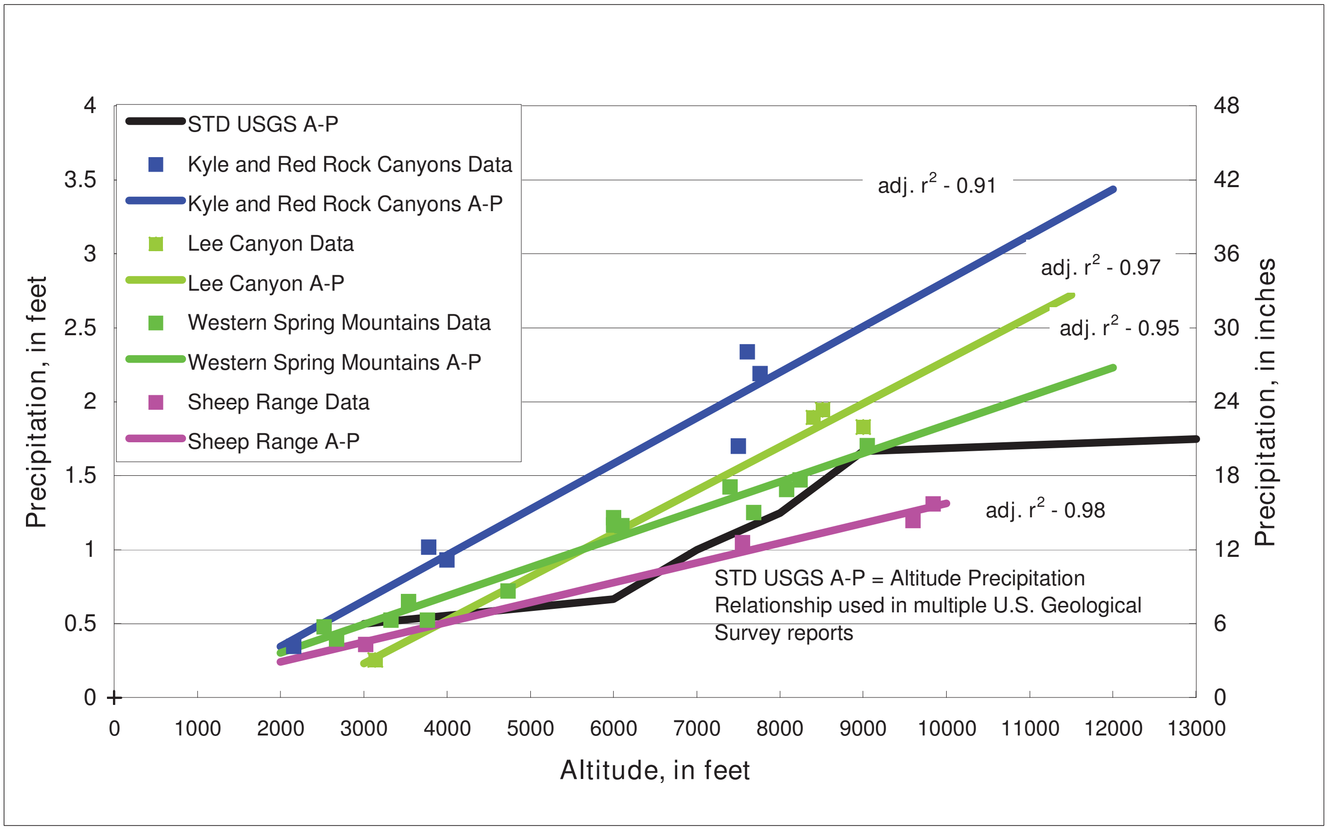

Figure 4a. □as □egas □alley Altitude□□recipitation □A□□□elationships

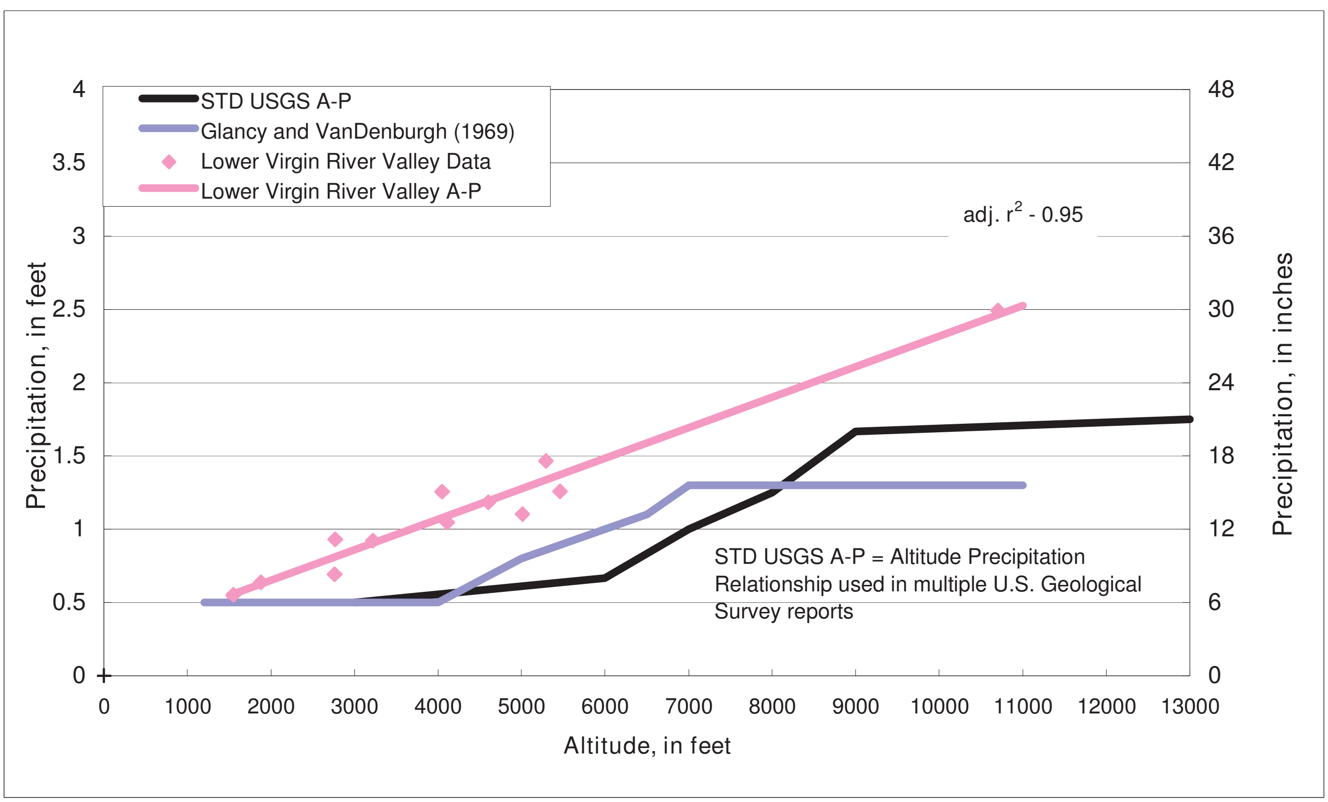

Figure 4b. □irgin □alley Altitude□□recipitation □A□□□elationships

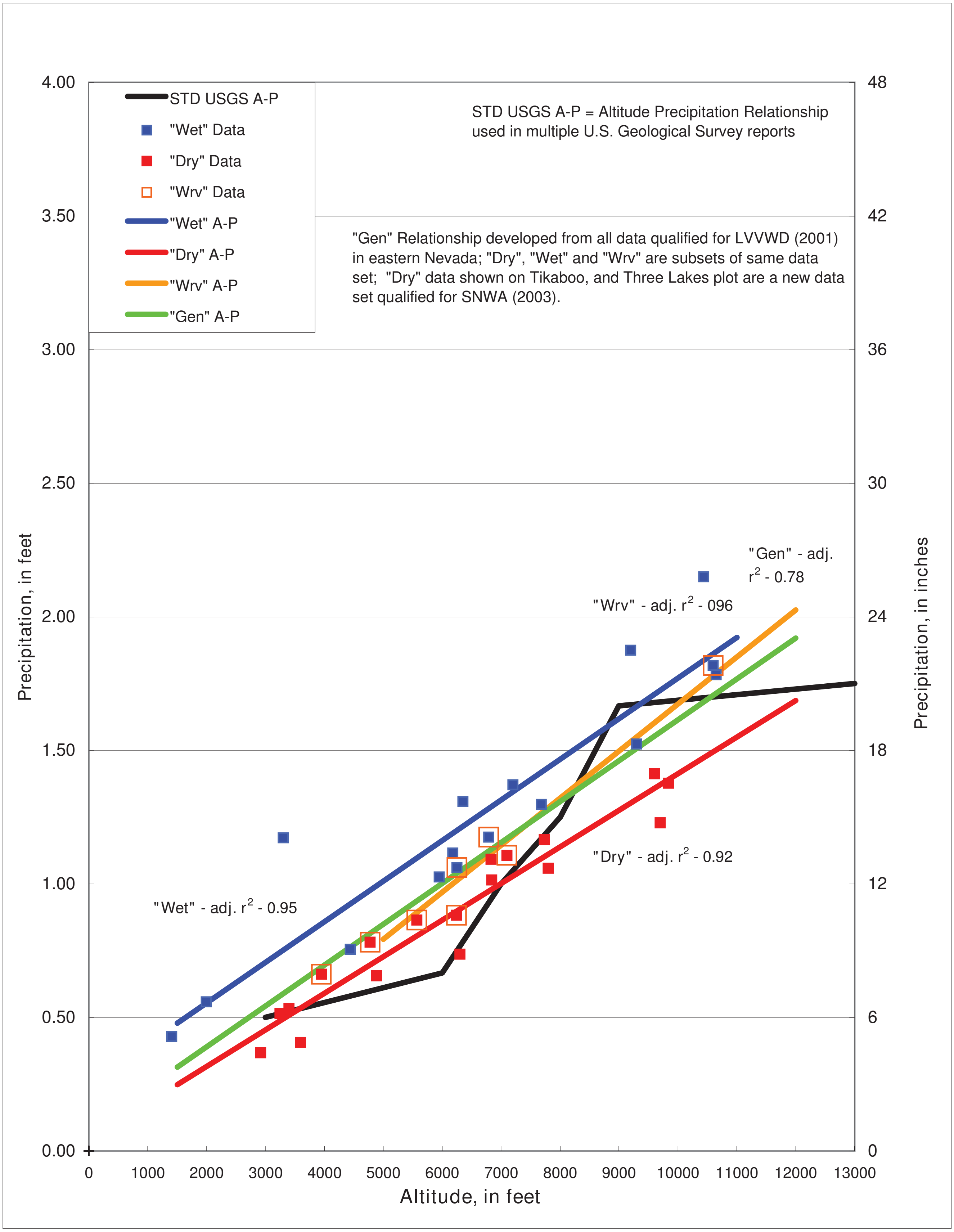

Figure 4c. White River Flow System Altitude-Precipitation (A-P) Relationships

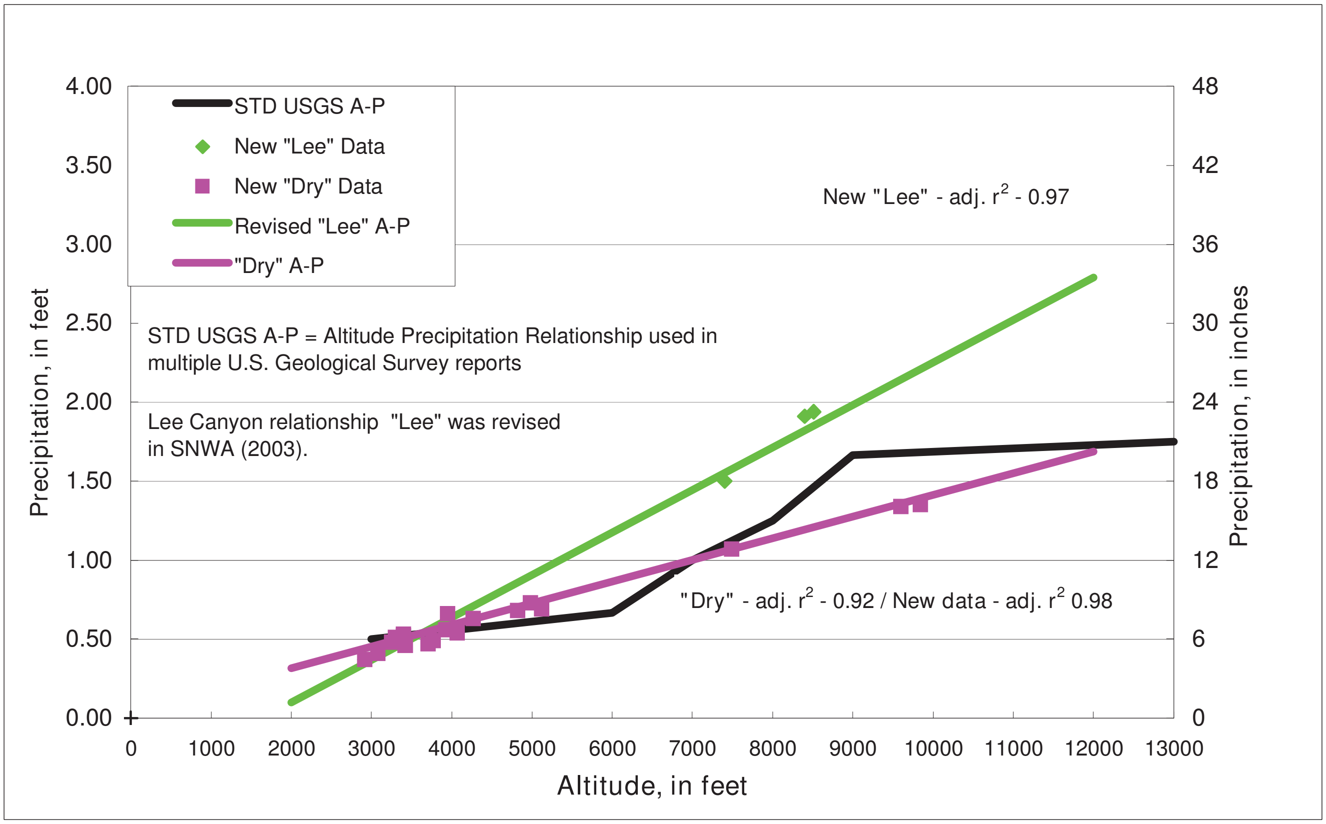

Figure 4d. Tikaboo and Three Lakes Valley Altitude-Precipitation (A-P) Relationships

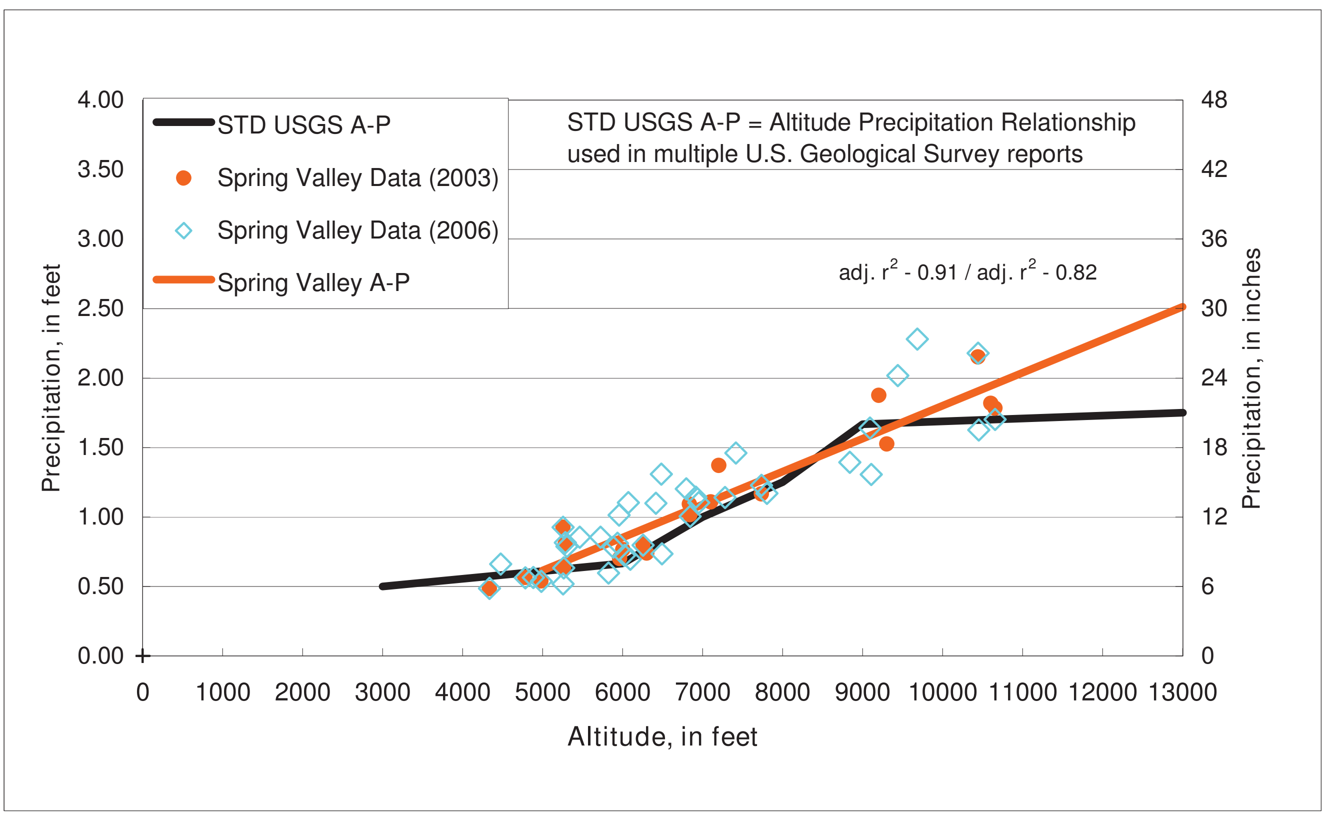

Figure 4e. Spring Valley Altitude-Precipitation (A-P) Relationships

New Natural Recharge Estimates by SNWA (2008b, 2008c)

In 2008, SNWA (2008b and 2008c) further developed the non- or modified Maxey-Eakin methodology introduced in the water-right hearing document for Delamar, Dry Lake, and Cave Valleys (SNWA, 2007). The method is similar to the Nichols (2000c) method in that it uses a version of the PRISM map, and coefficients other than the Maxey-Eakin values. A set of recharge coefficients was developed for each flow system included in the model domain and were applied to the May 3, 2007 PRISM map. The flow systems are White River, Meadow Valley Wash, Goshute Valley and Great Salt Lake Desert. The sets of recharge coefficients are listed in table 17.

Table 17. Recharge efficiencies as percentage of precipitation[1]

Precipitation Zone (in.)	WRFS[2]	MVWFS[3]	GVFS[4]	GSLDFS[5]	Maxey-Eakin[6]
Less than 8	0	0	0	0	0
8 to 12	0.43	0.10	1.19	0.94	3
12 to 15	3.91	1.42	6.21	5.16	7
15 to 20	15.34	7.87	15.44	13.44	15
More than 20	44.90	24.28	42.66	41.08	25

1. SNWA (2008b, table 5-1, p. 5-2).
2. WRFS - White River Flow System.
3. MVWFS – Meadow Valley Flow System.
4. GVFS – Goshute Valley Flow System.
5. GSLDFS – Great Salt Lake Desert Flow System.
6. Maxey-Eakin –Eakin and others (1951), Eakin (1966).

SNWA (2008b, table 5-2, p. 5-5) compared some of the historic and recent recharge estimates, which are reproduced in table 18.

Table 18. Estimated recharge volumes for basins in SNWA (2008b) study area[1], in acre-feet/year.

Basin Name	HA	SNWA (2008)	Recon[6]	Nichols (2000)	LVVWD (2001)	BCM[2] (2004)	BCM[3] (2004)	BARCAS[4] (2007)	DRI[5] (2007)	SNWA (2007)
Goshute Valley Flow System										
Steptoe Valley	179	98,600	85,000	131,469	--	11,419	94,391	154,068	92,000	--
Butte South	178B	27,300	15,000	--	--	22,240	18,284	35,345	28,000	--
Subtotal		**125,900**	**100,000**	**131,469**	--	**133,659**	**112,675**	**189,413**	**120,000**	--
Great Salt Lake Desert Flow System										
Spring Valley	184	81,600	75,000	103,569	87,000	66,987	56,179	93,128	45,000	--
Tippett Valley	185	5,700	6,900	12,389	--	9,717	7,659	12,357	--	--
Pleasant Valley	194	5,400	--	--	--	--	--	--	--	--
Snake Valley	195	104,500	--	--	--	--	--	--	--	--
Hamlin Valley	196	66,000	--	--	--	--	--	--	--	--
Big Snake Valley	254	175,900	100,000	--	--	92,728	81,955	111,337	28,000	--
Subtotal		**263,200**	**181,900**	--	--	**169,432**	**145,793**	**216,822**	**73,000**	--
White River Flow System										
Coal Valley	171	4,200	2,000	--	7,545	3,839	3,110	--	--	3,857
Garden Valley	172	25,700	10,000	--	7,002	17,974	15,559			24,818
Jakes Valley	174	13,000	17,000	38,203	24,194	10,974	8,310	15,680	33,000	12,288
Long Valley	175	21,000	10,300	47,740	31,112	16,289	13,536	24,665		19,928
Cave	180	15,400	14,000	--	19,595	10,264	9,380	10,859	28,000	14,659
Dry Lake	181	16,700	5,000	--	13,254	10,627	11,298	--	--	15,667
Delamar	182	6,800	1,000	--	4,597	7,764	6,604	--		6,401
Kane Springs Valley	206	4,500	600[(a)]	--	6,757	5,421	6,328	--	--	4,189
White River Valley	207	42,900	38,000	--	62,133	34,925	30,759	35,243	42,000	41,065
Pahroc Valley	208	4,900	2,200	--	7,545	4,432	4,832	--	--	4,507
Pahranagat Valley	209	5,900	1,800	--	7,407	7,043	7,186	--	--	5,507
Coyote Spring Valley	210	2,300	2,000[(a)]	--	4,000	5,184	5,951	--	--	2,128
Black Mountain Area	215	0		--	--	54	1,470	--	--	0
Garnet Valley	216	100	400	--	393	294	1,000	--	--	96
Hidden Valley	217	0	400	--	339	188	571	--	--	42
California Wash	218	0	--	--		23	652	--	--	0
Muddy River Springs Area	219	0	--	--	--	12	207	--	--	38
Lower Moapa	220	0	50		1,354	--	147	--	--	33
Subtotal		**163,600**	**102,150**		**197,227**	**135,307**	**126,700**	--	--	**155,223**
Meadow Valley Wash Flow Systems										
Lake Valley	183	12,700	13,000	--	41,320	14,718	12,353	13,092	29,000	--
Spring Valley (Little)	201	12,600	10,000	--	16,151	10,874	8,930	--	--	--
Patterson Valley	202	8,200	6,000	--	15,761	6,643	6,759	--	--	--
Dry Valley	198	2,700	--	--	4,237	2,192	1,815	--	--	--
Rose Valley	199	100	--	--	352	48	43	--	--	--
Eagle Valley	200	2,000	--	--	2,349	890	999	--	--	--
Panaca Valley	203	3,600	--	--	9,041	4,741	4,984	--	--	--
Clover Valley	204	18,900	--	--	10,557	16,274	14,389	--	--	--
Lower Meadow Valley Wash	205	11,100	8,000	--	22,823	11,683	20,092	--	--	--
Subtotal		**71,900**	**37,000**	--	**122,591**	**68,063**	**70,364**	--	--	--

1. SNWA (2008b, table 5-2, p. 5-5). Values reported in acre-feet/year.
2. Mean value of the Basin Characterization Model (BCM) reported by Flint and others, (2004).
3. Time series result of the Basin Characterization Model (BCM) reported by Flint and others, (2004).
4. Basin Characterization Model (BCM) results for the BARCAS draft report, by Flint and Flint, (2007).
5. Desert Research Institute (DRI) chloride balance study, Mizell and others, (2007, table 6, p.17).
6. Estimates from the reconnaissance series reports.

(a) The recharge for these two valleys were estimated together as 2,600 acre-feet/year by Eakin (1966).

SNWA (2008b, table 5-3, p. 5-6) reported their new recharge estimates and compared these volumes with precipitation volumes, which are reproduced in table 19.

Table 19. SNWA recharge volumes as a percentage of precipitation volume[1]

HA	Precipitation Volume (PRISM-800) (AF/YR)	Total Recharge Volume (AF/YR)	Recharge Volume (as Percent of Precipitation)
178B	502,030	27,300	5
179	1,271,360	98,600	8
Goshute Valley Flow System Total	**1,773,390**	**125,900**	**7**
184	1,115,613	81,600	7
185	212,996	5,700	3
194	79,362	5,400	7
195	1,592,560	104,500	7
196	649,174	66,000	10
254	2,321,097	175,900	8
Great Salt Lake Desert Flow System Total	**3,649,705**	**263,100**	**7**
183	400,964	12,700	3
198	91,900	2,700	3
199	8,738	100	1
200	46,367	2,000	4
201	242,839	12,600	5
202	317,671	8,200	3
203	233,956	3,600	2
204	306,717	18,900	6
205	551,874	11,100	2
Meadow Valley Flow System Total	**2,201,026**	**71,900**	**3**
171	267,397	4,200	2
172	350,969	25,700	7
174	289,002	13,000	4
175	449,902	21,000	5
180	265,033	15,400	6
181	571,040	16,700	3
182	235,967	6,800	3
206	145,587	4,500	3
207	1,010,761	42,900	4
208	309,740	4,900	2
209	418,495	5,900	1
210	272,214	2,300	1
215	168,683	0	0
216	54,873	100	0
217	33,040	0	0
218	106,283	0	0
219	53,504	0	0
220	94,697	0	0
White River Flow System Total	**5,097,186**	**163,600**	**3**
Grand Total	**12,721,308**	**624,500**	**5**

1. SNWA (2008b, table 5-3, p. 5-6)

Spring Valley

In Spring Valley Katzer and Donovan (2003) used an updated ET estimate (Nichols, 2000) and applied the Maxey-Eakin efficiencies to a new altitude-precipitation relation (adjusted $r^2 = 0.91$) to develop a total water-resource budget (Katzer and Donovan, 2003, tables 31 and 35, p. 50 and 62 respectively). By estimating all components of the water-resource budget, these investigators balanced the budget within a few percent. SNWA (2006) later updated the precipitation record and expanded the network considerably, from 19 to 39 precipitation sites. However, they developed essentially the same altitude – precipitation relationship, but the adjusted r^2 was reduced to 0.82 (SNWA, 2006, p. 3-

13, figure 3-4). This is to be expected as the distance between the study area and the precipitation stations increases. SNWA (2006) also relied on Nichols (2000a, 2000b, and 2000c) for ET discharge and used the Maxey-Eakin coefficients with their altitude-precipitation relationship to estimate ground-water recharge. A comparison of Katzer and Donovan (2003) with SNWA (2006) and others is provided in table 20.

Table 20. Ground-Water Resource Budgets, Spring Valley in 1000s of acre-feet/year.

INFLOW	Rush and Kazmi (1965)	Brothers and others, (1994)	Nichols (2000)	Katzer and Donovan (2003)	SNWA (2006)	Welch and others (2008)
Precipitation	(960) [1]	(966) [1]	(1,141) [1]	(1,110) [1]	(1,134) [1]	(?)[b]
Ground-Water:						
Recharge	75	75	104	71	87	79 / 93[c]
Inflow	2	2	0	2	2	33[d]
Surface-Water:						
Runoff	(90)[1]	35	NA	53	47	91 / 77[c]
TOTAL:	**77**	**112**	**104**	**126**	**136**	**203[c]**
OUTFLOW						
Evapotranspiration						
Phreatophytes	70	70	90	90	90	76[e]
Crops	1	21	[a]	6	6	14[f]
Mining, Domestic, and Stock	NA	2	NA	2	0.3	1[f]
Surface-Water Evaporation & ET	NA	15	NA	19	32	0
Ground-Water to:						
Hamlin Valley	4	4	10	4	4	33[g]
Snake Valley	NA		4	6	NA	16[g]
Steptoe Valley	0	0	0	2	0	0
Tippet Valley	0	0	0	0	0	2[g]
TOTAL:	**75**	**112**	**104**	**129**	**132**	**142**
Imbalance	2	0	0	3	3	8[h]

1. Not used in their budget, listed only for comparison.
a. Included in ET estimate of Nichols (oral commun., 2001), however, unpublished SNWA GIS analysis in 2004 shows about 3,000 acres of agriculture outside of Nichols' ET boundary. Thus Katzer and Donovan's (2003) budget was corrected (water use rate of 2 acre-ft/acre assumed).
b. Not reported.
c. Recharge reported (rounded) on p. 44 as 93 thousand acre-ft/yr (kafy), which is composed of recharge + 15% of runoff. Appendix A "Recharge" tab show the unrounded and non combined values. Recharge + Run-off = 170 .3 kafy. This + Inflow = 203 kafy.
d. From unnumbered figure on page 5, Composed of 4 kafy from Steptoe Valley, and 29 kafy from Lake Valley.
e. Reported 76 kafy on p. 45 and unrounded in Appendix A "Discharge" tab.
f. Reported unrounded in Appendix A "Water_use" tab.
g. From unnumbered figure on page 5.
h. Reported imbalance on page 4. Not based on the numbers shown in this table, which would have an imbalance of 61 kafy.

SNWA (2006) is similar to Katzer and Donovan (2003) except: (1) The search radius for the data (SNWA, 2006, table 3-2, p. 3-11, Katzer and Donovan 2003, table 23, p. 40) was defined as 50 miles beyond the borders of Spring Valley rather than a smaller and less precisely determined distance used in Katzer and Donovan (2003), (2) 6,000 feet above mean sea level (amsl) was defined as the minimum altitude for recharge (SNWA, 2006), and (3) runoff was described separately (SNWA, 2006). As stated previously, the altitude-precipitation relationship is similar with a slightly lower adjusted r^2 as would be expected from a more regionally selected data set.

In SNWA (2008a), the volume of perennial streamflow and the physical geologic characteristics of the watersheds were better defined than in Katzer and Donovan (2003) and SNWA (2006). These data were used to re-estimate recharge and total water resources for Spring Valley in this report in the following section.

BALANCED HYDROLOGIC BUDGETS AND PERENNIAL YIELD

In valleys where a large amount of outflow is probable or required, as little or no discharge by springs or phreatophytes is observed, the recharge estimates are less certain than in valleys that are closed or nearly closed or in balanced flow systems. This is the primary reason all recharge estimates have been accompanied by discharge estimates. Hydrologically, the best way to determine the probability of interbasin flow is by direct observation, using water levels and a very large difference (at least an order of magnitude) between probable recharge and measured and inferred discharge volumes. Geochemical and isotopic studies provide insight into the recharge process and interbasin flow, as part of a study that also includes the volumetric estimates of recharge and discharge. Interbasin flow is also partially determined by the hydrogeologic framework. Discharge by spring flow and phreatophytes is part of the interaction between ground-water, surface water, and atmospheric water. Climate is simply variable in any time frame. Therefore, basin analysis usually involves all of these disciplines and sub disciplines. An extensively developed valley, such as Las Vegas, also requires consideration of the anthropogenic changes to the hydrologic system and existing, probable, and potential imported water. Surprisingly, or not, a less developed valley can be best assessed for probable perennial yield using a hydrologic budget approach and the value is either the recharge or discharge combined with interbasin flow, or a part of these volumes. By contrast, in a well-developed valley, the natural budget conditions must be inferred, and the perennial yield can be directly measured through the analysis of the most recent hydrologic data and is usually a variable value that is partially influenced by basin management activities.

The perennial yield concept has been defined by numerous investigators over the years, but the most enduring definition is the official one by Scott and others (1971) who state:

> "Perennial yield of a ground water reservoir may be defined as the maximum amount of ground water that can be salvaged each year over the long term without depleting the ground water reservoir. Perennial yield is ultimately limited to the maximum amount of natural discharge that can be salvaged for beneficial use. Perennial yield cannot be more than the natural recharge to a ground water basin and in some cases is less" Scott and others (1971, p. 13).

In some valleys where there is significant surface water the perennial yield concept includes both surface and ground water and is termed “System Yield”.

The ground water pumped prior to achieving a new equilibrium is termed *“transitional storage reserve”* and the amount varies widely per valley. Scott and others (1971) state:

> “In valleys where natural discharge is partly or entirely by sub-surface outflow, the amount that can be salvage with a dewatering (taken from storage) of 50 ft is estimated to average roughly 50 percent of the outflow. The transitional storage reserve estimates for the regions are based on an average dewatering of 30 to 40 feet of valley fill reservoir” Scott and others (1971, p. 13).

One of the difficulties with the perennial yield concept is it is nearly impossible to capture or salvage the natural discharge by ET. Ground-water that is pumped initially comes from storage and, depending on the valley and its ground-water system, it may take a long time to achieve a new equilibrium condition that will exist only where and when pumping has lowered the water table below the ability of the phreatophytes to tap it and the pumping amount equals the natural recharge. In the first year or years of pumping all water comes from storage and the phreatophytes are still discharging to the atmosphere. As pumping progresses with time, less water comes from storage and more from the reduction of ET due to lowering the ground-water level. Eventually the transitional storage reserve is depleted and all water is from captured ET, and thus the natural discharge is equal to the natural recharge, which is equal to the perennial yield.

A rough estimate of the time it takes to capture the entire transitional reserve by lowering the water table 50 ft is provided by Worts (1967, p. 52) with the following equation:

$$Q = \frac{\text{Transitional storage reserve}}{t} + \frac{\text{Perennial yield}}{2}, \qquad (8)$$

where:
Q is the pumping rate, in acre-ft/year,
Transitional storage reserve is: area of alluvial aquifer times depth of dewatering times 10 percent specific yield,
t is the time in years to exhaust storage reserve, and
Perennial yield (varies by valley)

One of the caveats expressed by Worts (1967) is the equation is not valid for pumping rates less than the perennial yield.

Using Spring Valley as an example and substituting the appropriate hydrologic values into the above equation with the following assumptions, (1) surface area of alluvial aquifer = 350,000 acres (Katzer and Donovan, 2003, p. 63), (2) saturated depth to dewater = 50 ft., (3) specific yield = 10 percent, and (4) perennial yield = 80,000 acre-ft/yr, gives:

$$t = \frac{\text{Transitional storage reserve } (1{,}750{,}000 \text{ acre-ft}) \times 2}{2Q - P\ (80{,}000 \text{ acre-ft/yr})} \qquad (9)$$

Rewriting the equation and solving for $t = 40$ (43.8) years

In actuality, 40 years is a theoretical minimum because of the vast amount of valley fill aquifer that will contribute to the well field as the water table under the phreatophytes is drawn down. The surface area of the phreatophytes is about 142,000 acres (Nichols, 2000, T C17, p. C44), which leaves about 200,000 acres of alluvial aquifer that will contribute to some degree to the well field and will delay the draw down under the phreatophyte area. Depending on the hydrology/hydraulics of the aquifer system it may take many more years of pumping to remove sufficient water to ultimately capture the ground-water discharge by ET, which is considered the perennial yield.

Scott and others (1971, table 1) lists the recharge, perennial yield and transitional storage reserve. Unlike recharge and perennial yield, the transitional storage reserve is listed by region instead of valley. It is of interest because it quantifies a process, which would now be calculated using a model. These three values in combination are the fundamental hydrologic quantities for a given valley. Because the specified assumptions are ideal placement of wells, uniform conditions, and maximum effect, any variations from these conditions would increase the estimated time of exhaustion of the transitional storage reserve. Due to the difficulty in meeting the specified conditions of Worts (1967) in a non-idealized basin, the 40 year estimate may be at least an order of magnitude too small. Quantification of a better number using site specific data should provide insights (similar to the lithologicially based resource estimate) into aquifer system behavior.

AN ANALYSIS OF THE EFFECTS OF GEOLOGIC CONTROLS IN SPRING VALLEY ON GROUND-WATER RECHARGE

It has long been understood that the geologic framework influences the movement of ground-water primarily depending on the degree of permeability of the rock through which ground water moves. Carbonate rocks are the most permeable, and volcanic rocks, at least in most of Nevada, have less permeability than carbonate rocks, but more so than intrusive, metamorphic, and clastic rocks. Unconsolidated basin-fill sediments generally have permeabilities greater than carbonate rocks, but less permeability is found in consolidated older alluvial deposits. Faulting and associated fracturing can easily influence the permeability of any of these rocks. In evaluating the control on ground-water movement caused by the permeability of rocks it may not matter what the actual value of the recharge efficiencies are or even if the resulting recharge equates to a discharge value as long as the efficiencies increase with increasing altitude.

The Maxey-Eakin method of determining ground-water recharge was not designed to take into account the different hydrologic properties of the various lithologies that occur, but was originally developed as a reconnaissance tool for rapid use to determine ground-water recharge throughout the state. The method was never intended for use on individual drainages. Thus the application of the method in individual drainages in Spring Valley may be in question because there is no way to accurately estimate the ground-water discharge specific to any given single drainage without an incredible amount of data collection. If the sum of the parts equals the total, and in this case the parts are the perennial drainages in the Shell and Snake Ranges and the total is the entire drainage area of the perennial streams, then one might conclude that dissecting the total into individual drainages is acceptable. A large unknown is the actual ground-water discharge from the recharge associated with those drainages.

Because the Spring Valley perennial yield (80,000 af/y) has recently been estimated by NDWR (State Engineer ruling 5726, April 16th 2007, p. 32) and has been analyzed by multiple techniques, it was considered a good location to assess the magnitude of permeability differences due to lithology on recharge and resource estimates The possible implications to basin management cannot be assessed unless the discharge estimate and historical recharge estimates are compared.

Katzer and Donovan (2003) used streamflow measurements on perennial streams that flowed from drainages with varying percentages of carbonate, volcanic, metamorphic, and clastic rocks. These investigators found the estimated mountain-front runoff generally exceeded the estimated ground-water recharge, particularly for the non-carbonate drainages. When the estimated ground-water recharge was added to the mountain-front runoff the sum exceeded the estimated precipitation and therefore, the resultant water yield was too large. The investigators approach was to measure the area of carbonate rocks in each of the perennial drainages and apply the appropriate Maxey-Eakin recharge efficiencies to the amount of precipitation that falls on the carbonate rocks. The estimated recharge for the remainder of the perennial drainage area was assumed to be included in the mountain-front runoff as rejected recharge. This showed there was about 12,000 acre-feet/year of ground-water recharge occurring in the perennial streams' drainage areas compared to an unadjusted value of 28,000 acre-feet/year. While this seemingly decreases the amount of recharge, in actuality it does not. It simply better defines the areas where ground-water recharge occurs. The amount of ground-water recharge is determined by the ground-water discharge through ET. In Spring Valley the total amount of recharge appears to be greater than the discharge, so the additional recharge is considered ground-water outflow and there are ground-water levels and spring flow to support this finding.

One way to improve on this technique is to determine the area of each rock type by thousand-foot altitude zones. The resulting data from these calculations are listed in tables 21 through 31.

SNWA (2006 and 2008), provided new streamflow measurements and physical descriptions of the watersheds. These data and a GIS altitude interval map were used to develop an improved resource estimate for Spring Valley. Katzer and Donovan (2003) provided the initial estimate to quantify the concepts, and any differences reported here are the result of new information.

The surface geology of Spring Valley (shown on figure 5; SNWA 2006, fig 4-1, p. 4-2) is composed of 18 percent carbonate rock as listed in table 21. The permeability, both primary and secondary, of the carbonate rock is much greater than the other rock types (excluding alluvium) and thus, the perennial surface water runoff from this area is essentially zero. There are large springs that discharge from the base of the carbonate rock drainages, such as Swallow, Bastian, and Little Negro Canyons shown on figure 5. Under both predevelopment and current conditions, ground-water recharge occurs from the perennial streams as they cross the alluvial fans on their way to the valley lowlands. The land-surface area of the various rock types for the entire Spring Valley drainage is also listed in table 21.

Table 21. Exposed rock type area as a percentage for the entire Spring Valley drainage.

Square Miles	Acres	Percent	Classification
308.14	197,209	18	Carbonate
134.39	86,009	8	Clastic
13.00	8,322	1	Intrusive
59.04	37,786	4	Metamorphic
118.71	75,972	7	Volcanic
633.28	**405,298**		**Sub Total**
1,032.48	660,789	62	Alluvium
1,665.76	**1,066,086**	**100**	**Total Drainage Area**

Note: Calculations were made using the unrounded acreage total.

The total area of the exposed bedrock, as listed in table 21, is 38 percent of the entire drainage area. The area of Paleozoic carbonate rock represents nearly 18 percent of the entire drainage area, but nearly 50 percent of the bedrock area where most of the ground-water recharge occurs.

The rock type in the perennial stream watersheds is summarized in table 22. The area of the clastic rock where most of the perennial streamflow emanates is about 30 percent of the perennial stream watersheds, which is less than 10 percent of the entire mountain block watershed. Thus all the runoff occurs in less than 10 percent of the area. The clastic rock occupies the higher altitudes as listed in table 22.

Table 22. Exposed rock types in watersheds of perennial streams.

Square Miles	Acres	Percent	Avg. Altitude	Classification
9.09	5,819	5%	8,025	Alluvium
66.87	42,799	40%	8,907	Carbonate
51.73	33,106	31%	9,284	Clastic
3.09	1,979	2%	8,708	Intrusive
23.86	15,271	14%	8,500	Metamorphic
12.27	7,856	7%	8,483	Volcanic
166.92	**106,827**	**100%**	**8,214**	**Grand Total**

Note: Calculated using the unrounded acreage total.

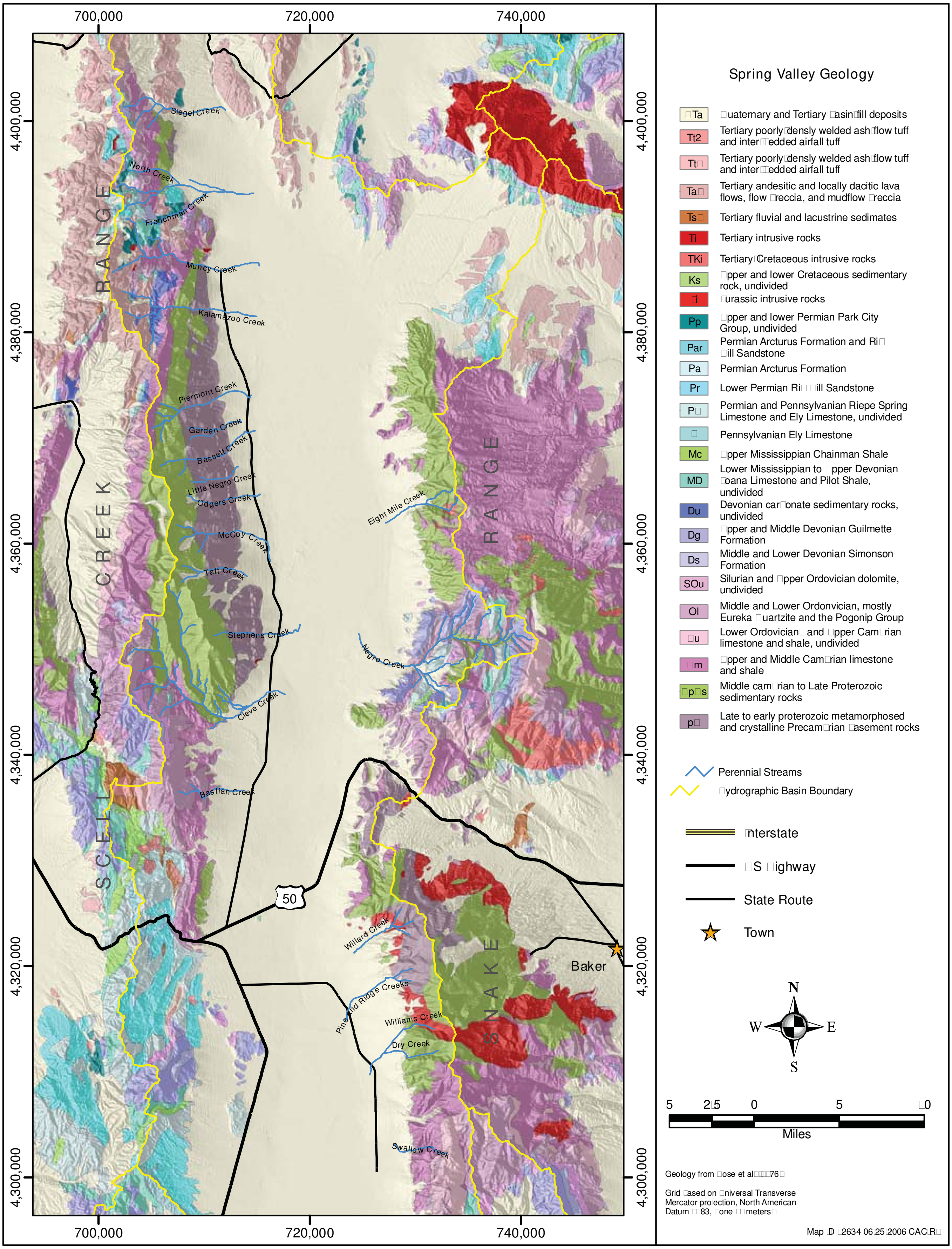

Figure 5. Map of geologic units and perennial streams in Spring Valley

The distribution of precipitation was quantified by 1,000 ft altitude zones for the perennial streams in Spring Valley (table 23).

Table 23. Area of altitude intervals for perennial stream watersheds in Spring Valley, in acres.

	Altitude interval[1,2], in feet							
	6,000 to 7,000	**7,000 to 8,000**	**8,000 to 9,000**	**9,000 to 10,000**	**10,000 to 11,000**	**11,000 to 12,000**	**> 12,000**	**Total[2]**
Cleve Creek	1,351	4,267	5,328	5,347	3,510	682	0	20,485
Siegel Creek	170	1,462	1,076	781	27	0	0	3,515
North Creek at Sunkist	6	359	1,159	451	47	0	0	2,021
Frenchman Creek	184	2,085	821	0	0	0	0	3,090
Muncy Creek	489	2,341	4,865	1,288	0	0	0	8,983
Kalamazoo Creek	456	2,959	4,448	1,408	67	0	0	9,338
Piermont Creek	107	773	1,602	1,771	546	3	0	4,802
Garden Creek	190	514	569	484	102	0	0	1,858
Bassett Creek	55	483	779	1,275	1,189	224	0	4,005
Little Negro Creek	176	480	588	427	178	67	0	1,916
Odgers Creek	113	365	663	711	493	170	0	2,514
McCoy Creek	65	531	916	1,119	953	407	0	3,992
Taft Creek	1	166	501	777	939	367	0	2,751
Stephens Creek	106	353	523	399	406	69	0	1,855
Bastian Creek	255	563	476	318	93	0	0	1,705
Eight Mile Creek	103	762	952	176	0	0	0	1,993
Negro Creek	2,427	5,490	5,216	3,686	564	178	1	17,562
Willard Creek	1	456	908	909	171	8	0	2,453
Swallow Creek	137	652	775	548	156	0	0	2,268
Dry and Williams Canyons	0	298	792	1,213	1,195	421	0	3,920
Pine and Ridge Creeks	0	639	806	504	332	236	73	2,590
Meadow Creek	45	374	660	588	158	0	0	1,824
Shingle Creek	0	96	367	422	399	104	0	1,387
Totals	**6,437**	**26,458**	**34,790**	**24,602**	**11,525**	**2,936**	**74**	**106,827**

1. Precipitation < 6,000 ft is not assumed to contribute to ground-water recharge.
2. Calculated using the unrounded acreage total.

Once the area distribution by altitude zones is determined then the precipitation rate for the average altitude is multiplied by the total area of the zone to obtain the volume of precipitation. In Katzer and Donovan (2003, p. 40) the following regression equation was used to estimate the rate of precipitation:

$$P = 0.00023709\,(A) - 0.5701628 \qquad (10)$$

where
P is precipitation, in feet, and
A is altitude, in feet above mean sea level.

SNWA (2006, p. A-4) utilized a similar equation, P = 0.000237 (A) – 0.537863, which yielded slightly higher precipitation and was used to calculate the precipitation in table 24.

Table 24. Distribution of precipitation by altitude intervals for perennial stream watersheds in Spring Valley, in acre-feet/year.

	Altitude interval[1,2], in feet							
	6,000 to 7,000	7,000 to 8,000	8,000 to 9,000	9,000 to 10,000	10,000 to 11,000	11,000 to 12,000	> 12,000	Total[2]
Cleve Creek	1,355	5,290	7,868	9,163	6,847	1,492	0	32,013
Siegel Creek	170	1,812	1,589	1,338	53	0	0	4,963
North Creek at Sunkist	6	445	1,711	773	92	0	0	3,027
Frenchman Creek	184	2,585	1,212	0	0	0	0	3,981
Muncy Creek	490	2,902	7,184	2,207	0	0	0	12,783
Kalamazoo Creek	457	3,668	6,568	2,413	131	0	0	13,237
Piermont Creek	107	958	2,366	3,035	1,065	7	0	7,538
Garden Creek	191	637	840	829	199	0	0	2,696
Bassett Creek	55	599	1,150	2,185	2,319	490	0	6,798
Little Negro Creek	176	595	868	732	347	147	0	2,865
Odgers Creek	113	452	979	1,218	962	372	0	4,097
McCoy Creek	65	658	1,353	1,918	1,859	890	0	6,743
Taft Creek	1	206	740	1,331	1,832	803	0	4,913
Stephens Creek	106	438	772	684	792	151	0	2,943
Bastian Creek	256	698	703	545	181	0	0	2,383
Eight Mile Creek	103	945	1,406	302	0	0	0	2,755
Negro Creek	2,433	6,806	7,702	6,316	1,100	389	2	24,750
Willard Creek	1	565	1,341	1,558	334	18	0	3,816
Swallow Creek	137	808	1,144	939	304	0	0	3,333
Dry and Williams Canyons	0	369	1,169	2,079	2,331	921	0	6,870
Pine and Ridge Creeks	0	792	1,190	864	648	516	177	4,187
Meadow Creek	45	464	975	1,008	308	0	0	2,799
Shingle Creek	0	119	542	723	778	228	0	2,390
Totals	**6,454**	**32,811**	**51,372**	**42,159**	**22,481**	**6,423**	**179**	**161,879**

1. Precipitation < 6,000 ft is not assumed to contribute to ground-water recharge.
2. Calculated using the unrounded acreage total.

The ground-water recharge and resource calculation in this study is a multi-step process: First, the estimate by Katzer and Donovan (2003, p. 44) is based on the efficiency equation,

$$R_e = 0.05\,(P)^{2.75} \qquad (11)$$

where
R_e is efficiency, in percent, and
P is precipitation in ft.

For the second step, the resulting calculated efficiency was then multiplied by the volume of precipitation per altitude zone (table 26). The equation is a continuous function, intended to reproduce the stepped recharge efficiencies in the range between 8 and 20 inches of precipitation. For this report the Katzer and Donovan (2003) efficiency equation to calculate recharge was used with two limitations: (1) The 6,000-foot contour was assumed to be the lower bound of recharge, and (2) All precipitation at rates greater than 20 inches was assumed to have a recharge efficiency equal to 25 percent. The calculated potential recharge is listed in table 25.

Table 25. Distribution of potential recharge by altitude intervals for perennial stream watersheds in Spring Valley, in acre-feet/year

	Altitude interval[1,2], in feet							
	6,000 to 7,000	**7,000 to 8,000**	**8,000 to 9,000**	**9,000 to 10,000**	**10,000 to 11,000**	**11,000 to 12,000**	**> 12,000**	**Total[2]**
Cleve Creek	68	477	1,149	2,291	1,712	373	0	6,070
Siegel Creek	9	164	232	334	13	0	0	752
North Creek at Sunkist	0	40	250	193	23	0	0	507
Frenchman Creek	9	233	177	0	0	0	0	420
Muncy Creek	25	262	1,049	552	0	0	0	1,888
Kalamazoo Creek	23	331	959	603	33	0	0	1,949
Piermont Creek	5	86	346	759	266	1	0	1,464
Garden Creek	10	57	123	207	50	0	0	447
Bassett Creek	3	54	168	546	580	122	0	1,473
Little Negro Creek	9	54	127	183	87	36	0	496
Odgers Creek	6	41	143	305	240	93	0	828
McCoy Creek	3	59	198	479	465	223	0	1,427
Taft Creek	0	19	108	333	458	201	0	1,118
Stephens Creek	5	40	113	171	198	38	0	564
Bastian Creek	13	63	103	136	45	0	0	360
Eight Mile Creek	5	85	205	75	0	0	0	371
Negro Creek	123	614	1,125	1,579	275	97	1	3,814
Willard Creek	0	51	196	389	83	4	0	724
Swallow Creek	7	73	167	235	76	0	0	558
Dry and Williams Canyons	0	33	171	520	583	230	0	1,537
Pine and Ridge Creeks	0	72	174	216	162	129	44	796
Meadow Creek	2	42	142	252	77	0	0	515
Shingle Creek	0	11	79	181	195	57	0	522
Totals	**325**	**2,962**	**7,502**	**10,540**	**5,620**	**1,606**	**45**	**28,600**

1. Precipitation < 6,000 ft is not assumed to contribute to ground-water recharge.
2. Calculated using the unrounded acreage total.

The third step in the resource analysis is to multiply the potential recharge listed in table 25 by the percent of carbonate rock in each altitude zone listed in table 26. The resulting calculation shows the amount of potential recharge in each of the perennial stream watersheds (table 27).

Table 26. Distribution of carbonate rock type percentage by altitude intervals for perennial stream watersheds in Spring Valley.

	Altitude interval[1,2], in feet							
	6,000 to 7,000	7,000 to 8,000	8,000 to 9,000	9,000 to 10,000	10,000 to 11,000	11,000 to 12,000	> 12,000	Ave[2]
Cleve Creek	24	47	38	52	38	0	0	41
Siegel Creek	0	35	99	94	100	0	0	66
North Creek at Sunkist	0	39	82	100	100	0	0	78
Frenchman Creek	97	56	73	0	0	0	0	63
Muncy Creek	57	83	58	17	0	0	0	59
Kalamazoo Creek	4	48	35	40	100	0	0	39
Piermont Creek	0	0	0	38	43	2	0	19
Garden Creek	0	0	0	0	0	0	0	0
Bassett Creek	0	0	0	0	0	0	0	0
Little Negro Creek	0	0	0	0	0	0	0	0
Odgers Creek	0	0	0	0	0	0	0	0
McCoy Creek	0	0	0	0	0	0	0	0
Taft Creek	0	0	0	0	0	0	0	0
Stephens Creek	0	0	0	0	0	0	0	0
Bastian Creek	90	100	100	100	100	0	0	99
Eight Mile Creek	0	0	17	57	0	0	0	13
Negro Creek	71	73	77	89	100	100	75	78
Willard Creek	0	0	0	0	0	0	0	0
Swallow Creek	73	100	100	100	100	0	0	98
Dry and Williams Canyons	0	0	0	0	2	12	0	2
Pine and Ridge Creeks	0	0	0	0	0	0	0	0
Meadow Creek	0	0	14	67	94	0	0	35
Shingle Creek	0	0	0	0	0	0	0	0
Totals	24	47	38	52	38	0	0	41

1. Precipitation < 6,000 ft is not assumed to contribute to ground-water recharge.
2. Calculated using the unrounded acreage total and unrounded percentages. Ave = Weighted Average which is equal to the total acreage of the interval divided by total acreage of carbonate rock.

Table 27. Distribution of modified recharge by altitude intervals for perennial stream watersheds in Spring Valley based on the percentage of carbonate rock, in acre-feet/year.

	Altitude interval[1], in feet							
	6,000 to 7,000	7,000 to 8,000	8,000 to 9,000	9,000 to 10,000	10,000 to 11,000	11,000 to 12,000	> 12,000	Ave[2]
Cleve Creek	16	222	440	1,180	653	0	0	2,512
Siegel Creek	0	57	230	313	13	0	0	614
North Creek at Sunkist	0	16	205	192	23	0	0	435
Frenchman Creek	9	131	130	0	0	0	0	270
Muncy Creek	14	217	612	92	0	0	0	935
Kalamazoo Creek	1	158	340	243	33	0	0	775
Piermont Creek	0	0	1	290	115	0	0	406
Garden Creek	0	0	0	0	0	0	0	0
Bassett Creek	0	0	0	0	0	0	0	0
Little Negro Creek	0	0	0	0	0	0	0	0
Odgers Creek	0	0	0	0	0	0	0	0
McCoy Creek	0	0	0	0	0	0	0	0
Taft Creek	0	0	0	0	0	0	0	0
Stephens Creek	0	0	0	0	0	0	0	0
Bastian Creek	12	63	103	136	45	0	0	359
Eight Mile Creek	0	0	34	43	0	0	0	77
Negro Creek	87	449	865	1,409	275	97	0	3,184
Willard Creek	0	0	0	0	0	0	0	0
Swallow Creek	5	73	167	235	76	0	0	556
Dry and Williams Canyons	0	0	0	0	10	28	0	38
Pine and Ridge Creeks	0	0	0	0	0	0	0	0
Meadow Creek	0	0	19	170	72	0	0	261
Shingle Creek	0	0	0	0	0	0	0	0
Totals	**144**	**1,386**	**3,147**	**4,304**	**1,316**	**125**	**0**	**10,422**

1. Precipitation < 6,000 ft is not assumed to contribute to ground-water recharge.
2. Calculated using the unrounded acreage total and unrounded percentages. Ave = Weighted Average which is equal to the total acreage of the interval divided by total acreage of carbonate rock.

The differences between the potential recharge for all rock types and modified recharge estimates for carbonate rock are listed in table 28.

Table 28. Summary of modified recharge calculation in percentages and in acre-feet/year.

Drainage	Percentage of carbonate rock in drainage[1] (A)	Ratio of Potential to Modified recharge estimate[2] (D / C) (B)	Potential ground-water recharge[3] (C)	Modified recharge estimate[4] (D)
Cleve	41%	41%	6,070	2,512
Siegel	66%	82%	752	614
North at Sunkist	78%	86%	507	435
Frenchman	63%	64%	420	270
Muncy	59%	50%	1,888	935
Kalamazoo	39%	40%	1,949	775
Piermont	19%	28%	1,464	406
Garden	0%	0%	447	0
Bassett	0%	0%	1,473	0
Little Negro	0%	0%	496	0
Odgers	0%	0%	828	0
McCoy	0%	0%	1,427	0
Taft	0%	0%	1,118	0
Stephens	0%	0%	564	0
Bastian	99%	100%	360	359
Eight Mile	13%	21%	371	77
Negro	78%	83%	3,814	3,184
Willard	0%	0%	724	0
Swallow	98%	100%[5]	558	556
Dry and Williams	2%	2%	1,537	38
Pine and Ridge	0%	0%	796	0
Meadow	35%	51%	515	261
Shingle	0%	0%	522	0
TOTALS			**28,600**	**10,442**

1. Summary column of table 26.
2. Ratio of potential recharge to modified recharge (Column D divided by Column C).
3. Summary column of table 25.
4. Summary column of table 27.
5. Rounded from 99.6%.

To complete this analysis, the long term average runoff from the perennial streams was required and converted from cubic-feet per second as reported in SNWA (2008a) and is listed in table 29.

Table 29. Estimated precipitation recharge and runoff for selected drainages in Spring Valley in acre-feet/year.

Drainage	Total area in acres	Total estimated precipitation[1]	Potential ground-water recharge[2]	Modified recharge estimate[3]	Mountain-front runoff[4]	Watershed Yield[5]
Cleve	20,485	32,013	6,070	2,512	7,607	10,119
Siegel	3,515	4,963	752	614	746	1,360
North at Sunkist	2,021	3,027	507	435	898	1,334
Frenchman	3,090	3,981	420	270	391	661
Muncy	8,983	12,783	1,888	935	1,377	2,312
Kalamazoo	9,338	13,237	1,949	775	4,347	5,122
Piermont	4,802	7,538	1,464	406	1,217	1,623
Garden	1,858	2,696	447	0	283	283
Bassett	4,005	6,798	1,473	0	3,615	3,615
Little Negro	1,916	2,865	496	0	623	623
Odgers	2,514	4,097	828	0	1,717	1,717
McCoy	3,992	6,743	1,427	0	4,883	4,883
Taft	2,751	4,913	1,118	0	1,898	1,898
Stephens	1,855	2,943	564	0	753	753
Bastian	1,705	2,383	360	359	1,992	2,351
Eight Mile	1,993	2,755	371	77	710	787
Negro	17,562	24,750	3,814	3,184	1,898	5,082
Willard	2,453	3,816	724	0	667	667
Swallow	2,268	3,333	558	556[a]	5,542	5,542[a]
Dry and Williams	3,920	6,870	1,537	38	739	777
Pine and Ridges	2,590	4,187	796	0	855	855
Meadow	1,824	2,799	515	261	565	826
Shingle	1,387	2,390	522	0	696	696
TOTALS	**106,827**	**161,879**	**28,600**	**10,442**	**44,021**	**53,887**

1. Precipitation estimated by using equation listed in SNWA (2006); (P = 0.000237(A))-0.537863).
2. Ground-water recharge normally assumed to be generated by a Maxey-Eakin estimate.
3. Ground-water recharge in carbonate rock areas of watershed.
4. Estimated average long term runoff from SNWA 2008, calculated from the reported cfs value.
5. Ground-water recharge for carbonate rock areas and estimated runoff.
a. Average runoff exceeds estimated precipitation.

Once the natural recharge was estimated and modified for the selected drainages, the potential recharge was estimated for the entire remaining area of Spring Valley (table 30).

Table 30. Area, precipitation and ground-water recharge, excluding perennial drainages listed in table 29.

Altitude interval	Total area in acres	Estimated precipitation in feet / year	Estimated precipitation in inches / year	Estimated precipitation in acre-feet	Recharge efficiency	Estimated ground-water recharge
> 12,000	28	2.42	29.10	69	0.25	17
11,000 to 12,000	861	2.19	26.25	1,884	0.25	471
10,000 to 11,000	5,496	1.95	23.41	10,720	0.25	2,680
9,000 to 10,000	16,286	1.71	20.56	27,909	0.25	6,977
8,000 to 9,000	57,660	1.48	17.72	85,142	0.15	12,434
7,000 to 8,000	154,574	1.24	14.88	191,616	0.09	17,297
6,000 to 7000	375,522	1.00	12.03	376,512	0.05	18,962
< 6000	348,831	0.83	9.91	287,995	0.00	0
TOTALS	**959,259**			**981,847**		**58,839**

Applying the ground-water recharge technique to the entire Spring Valley drainage area equals 87,400 acre-feet/year (28,600, table 26 + 58,839, table 31 = 87,400). This recharge is balanced by a ground-water discharge value of 90,000 acre-feet/year (Nichols, 2000) and for this report these two values are considered equal. Adding the perennial stream runoff of 44,000 acre-feet/year increases the apparent water resource yield to 131,400 acre-feet/year (87,400 + 44,000 = 131,400).

However, the yield is not that simple to account for and has some double accounting that must be removed. In the area of perennial stream drainages there are carbonate rocks of high permeability and clastic rocks of low permeability. The two hydrologic processes taking place are ground-water recharge occurring in the high permeability rock areas and surface-water runoff from the low permeability rock areas.

In order to separate and quantify these two processes, we estimated the total annual ground-water recharge in the mountain block exclusive of the perennial stream drainage areas to be 58,839 acre-feet/year. Then we determined the area of the carbonate rocks in the perennial stream drainages, which have an estimated annual ground-water recharge value of 10,400 acre-feet/year bringing the total mountain block recharge to 69,200 acre-feet/year (10,400, table 30 + 58,839, table 31, = 69,200). This is not the entire ground-water recharge estimate for Spring Valley nor is it the entire water resource yield for Spring Valley.

The surface-water runoff from the perennial streams equal 44,000 acre-feet/year (table 30), which when added to the total mountain block recharge of 69,200 equals a grand total water yield of 113,200 acre-feet/year; not the 131,400 apparent yield stated previously. The fate of the 44,000 acre-feet/year of surface-water runoff from the perennial streams is such that about 18,200 acre-feet/year is estimated to recharge the ground-water aquifers (determined by difference, 87,400 – 69,200 = 18,200). Thus the ground-water budget is balanced by the estimated ground-water discharge of 90,000 acre-feet/year. However, this leaves 25,800 acre-feet/year of surface-water runoff that is unaccounted for in the ground-water recharge estimate using the Maxey-Eakin method. The fate of this block of water is probably to ET from phreatophytes and the playa surface. However, if captured it could be considered an additional water resource yield.

Even though over-estimating ground-water recharge in the mountain block is potentially eliminated, a significant amount of recharge remains unaccounted for. By incorporating the surface-water runoff from the clastic rocks into the water-resource budget we may be closer to the actual water yield of the entire area, but are unable at this time to define the actual ground-water recharge from the carbonate rocks, which may be several thousand acre-feet per year more than estimated. If this is true, then there is ground-water discharge as outflow from the valley. The combined resource analysis, equivalent to Katzer and Donovan (2003, table 34) is summarized in table 31.

Table 31. Total resource estimate for Spring Valley using the method described in Katzer and Donovan (2003) and updated precipitation and watershed parameters described in SNWA 2006 and SNWA 2008.

Area	Area in acres	Totals in AF/YR[1], rounded
Area and recharge, excluding selected perennial drainages (table 29)	959,000	58,800
Area of selected perennial drainages (table 28)	107,000	
Potential recharge estimated of selected perennial drainages (table 28)		*(28,600)*[2]
Adjusted recharge of selected perennial drainages (table 28)		10,400
Long term runoff of selected perennial drainages (table 28)		44,000
TOTALS	**1,066,000**	**113,200**

1. Added to recharge total of other areas to provide basin recharge total. Not included for total of the resource estimate.

The results of this study show that water resource from precipitation for Spring Valley is estimated to be 113,200 acre-feet/year, about 15 percent less than estimated by Katzer and Donovan (2003) and SNWA (2006).

FINAL COMMENTS ON SAFE YIELD AND SUSTAINABILITY

In terms of available water resources the historical review of the Maxey-Eakin and subsequent recharge estimates, presented in this report, are less important than perennial yield or safe yield, which vary over time, as does actual recharge and ET. Although recharge estimates can be a first approximation of perennial yield, safe yield is only determined over time using pumping stresses in conjunction with monitoring and basin management. Meinzer (1932) noted the following regarding monitoring:

> "It is also becoming evident that time is required to obtain reliable results in most quantitative investigation of ground water. In this respect ground-water work differs from most other geologic work. It does not deal primarily with features which are fossilized product of events that occurred in past ages and which can be studied at any convenient time, but deals rather with forces that are now operating and producing changes

> which can be kept under observation. Past changes that are not recorded are gone forever; future changes can be observed only with the lapse of time. For this reason systematic observations should be made and records kept in every area in which large ground-water developments have been made or contemplated" Meinzer (1932, p. 144).

Pumping in conjunction with monitoring and management will validate a recharge estimate; however, what is being measured is the safe yield, which is a variable and dependent on management strategies (Lohman, 1972). Ongoing ground-water production or anthropogenic activities may alter the recharge values and change the estimation of safe yield.

The recent discussions about climate change emphasize sustainability, the potential of the resource and the ability of resource managers to continue to meet the demand for water resources. ET and recharge are always variables in the climatic question and raise legitimate concerns about the potential of hydrologic systems to continue to meet the demand for water resources. Longer term climatic changes and more regional effects increase the complexity of determining local variations. Lohman (1972) circumvented all time frames and variability by defining the "safe yield" as follows:

"The amount of ground-water one can withdraw without getting into trouble" Lohman (1972, p. 62).

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SUMMARY

The Maxey-Eakin method of estimating recharge was the standard for estimating ground-water recharge in Nevada for many decades. As indicated, the method is empirical, non-physically based, and provided a reconnaissance-level value of ground-water recharge, discharge, and perennial yield for the State's administrative process to allocate the waters of Nevada for the good of the public interest. In recent years numerous investigators have modified the method by applying the Maxey-Eakin recharge efficiencies to not only the various Hardman regional altitude-precipitation relationships, but also to local basin scale altitude-precipitation relationships.

The critiques of Watson and others (1976); Avon and Durbin (1994) and Epstein (2004) indicate Maxey-Eakin natural recharge estimates are reasonable and most likely conservative. The validity of the recharge estimates are, however, ultimately determined by discharge estimates and observed hydrologic changes in response to ground-water development.

The initial Maxey-Eakin recharge estimates in any valley are usually the comparison volumes for subsequent analysis. Subsequent analysis usually incorporates new data collection to test previous assumptions and provide new testable hypotheses. Also, the difference between ideal or typical characteristics of Nevada valleys and local characteristics of an individual valley were described in the initial analysis; however, the data to quantify the effects on recharge and discharge volumes and locations were not yet available. This report provides historical review and shows how local basin characteristics (specifically precipitation, rock type and runoff) were quantified and accommodated in newer recharge or system yield estimates.

It is also expected that precipitation maps will continue to change, possibly in large areas due to the low density of precipitation data. The "true" value of natural recharge and perennial yield will most likely be best determined by the response of the aquifer systems of interest through time and hence monitoring and mitigation are more important in basin management than an estimate of recharge regardless of how it is made, and it will still be a single point estimate of a transient phenomenon.

Recharge calculations in Nevada are most rigorous when accompanied by an independent discharge estimate. All ground-water recharge studies should have this feature; however, the discharge estimate is easier to develop in some valleys than others. Many valleys have discharge only as underflow (interbasin flow); whereas others have very large springflow, with minimal local recharge. Discharge estimates continue to change with time and techniques resulting in a corresponding change in recharge, not always increasing as evidenced by comparing the results between LVVWD (2001) and SNWA (2007, and 2008). However, many of the newer studies have estimated more discharge and more recharge than the earlier Reconnaissance studies. Investigating multi-valley flow systems as opposed to individual valleys provides a more rigorous evaluation.

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