Hydrology and Water Resources of Spring, Cave, Dry Lake, and Delamar Valleys, Nevada and Vicinity

PRESENTATION TO THE OFFICE OF THE NEVADA STATE ENGINEER

Prepared by

SOUTHERN NEVADA WATER AUTHORITY

June 2011

Suggested citation:
Burns, A.G., and Drici, W., 2011, Hydrology and water resources of Spring, Cave, Dry Lake, and Delamar valleys, Nevada and vicinity: Presentation to the Office of the Nevada State Engineer: Southern Nevada Water Authority, Las Vegas, Nevada.

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Pertaining to:
Groundwater Applications 54003 through 54021 in
Spring Valley
and
Groundwater Applications 53987 through 53992 in
Cave, Dry Lake, and Delamar Valleys

June 2011

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6·23·11

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Acronyms

AMT	audiomagnetotelluric
BARCASS	Basin and Range Carbonate Aquifer System Study
Barker GRFM	Barker generalized radial flow model
BCM	Basin Characterization Model
BLM	Bureau of Land Management
CCRP	Central Carbonate-Rock Province
CWP	Cooperative Water Project
DEM	digital elevation model
DOI	U.S. Department of Interior
DRI	Desert Research Institute
DTW	depth to water
EC	Eddy Covariance
EIS	environmental impact statement
ET	evapotranspiration
GIS	geographic information system
GSLDFS	Great Salt Lake Desert Flow System
HA	hydrographic area
HGU	hydrogeologic unit
HMP	hydrologic monitoring plan
K	hydraulic conductivity
LVVWD	Las Vegas Valley Water District
MRSA	Muddy River Springs Area
NA	not applicable
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NCDC	National Climatic Data Center
NDVI	Normalized Difference Vegetation Index
NDWR	Nevada Division of Water Resources
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NSE	Nevada State Engineer
NWS	National Weather Service
PDF	portable document format
PET	potential evapotranspiration
PRISM	Parameter-elevation Regressions on Independent Slopes Model

ACRONYMS (CONTINUED)

PSZ	Pahranagat Shear Zone
RASA	Regional Aquifer-System Analysis
RAWS	Remote Automated Weather Stations
SNOTEL	SNOwpack TELemetry
SNWA	Southern Nevada Water Authority
UGS	Utah Geological Survey
UNLV	University of Nevada, Las Vegas
USAF	U.S. Air Force
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
WRCC	Western Regional Climate Center
WRFS	White River Flow System

ABBREVIATIONS

°C	degree Celsius
°F	degree Fahrenheit
afy	acre-foot per year
amsl	above mean sea level
bgs	below ground surface
cfs	cubic foot per second
d	day
ft	foot
ft^2	square foot
in.	inch
km	kilometer
m	meter
mi	mile
mm	millimeter
mph	miles per hour
yr	year

1.0 INTRODUCTION

The purpose of this report is to present an assessment of the hydrology and water resources of Spring (hydrographic area [HA] 184), Cave (HA 180), Dry Lake (HA 181) and Delamar (HA 182) valleys. This assessment was completed in support of the water-right hearings related to Southern Nevada Water Authority's (SNWA) applications 54003 through 54021, inclusive, in Spring Valley; and applications 53987 through 53992, inclusive, in Cave, Dry Lake, and Delamar valleys (Figure 1-1). The subject four basins are also referred to as the "Project Basins" in this report, and the "area of interest" includes the Project Basins and other basins in the vicinity. In Nevada, a hydrographic area is delineated based on topography, has an HA number, and is named after the valley it represents. The groundwater basins underlying the Project Basins may have different boundaries than the HAs, but they are generally known and coincide with the HA boundary except where interbasin flow across the HA boundary occurs. Thus, for the purpose of deriving groundwater budgets, the groundwater basins are assumed to coincide with the HAs. Furthermore, in this report, the terms "HA," "basin," and "valley" are used interchangeably to refer to the individual groundwater basins. Details regarding the Project background and the administrative history regarding the SNWA applications are presented in the Conceptual Plan of Development (SNWA, 2011a) and Holmes et al. (2011), respectively.

1.1 Purpose and Scope

The purpose of the work described in this report is to present the technical basis and justifications supporting SNWA's aforementioned groundwater applications in Spring, Cave, Dry Lake and Delamar valleys. The objectives are as follows:

- To derive a groundwater budget for each Project Basin
- To estimate the groundwater resources available in each Project Basin
- To estimate the annual volume of unappropriated groundwater in each Project Basin

Although the focus of the work presented in this report is on Spring, Cave, Dry Lake, and Delamar valleys, certain aspects of the analyses required the scope of work to be extended into larger areas encompassing the Project Basins. The scope of work includes: (1) comprehensive searches for information in the literature and existing databases maintained by local and national agencies; (2) data-quality evaluation; (3) analysis of the data to assess the hydrologic systems of the Project Basins and derive groundwater budgets for the Project Basins; (4) estimation of the groundwater resources of each basin; and (5) estimation of the unappropriated groundwater resources in each basin. To estimate the unallocated portion of the groundwater resources, senior rights documented by Stanka (2011) were deducted from the available groundwater resources.

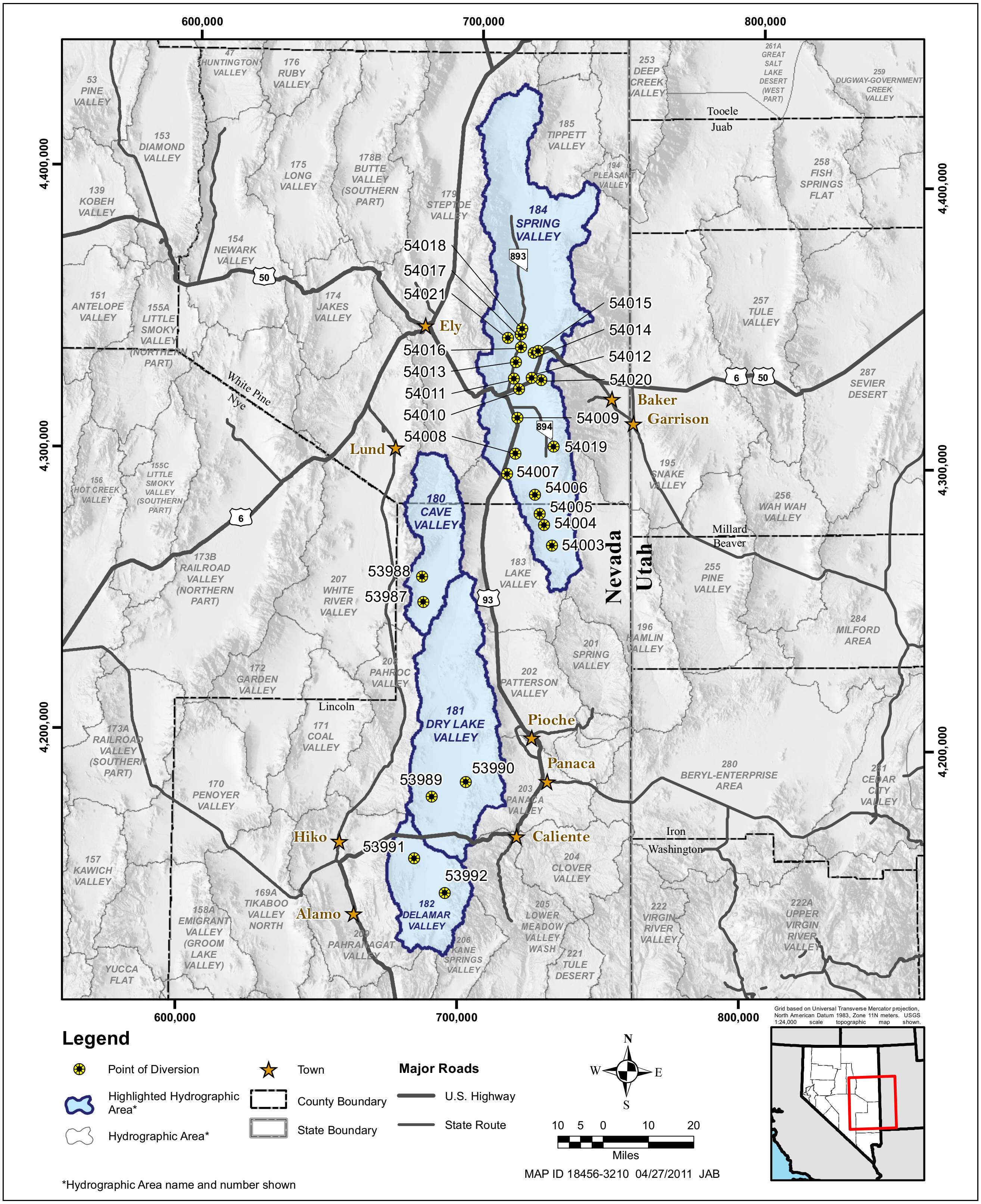


Figure 1-1
Location of Application Points of Diversion in Spring, Cave, Dry Lake, and Delamar Valleys

1.2 LVVWD and SNWA History of Supporting Applications

This section summarizes the studies conducted by the Las Vegas Valley Water District (LVVWD), SNWA, and participating agencies.

1.2.1 LVVWD/SNWA Studies

Work performed by LVVWD, SNWA, and participating agencies in the Project Basins and vicinity includes past studies and on-going data collection efforts. The following list includes selected studies with information relevant to this analysis:

- Desert Research Institute (DRI) Publication No. 41054 (Hess and Mifflin, 1978), produced by the DRI under contract with LVVWD, describes a feasibility study about groundwater development from the carbonate aquifers of Nevada. The report includes a compilation of information on the carbonate rocks in eastern and southern Nevada and a plan for further studies.

- The Cooperative Water Project (CWP) Report Series consists of a series of 19 reports published by LVVWD in support of groundwater applications filed with the Nevada State Engineer (NSE's) Office in 1989 as part of its CWP.

- Reports prepared to support LVVWD/SNWA permit applications at the NSE's Office include (1) a U.S. Geological Survey (USGS) report containing estimates of groundwater budgets for selected basins of the area of interest (Nichols, 2000); and (2) a LVVWD report on water resources and groundwater modeling of the White River and Meadow Valley flow systems (LVVWD, 2001).

1.2.2 SNWA In-State Groundwater Project EIS Studies

In support of the environmental impact statement (EIS) for SNWA's In-State Groundwater Project, SNWA, in cooperation with the Bureau of Land Management (BLM), conducted hydrogeologic studies for the area containing the Project Basins located in east-central Nevada and a small portion of Utah. These studies were used to develop the EIS associated with SNWA's applications for right-of-way from the BLM. These studies are documented in the following reports:

- *Baseline Characterization Report for Clark, Lincoln, and White Pine Counties Groundwater Development Project* (SNWA, 2008).

- *Conceptual Model of Groundwater Flow for the Central Carbonate-Rock Province–Clark, Lincoln, and White Pine Counties Groundwater Development Project* (SNWA, 2009a).

- *Transient Numerical Model of Groundwater Flow for the Central Carbonate-Rock Province–Clark, Lincoln, and White Pine Counties Groundwater Development Project* (SNWA, 2009b).

- *Addendum to the Groundwater Flow Model for the Central Carbonate-Rock Province: Clark, Lincoln, and White Pine Counties Groundwater Development Project* (SNWA, 2010a).

- *Simulation of Groundwater Development Scenarios Using the Transient Numerical Model of Groundwater Flow for the Central Carbonate-Rock Province—Clark, Lincoln, and White Pine Counties Groundwater Development Project* (SNWA, 2010b).

Currently, SNWA continues data collection and analysis activities in support of water-right acquisition and development in the area. These activities are part of several studies within the Project Basins and vicinity. Some are being conducted with the support of other agencies, such as USGS, DRI, and Nevada Division of Water Resources (NDWR) among others. These studies include geophysical surveys, surface-water and groundwater monitoring, well installation and testing, and evapotranspiration (ET) and weather-station data collection. Many aspects of these studies have been completed and are documented in SNWA reports (Pari and Baird, 2011; Prieur et al., 2009; 2010a, b, and c; 2011a, b, and c; Shanahan et al., 2011). A summary of the data collection and analysis activities relevant to the groundwater-resource assessment is documented in this report and provided in Appendix A. Activities specific to the four Project Basins addressed in this document are part of the SNWA hydrologic monitoring, management and mitigation programs associated with the Project Basins and are described in Prieur (2011).

1.3 Other Previous Studies

Many documents reporting the findings of various geologic and hydrologic studies that are relevant to the assessment described in this report were reviewed. Of particular interest are major studies that provide information on the geology and/or hydrology of the Project Basins and the region in which they are located. Major investigations of interest include the following.

1.3.1 NDWR/USGS Reconnaissance Investigations

During the late 1940s to the early 1980s, the USGS, in cooperation with the NDWR, completed reconnaissance-level hydrologic evaluations or reevaluations of nearly every valley in Nevada. The purpose of the studies was to provide a general appraisal of the groundwater resources as quickly as possible (Eakin, 1963). The results of these studies are presented in two report series, the USGS Water Resources Bulletin Series and the NDWR/USGS Ground-Water Resources—Reconnaissance Series. The Reconnaissance Series describes estimates of groundwater recharge, groundwater discharge, and perennial yields for each valley or area in Nevada. The recharge estimates presented in these reports were based on a method developed by Maxey and Eakin (1949), using the groundwater-balance method and an empirical relationship between precipitation and groundwater recharge. An index of the hydrographic areas of Nevada and the associated publications is presented in Rush (1968). Using the Bulletin and Reconnaissance Series, Scott et al. (1971) provided a hydrologic summary for the 232 hydrographic areas in Nevada in a report titled Nevada's Water Resources—Nevada Water Resources Report No. 3. The report was one in a series of reports prepared for the development of a Nevada State Water Plan and included precipitation, surface-water runoff, and groundwater recharge data in addition to perennial and system yield data for each hydrographic area.

1.3.2 U.S. Air Force MX Missile-Siting Investigation-Water Resources Program Study

In the late 1970s and early 1980s, hydrogeologic evaluations were conducted in support of the U.S. Air Force (USAF) MX Missile-Siting Investigation–Water Resources Program Study. The purpose of these evaluations was to assess the potential for water-supply development in 36 hydrographic areas in the Great Basin region that were proposed for the deployment of the MX missile system. This program involved literature reviews, exploratory drilling, aquifer testing, groundwater sampling for water-quality analysis, and the development of groundwater flow models to assist in predicting potential impacts of pumping in some basins. Development of groundwater from the basin-fill aquifers was the preferred water-supply source. Most of the valleys had adequate unappropriated groundwater supplies in the basin fill to meet estimated water requirements (Ertec Western, Inc., 1981b). These studies are documented in several reports by Ertec Western, Inc., (1981a through e) and summarized by Bunch and Harrill (1984).

1.3.3 Great Basin Regional Aquifer-System Analysis Study

The Great Basin Regional Aquifer-System Analysis (RASA) study took place in the 1980s and was undertaken as part of the USGS National RASA program. The main purpose of this program was to develop a geologic, hydrologic, and geochemical framework for regional aquifer systems nationwide (Harrill et al., 1988) to support effective future groundwater management (Harrill and Prudic, 1998). The results of the RASA study are described in nearly 60 reports, including the USGS Professional Paper 1409 series (1409A through H). The first report of this series, Harrill and Prudic (1998), provides a summary of the RASA study.

Previous RASA reports for the Great Basin region include the USGS Hydrologic Atlas HA-694 series, which consists of the following documents:

- USGS Hydrologic Atlas HA-694-A (Plume and Carlton, 1988) describes the hydrogeology of the Great Basin region.
- USGS Hydrologic Atlas HA-694-B (Thomas et al., 1986) describes water levels in the basin-fill deposits and the potentiometric surface in consolidated rocks of the carbonate-rock province of the Great Basin region.
- USGS Hydrologic Atlas HA-694-C (Harrill et al., 1988) describes interpretations of groundwater-budget components including interbasin flow locations and magnitudes.

Another RASA report for the Great Basin region is that of Prudic et al. (1995). Prudic et al. (1995) present a conceptual evaluation of regional groundwater flow based on a numerical groundwater flow model. The two-layer model was used to simulate the concept of numerous shallow-flow regions superimposed over fewer deep-flow regions. The Reconnaissance Series Reports provide the basic estimates of recharge and discharge for this regional flow model.

1.3.4 White Pine Power Project

The White Pine Power Project was set up to support a proposed coal-fueled, steam-electric generating facility in basins located in White Pine County, Nevada. It was assumed that about 25,000 afy of water would be needed in the facility for cooling purposes. A hydrologic study was conducted to investigate the water resources of the target basins, which included Spring, Steptoe and White River valleys.

The White Pine Power Project hydrologic study was conducted and documented in the early 1980s. (Leeds, Hill and Jewett, Inc., 1981a and b; 1983), and was conducted in three phases. Initially, several wells were installed and tested in the valley-fill and carbonate aquifers of the three valleys. Then, additional wells were installed and tested in Spring and Steptoe valleys. Aquifer-property data were derived from step-drawdown and hydraulic-test data and documented in Leeds, Hill and Jewett, Inc. (1981b; 1983).

1.3.5 BARCASS

The Basin and Range Carbonate Aquifer System Study (BARCASS) was a study initiated as a result of federal legislation enacted in December, 2004 (Section 131 of the Lincoln County Conservation, Recreation, and Development Act of 2004 [U.S. Congress, 2004]). The purpose of BARCASS was to investigate the groundwater flow system underlying parts of White Pine and Lincoln counties, Nevada, and adjacent areas in Utah. Participating agencies included USGS, DRI, and a designee from the State of Utah. The BARCASS area included Spring and Cave valleys and other basins of interest.

Twelve hydrographic areas in the Great Basin were included in BARCASS. Of those twelve, Long, Butte, Steptoe, Spring, Tippett, Snake (including Pleasant and Hamlin), Lake, White River, and Jakes valleys are included within the scope of this study. At the time, BARCASS included the most recent evaluation of ET within the northern part of the area of interest (Moreo et al., 2007; Smith et al., 2007; Welch et al., 2007).

The BARCASS findings have been documented in a series of reports as follows:

- Summary report (Welch et al., 2007)
- Geophysical framework investigations (Watt and Ponce, 2007)
- Recharge distribution (Flint and Flint, 2007)
- Mapping of ET units (Smith et al., 2007)
- ET-rate measurements (Moreo et al., 2007)
- Water-level surface maps (Wilson, 2007)
- Delineated irrigated acreage (Welborn and Moreo, 2007)
- Methodology for mapping vegetation using satellite imagery (Cablk and Kratt, 2007)
- Steady-state water budget accounting model (Lundmark, 2007; Lundmark et al., 2007)
- Groundwater-chemistry interpretations (Hershey et al., 2007)
- Recharge estimates using the chloride mass-balance method (Mizell et al., 2007)
- Uncertainty analysis of groundwater-ET estimates (Zhu et al., 2007)

1.4 Technical Approach

The technical approach followed in the assessment of the water resources of the Project Basins includes the following: data compilation and evaluation, interpretation of the hydrologic systems, and evaluation of groundwater availability in the Project Basins.

1.4.1 Data Compilation and Evaluation

The hydrologic interpretations and estimates of available groundwater resources described in this report are based on extensive reviews of previous scientific investigations and data collection activities dating back the early 1990's. Previous investigations include detailed and reconnaissance-level geologic, hydrologic, and geochemical investigations of the Project Basins and adjacent basins (Figure 1-1). A summary of studies that are relevant to this study is presented in Section 1.2 and Section 1.3, and more details are provided throughout this report.

Substantial data acquisition efforts were also completed by SNWA. Field data collection activities during the 2003 to 2010 field seasons included drilling and testing SNWA monitor and test wells, geologic mapping, surface geophysical surveys, vegetation mapping, water-chemistry sampling, depth-to-water (DTW) measurements, and streamflow measurements. These data augmented existing hydrologic, geologic, and water-chemistry databases compiled from previous investigations by SNWA. Additionally, data compilation and collection efforts have been enhanced through cooperative agreements between SNWA and the University of Nevada, Reno, DRI, and USGS. These agreements involve long-term monitoring of hydrologic conditions, geophysical studies, and other selected studies to evaluate groundwater discharge, water chemistry, and groundwater flow. These efforts are summarized in Appendix A.

The compiled data were evaluated to assess their quality and limitations. Data were filtered to remove poor quality and erroneous records. The final data sets were applied in data analyses completed in support of a series of geologic, hydrologic, and geochemical investigations to assess the water resources of the Project Basins and adjacent basins. Recent data and interpretations, where available, were given priority and were incorporated in the data analyses as appropriate. The analysis of the ET, geologic and geochemical data are presented in separate reports (Fenstermaker et al., 2011; Rowley et al., 2011; Thomas and Mihevc, 2011).

1.4.2 Hydrologic System Interpretation

To understand the groundwater flow system of a given basin, it is necessary to examine each of its main components, which are as follows:

- Geological framework
- Groundwater hydrology
- Geochemical framework

The geologic framework is a description of the extremely complex subsurface environment through which groundwater moves. The complexities include various types of rocks and numerous structural features that control groundwater occurrence and movement. The geologic framework is extremely important in understanding the behavior of groundwater, particularly in the Basin and Range Province. The geologic framework is documented in a separate expert report prepared by Rowley et al. (2011). Several features of the hydrologic system of a given basin are necessary to characterize its three main components. They consist of the basin's physical setting and hydrogeology; the distributions of precipitation, natural recharge, perennial streamflow, interbasin flow, and groundwater discharge by ET.

The data compilation and analysis activities are documented by data type. The physical setting, precipitation distribution, and well and spring data which relate to most aspects of the hydrologic systems, are discussed first. The groundwater-balance method was used to derive estimates of groundwater recharge as a function of the other components of the groundwater budget. The groundwater-balance method was applied to Spring Valley rather than to the entire Great Salt Lake Desert Flow System (GSLDFS) in which Spring Valley is located, because Spring Valley has little interconnectivity with the other basins of the GSLDFS. Because Cave, Dry Lake, and Delamar valleys have important hydraulic connections to other basins of the White River Flow System (WRFS), the groundwater-balance method was applied to the whole flow system to estimate the recharge efficiencies. These efficiencies were then used to derive recharge estimates for Cave, Dry Lake, and Delamar valleys. Also, because uncertainties exist in the definition of the WRFS, several interpretations have been documented in the literature, including those of Eakin (1966) and LVVWD (2001). The flow system configuration selected for this study is that of Eakin (1966).

Using the groundwater-balance method to derive basin recharge estimates for Spring Valley and the WRFS required the generation of recharge efficiencies using the following information:

- A spatial distribution of precipitation
- Estimates of groundwater ET
- Estimates of groundwater flow through the external boundaries

The best method of representing the spatial distribution of precipitation was selected (Appendix B). Groundwater ET was estimated for Spring Valley and the WRFS basins, using the most recent information (Section 5.0, Appendices D and F). External boundary fluxes of Spring Valley and the WRFS were estimated using Darcy flux calculations (Freeze and Cherry, 1979), where possible (Appendix E).

Groundwater recharge distributions for the Project Basins (Section 6.0) were then derived using the recharge efficiencies (Appendix F). Estimates of interbasin flow for the Project Basins were derived based on the recharge estimates (Section 6.0) or Darcy flux calculations (Section 7.0), depending on the basin.

Estimates of basin recharge and discharge were then used to evaluate the occurrence and movement of groundwater and to construct the groundwater budgets (Sections 8.0 and 9.0). Finally, estimates of the unappropriated groundwater resources in the Project Basins are provided in Section 10.0. The methods used to estimate each of the components are described in the corresponding section. Detailed reports of the hydrogeology of the Project Basins and geochemical environment are provided in separate expert reports prepared by Rowley et al. (2011) and Thomas and Mihevc (2011), respectively.

1.5 Document Organization

This report contains eleven sections, seven appendices, and a set of electronic files located on a DVD accompanying printed copies of this document. A brief description of each part of this document follows:

- Section 1.0 is this introduction.
- Section 2.0 provides some basic groundwater concepts and describes the physical setting of the Project Basins. This section is included for readers who are not familiar with these subjects.
- Section 3.0 describes the precipitation distribution used to estimate the distribution of recharge for the Project Basins.
- Section 4.0 describes the available hydrologic data, including well, spring, and aquifer property data for the Project Basins.
- Section 5.0 presents the estimates of groundwater ET derived for the Project Basins.
- Section 6.0 presents the estimates of potential recharge from precipitation derived for the Project Basins.
- Section 7.0 presents the estimates of interbasin flow derived for the Project Basins.
- Section 8.0 provides a description of groundwater occurrence, sources and movement for the Project Basins.
- Section 9.0 summarizes the groundwater budgets of the Project Basins.
- Section 10.0 provides estimates of unappropriated groundwater in the Project Basins.
- Section 11.0 provides a list of references cited in the report.
- Appendix A describes ongoing SNWA data collection and analysis activities that are relevant to the groundwater assessment presented in this document.
- Appendix B provides the detailed analysis followed to derive estimates of precipitation for purposes of deriving recharge estimates for the Project Basins.
- Appendix C provides inventories of hydrologic data including well, spring and hydraulic-property data for the Project Basins and vicinity.

- Appendix D describes the derivation of groundwater-ET estimates for Spring Valley and White River Valley using new data acquired within the last few years.

- Appendix E describes the external boundary flow estimates for Spring Valley and the WRFS.

- Appendix F presents the details of the application of the groundwater-balance method as implemented in the Excel® Solver to derive recharge efficiencies for the Project Basins.

- Appendix G presents the details of the use of the Excel® Solver to generate the recharge efficiencies for the Project Basins.

- Plate 1 contains a map showing the major geologic and hydrologic features and controls on groundwater in Spring Valley. Selected relevant features in neighboring basins are also included on the map.

- Plate 2 contains a map showing the major geologic and hydrologic features and controls on groundwater in Cave, Dry Lake, and Delamar valleys. Selected relevant features in neighboring basins are also included on the map.

- Electronic files contain the detailed data sets for wells, springs, and aquifer properties; and the recharge solutions using the Excel® Solver. The electronic files are provided on a DVD accompanying the hard-copy version of this report.

2.0 GENERAL CONCEPTS, PHYSICAL SETTING, AND LAND AND WATER USE

This section describes the fundamental concepts and misconceptions regarding groundwater, and presents a general overview of the factors affecting its occurrence and movement within the Project Basins and vicinity. In addition, the physical setting of the area of interest and the land and water use within the Project Basins is described.

2.1 Groundwater - General Concepts

Unlike surface water (i.e. rivers, streams, lakes), groundwater occurs and moves underground and is, therefore, more difficult to fully understand and quantify. This section describes the general concepts of groundwater, including where and how it occurs, and how it moves through the environment.

2.1.1 Groundwater - The Myth of the Underground Rivers

A USGS report describing the fundamental concepts of groundwater hydrology entitled "Basic Ground-Water Hydrology" was prepared by Heath (2004). In this report, the author states:

> The belief that groundwater occurs in underground rivers resembling surface streams whose presence can be detected by certain individuals, is a common misconception (Heath 2004, p. v).

Heath (2004, p. v) also states:

> In order for the Nation to receive maximum benefit from its ground-water resource, it is essential that everyone, from the rural homeowner to managers of industrial and municipal water supplies to heads of Federal and State water-regulatory agencies, become more knowledgeable about the occurrence, development, and protection of ground water. This report has been prepared to help meet the needs of these groups, as well as the needs of hydrologists, well drillers, and others engaged in the study and development of ground-water supplies.

Heath (2004, p. 1) also explains that:

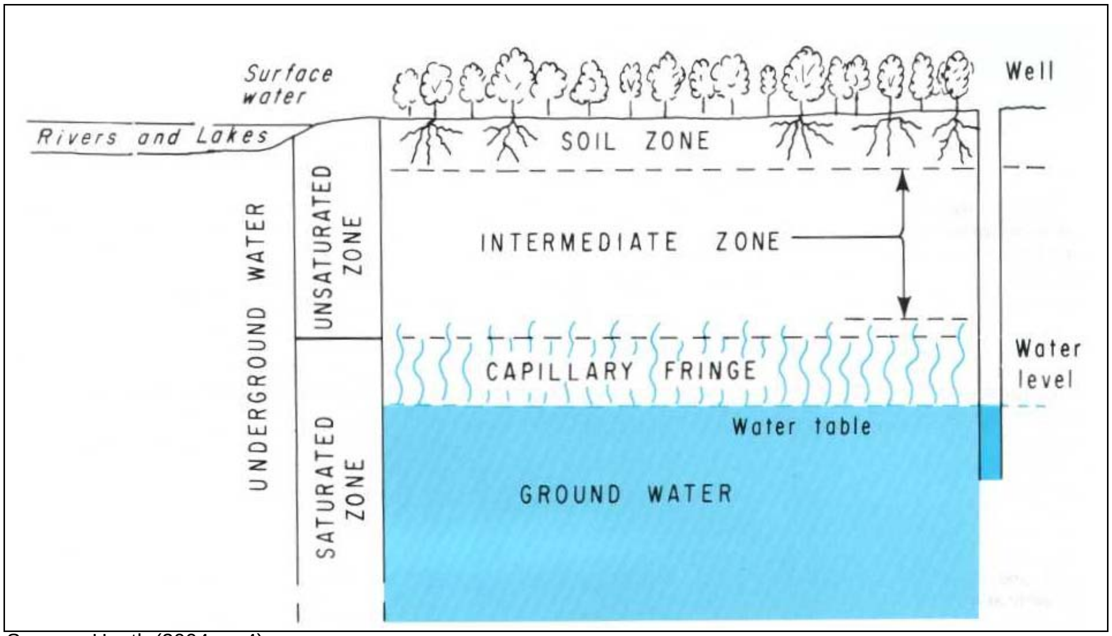
> The ground-water environment is hidden from view except in caves and mines, and the impression that we gain even from these are, to a large extent, misleading. From our observations on the land surface, we form an impression of a "solid" Earth. This impression is not altered very much when we enter a limestone cave and see water flowing in a channel that nature has cut into what appears to be solid rock. In fact,

from our observations, both on the land surface and in caves, we are likely to conclude that ground water occurs only in underground rivers and "veins." We do not see the myriad openings that exist between the grains of sand and silt, between particles of clay, or even along the fractures in granite.

Heath (2004, p. 4) describes water present below the land surface, using the sketch shown in Figure 2-1, as follows:

All water beneath the land surface is referred to as *underground water* (or subsurface water). The equivalent term for water on the land surface is surface water. Underground water occurs in two different zones. One zone, which occurs immediately below the land surface in most areas, contains both water and air and is referred to as the *unsaturated zone*. The unsaturated zone is almost invariably underlain by a zone in which all interconnected openings are full of water. This zone is referred to as the *saturated zone*.

Water in the saturated zone is the only underground water that is available to supply wells and springs and is the only water to which the *ground water* is correctly applied. Recharge of the saturated zone occurs by percolation of water from the land surface through the unsaturated zone.



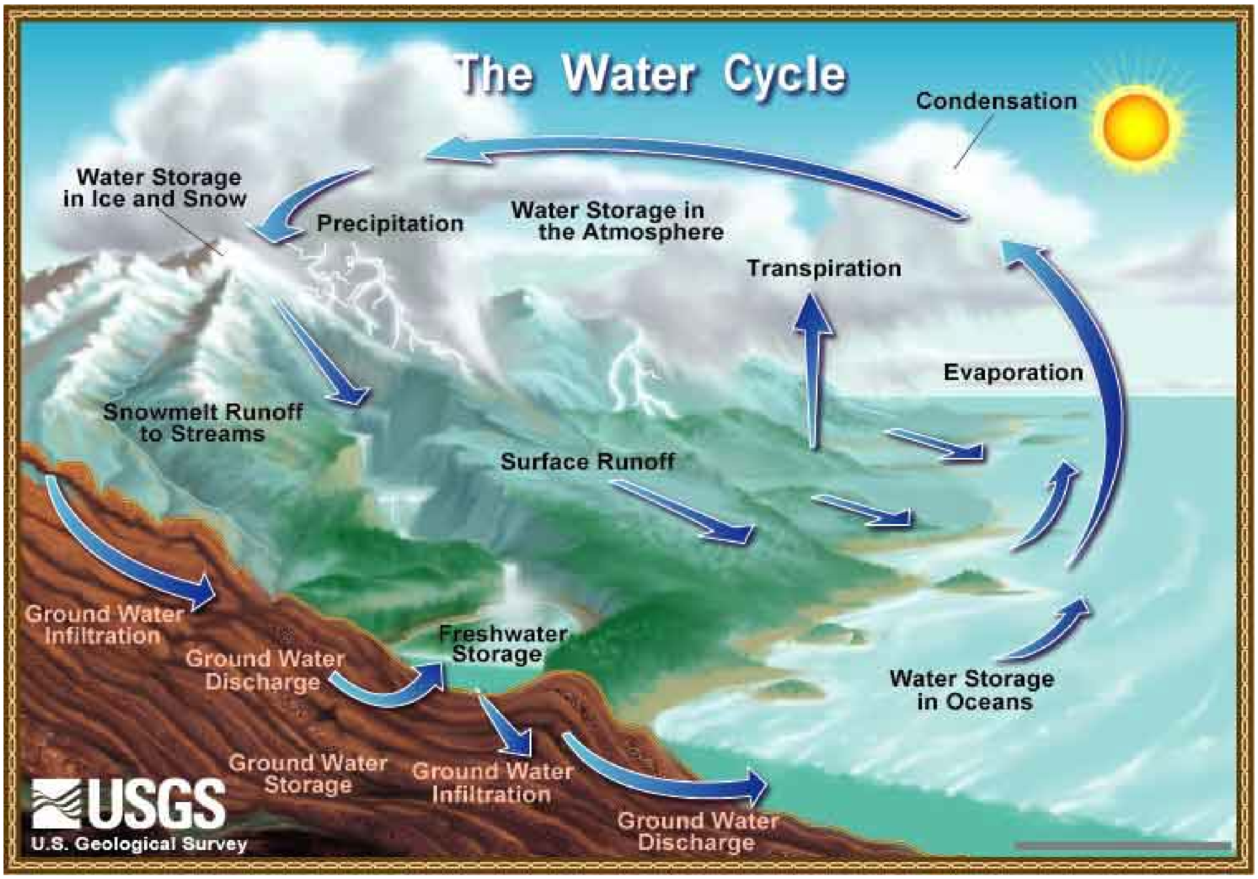
Source: Heath (2004, p. 4)

Figure 2-1
Simplified Representation of Subsurface Water

Just like water in streams, groundwater moves from areas of higher hydraulic heads to areas of lower hydraulic heads. However, the movement of groundwater through the interconnected openings is extremely slow as compared to flow in streams. Heath (2004, p. 5) compares travel times for water flowing on land surface and water flowing in the subsurface. The rate of movement of water on the land surface is of the order of tens of kilometers per day. In contrast, the rate of movement of groundwater below the land surface is of the order of meters per year.

2.1.2 Factors Affecting Groundwater

Practically, every component of the physical setting and land and water use by humans affect groundwater in some way. Components of the physical setting consist of the physiography, climate, soil and vegetation, and geology. As a matter of fact, these factors affect the whole water cycle (also referred to as the *hydrologic cycle*), of which groundwater is an integral part. A general description of the water cycle is provided to highlight the role of groundwater in the water cycle (Figure 2-2).



Source: Evans (2004)

Figure 2-2
Simplified Representation of the Hydrologic (Water) Cycle

As the name indicates, water moves between the subsurface, surface, and atmosphere of the earth in a cyclical manner. The water cycle, therefore, has no beginning and no end. This simplified description of the water cycle starts with precipitation. Precipitation on the land surface may occur in the form of rain, hail or snow. The spatial distribution of precipitation depends on the location, climate, and topography of the area. Once on the land surface, precipitation may follow several paths depending on its state; and the temperature, topography, land cover, and geology of the area. The water derived from all forms of precipitation follows different paths: it can return to the atmosphere in the form of vapor, flow on the land surface, or infiltrate into the subsurface. The portion of the water that does not evaporate in place, is eventually stored in water bodies located on the land surface, in the subsurface as groundwater, or as soil moisture in the unsaturated zone above the groundwater table. Water stored in surface bodies is subjected to further losses to the atmosphere and the subsurface. Water stored in the subsurface may exit the ground surface through springs or into surface water bodies (lakes, streams, rivers, etc.). Water moving through the hydrologic cycle is stored in different forms for variable periods of time before moving to the next part of the cycle. Heath (2004, p. 1) presents the rates of exchange of water stored in the atmosphere, on the surface and subsurface of the earth. The time of exchange spans from 0.027 year (10 days) for water vapor in the atmosphere to 8,000 years for water in glaciers. Water stored in the subsurface (groundwater) has a rate of exchange of 280 years while water in rivers has a rate of exchange of 0.031 year (11 days). Therefore, except for water stored in glaciers (in the form of ice), water stored in the subsurface stays there much longer than water stored in any surface-water body. This is because water flowing through rocks moves a lot more slowly than water flowing on the surface of the earth or through the atmosphere.

2.1.3 Groundwater Basins, Flow Systems, Budgets and Perennial Yield

Groundwater accumulates in basins, which correspond to areas generally surrounded by mountains. A basin may be surrounded by virtually impermeable boundaries or may have portions of its boundaries that are hydraulically connected to adjacent basins. When several basins share open boundaries and groundwater moves from one basin to the next, they are said to form a flow system. Groundwater moves from basin to basin only if the rocks located along the boundaries between two basins are permeable. This groundwater flow across basin boundaries is termed interbasin flow.

A groundwater budget is an accounting of the groundwater that enters, leaves and is stored in a given portion of an aquifer system. A groundwater budget may be derived for a single basin or a flow system, or any finite three-dimensional portion of an aquifer. Groundwater enters a basin or flow system in the form of recharge from precipitation or via interbasin flow from other connected basins. Groundwater leaves a basin or flow system via ET, interbasin flow or pumping. Groundwater in storage is the volume of groundwater contained in the openings present within the rocks (pores, faults, fractures).

The term “perennial yield” of a groundwater basin refers to “... 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 et al., 1971, p. 13).” This is because groundwater that is being removed on an annual basis is continually being replaced by recharge from precipitation or interbasin flow. Although the concept is easy to comprehend, the quantification of the perennial yield is subject to interpretation.

2.2 Physical Setting of Project Basins

Descriptions of the physical setting of the Project Basins and vicinity, including the physiography, climate, soil and vegetation, hydrogeology, and flow systems are provided in this subsection.

2.2.1 Physiography

Physiography is the study of the physical features of the earth's surface. The Project Basins are located within the Basin and Range Province described by Fenneman (1931) (Figure 2-3) which consists of a series of parallel to subparallel, north-trending mountain ranges separated by elongated alluvial valleys. According to Rowley et al. (2011), this region has undergone the most severe structural extension of the continental crust of any location in the world. The Project Basins are further classified by Heath (2004) as being in the Alluvial Basins Groundwater Region of the western United States, and they are also part of the Carbonate-Rock Province of eastern Nevada and western Utah described by Plume and Carlton (1988) (Figure 2-3).

2.2.2 Climate

Climate is a term that describes the meteorological conditions that prevail in a given region, including temperature, precipitation, and wind patterns. The climate within the Project Basins and adjacent basins is variable and influenced by the large range in latitude, variations in land-surface elevation, and the barrier provided by the Pacific mountain systems to the west, which prevents winds off the Pacific Ocean from reaching Nevada (Houghton et al., 1975).

Temperatures within the area of interest have large daily and annual changes because the typically clear skies of Nevada allow for heating of the ground in the day and radiant cooling at night. Temperatures greater than 90°F are common in the summer at lower elevations, while cooler temperatures of about 30°F are experienced at higher elevations.

Precipitation in the Project Basins and vicinity varies by season and is the result of frontal systems originating in the Pacific Ocean, low pressure systems in the Great Basin, and summer thundershowers (Houghton et al., 1975). The Project Basins lie within the northeast, south-central, and extreme south climatic divisions defined by Houghton et al. (1975). Precipitation within each of the Project Basins is least on the valley floor and greatest in the mountains. Based on the precipitation recorded at stations located within the areas of interest (Appendix B), annual precipitation ranges from about 5 in. in the south at the Logandale station (Western Regional Climate Center [WRCC]) to 27 in. in the north at the Berry Creek SNOTEL (SNOwpack TELemetry) Station (Natural Resources Conservation Service [NRCS]). Large precipitation events, mainly in the form of snowfall, are more common in the winter months in the high-elevation areas but are of short duration, and high-intensity rainfall events associated with isolated thunderstorms are common in the summer, causing flash floods in the lower elevations.

Wind speed and direction are controlled by prevailing storm tracks and orographic effects induced by the basin and range topography. The annual average wind speed at the Ely Airport was reported at 9.5 mph for the period of 1996 to 2006, while the monthly average wind speeds ranged between 8.8

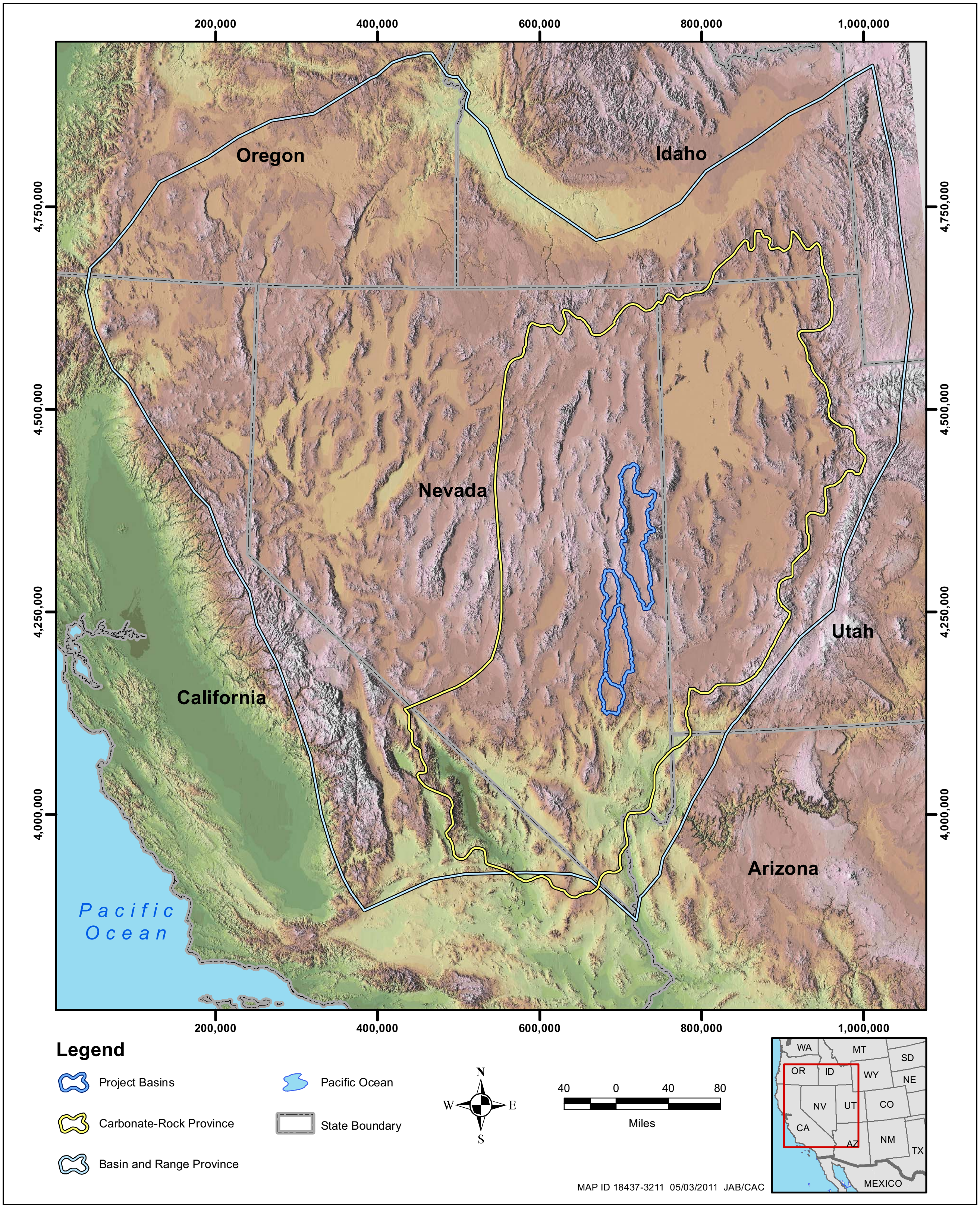


Figure 2-3
Location of Spring, Cave, Dry Lake and Delamar Valleys in the Basin and Range and Carbonate-Rock Provinces

and 10.3 mph over the same period of time (WRCC, 2011). Evaporation rates within the area of interest are controlled by low humidity, abundant sunshine, and dry winds (Houghton et al., 1975). The annual evaporation rate at the Caliente Station is about 64 in./yr for the period of 1928 to 2005 (WRCC, 2011). Based on mean monthly data at this station, all of the evaporation occurs from March to October (WRCC, 2011).

2.2.3 Soil and Vegetation

Generally, the Project Basins and neighboring basins (in the Great Basin) contain basin-fill sediments that accumulated to thicknesses of locally more than 10,000 ft in some of these basins. The fill is the result of erosion of the mountain ranges surrounding the valleys (Rowley et al., 2011). Some of these valleys are occupied by playas (temporary lakes), which normally have a very high-salt concentration as a result of evaporation.

The vegetation of the valley floors of the Project Basins and vicinity is typical of the Great Basin. Many of the plant groups that occupy the valley floor are referred to as phreatophytes. Phreatophytes were first defined by Meinzer (1927) as plants that are able to obtain a perennial and secure supply of water by sending their roots down to the groundwater table. The plant assemblage is composed primarily of greasewood, saltgrass, and rabbitbrush. Spiny hopsage, shadscale, and big sagebrush, although not generally considered phreatophytic, can occur within this assemblage. Phreatophytes have the ability to use both soil moisture and shallow groundwater to survive in desert environments via transpiration. ET, a combination of evaporation and transpiration of water, is a key component when estimating groundwater discharge in a basin; therefore, identifying the location of phreatophytes within a basin and quantifying their groundwater use are important when evaluating basin-water budgets.

The phreatophytic areas for each valley, including their distribution and volumes of water use, within the Project Basins are described in further detail in Section 5.0 of this report.

2.2.4 Hydrogeology

The term hydrogeology, as used in this document, refers to the geologic units that make up the surface and subsurface of the area and play a role in the occurrence and movement of groundwater.

2.2.4.1 Hydrogeologic Framework

The present-day hydrogeology of the area has been formed and shaped over long periods of time by many natural processes. A summary of the hydrogeology of the area, including the hydrogeologic units (HGU) present and the main structural events is included in this subsection. The detailed descriptions, including maps and cross sections, may be found in the expert report prepared by Rowley et al. (2011).

The study area is within the Great Basin subprovince of the Basin and Range physiographic province, characterized by north-trending basins and ranges that are formed by generally north-striking basin-range normal faults. The area has been subjected to several periods of deformation since

Precambrian time. The most recent episode of deformation, which produced the present topography, is the basin-range episode of normal faulting. This topography consists of a number of closed basins and partially closed basins, typical of the Great Basin region where surface-water flow is restricted to within that region. Exceptions occur only along the southeastern Great Basin boundary, where a few basins have surface water exiting to the Colorado River. These exceptions include the Virgin River, Muddy River, Las Vegas Wash, and the associated basins in which these streams occur.

The geology of the area comprising the Project Basins is dominated by a thick sequence of carbonate rocks overlying quartzites and shales above an older metamorphic core complex. The total thickness of the carbonate rocks is between 30,000 and 33,000 ft in parts of the area of interest (Tschanz and Pampeyan, 1961, 1970). Occasional shale and quartzite units are interbedded with the carbonates. Volcanic rocks are commonly found above pre-Cenozoic sediments. These volcanic rocks erupted from several caldera complexes (groups of volcanoes) and are locally intruded by cogenetic plutons. Preceding, intermixed with, and postdating the volcanic rocks are volcaniclastic sedimentary units. These Cenozoic sediments include limestone and sands and gravels. The latest depositional episode was the creation of the valley fill within the basins of the region, as those basins were formed. This valley fill is dominated by clay, silt, sands, and gravels and is largely in stream channels and playa areas.

The most recent geologic episodes produced present-day topography and geologic features controlling groundwater flow. The three events are as follows:

1. A compressive deformation that resulted in a number of thrust faults and created a highland to the northwest of the area of interest. Erosion of the highland resulted in Mississippian shales, sands, and gravels deposited within the area of interest.

2. A compressive deformation thrust western facies carbonates and related sediments over eastern facies continental and near-shore sediments.

3. Basin-range extensional deformation began with the formation of detachment faults over uplifted areas, commonly areas of plutons. These detachments continued during the volcanic episode of extension, where gaps created by extension allowed the intrusion of Tertiary magma that created the caldera complexes and Tertiary volcanics. Following the volcanic episode, the existing basin-range topography formed because of motion along steeply dipping normal faults as the crust cooled and continued to stretch.

Carbonate rocks have little primary porosity and permeability but have developed secondary permeability through fractures and faults resulting from repeated folding and faulting events. Some of the fractures have been enlarged by dissolution in the resident groundwater. Carbonate rocks form the main regional aquifer in the area of interest.

Paleozoic clastic and Tertiary volcanic rocks which are exposed in some of the surrounding mountains in the area, have also developed secondary fracturing, and may act as aquifers or confining units depending on the degree of fracturing.

The valley fill consists of younger and older sediments. The younger sediments generally consist of unconsolidated sand and gravel in some of the valleys where they generally form aquifers. In some of the valleys where silty clay and clay dominate, however, they may form aquitards. The older sediments become increasingly consolidated with depth and are generally less permeable.

2.2.4.2 Groundwater

This subsection generally describes the occurrence and movement of groundwater through the HGUs of the Project Basins and vicinity and the flow systems that encompass the Project Basins.

2.2.4.2.1 Occurrence and Movement

Groundwater occurs at different depths beneath most of the area of interest within the openings of the HGUs present. The primary regional aquifers in the study area consist of Paleozoic carbonate rocks, volcanic rocks (generally Tertiary ash-flow tuffs), and Miocene to Holocene basin-fill sediments. The primary regional aquitards within the flow systems are Precambrian to Cambrian schist, quartzite, slate, and shale, Mississippian shale, Mesozoic clastic sedimentary rocks, and Jurassic to Tertiary plutonic rocks. Depth to water vary greatly and are generally shallower on the valley floors and increase towards the mountain ranges.

Groundwater movement occurs within the connected openings of the HGUs of the area. Groundwater movement is generally classified into two general types: porous-media flow and fracture flow. Porous-media flow occurs through the primary porosity of rocks and is dominant in unconsolidated sediments and unfractured consolidated sediments. Fracture flow occurs through the faults and associated joints and fractures of consolidated rocks. The direction of groundwater flow through fractured media is influenced by the orientation of the major faults present and the rates of flow are affected by the width of large faults. An examination of some geologic maps provides examples of widths of large fault zones ranging between 0.5 to greater than 3 mi. Additional details regarding groundwater flow in faults are provided in Rowley et al. (2011).

2.2.4.2.2 Flow Systems

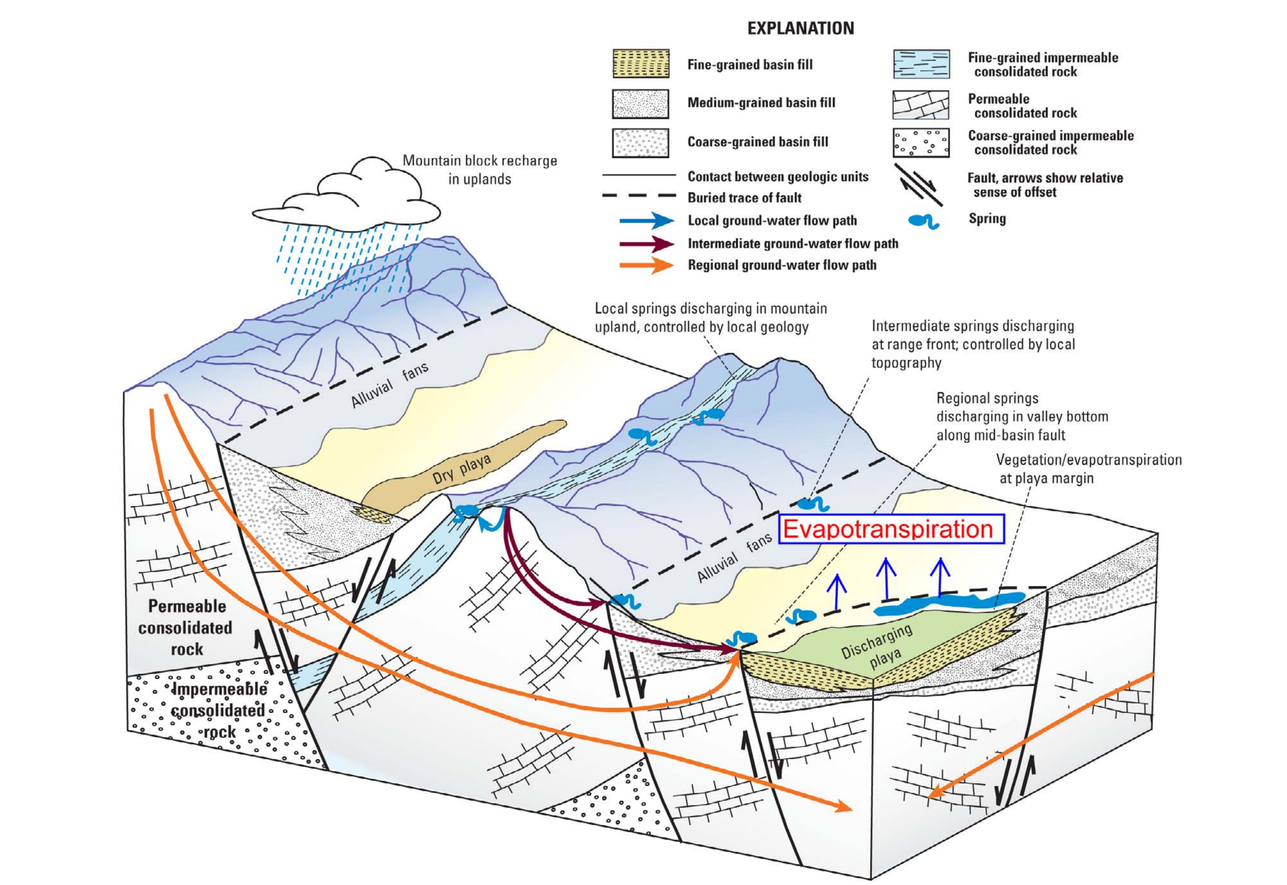
The first recognition of interbasin flow in the general area of interest was documented by Mendenhall (1909) who suggested that the source of many of the desert springs in southern Nevada is from distant mountains, rather than from precipitation in the area immediately surrounding the springs. Later, Meinzer (1917) noted that, although bedrock separating the basin blocks was considered impermeable for the most part, water from a valley near Tonopah, Nevada, leaks through a mountain range into an adjacent valley. Dry playas are found in some valleys of the northern area of interest (WRFS), where the groundwater table is well below the playa surface. Carpenter (1915) recognized that, if a basin receives recharge but has no surface discharge of groundwater, the groundwater must flow to adjacent lower basins where discharge takes place. However, many valleys receiving heavy recharge in the northern part of the area of interest discharge groundwater internally via spring discharge or ET, and externally as interbasin flow to downgradient basins.

The four Project Basins are located within two groundwater flow systems:

- Spring Valley is located in the GSLDFS. Although Spring Valley is part of the GSLDFS, it is primarily a closed basin because most groundwater discharge from this basin occurs by ET.

- Cave, Dry Lake, and Delamar valleys are located on the eastern side of the WRFS (see Appendix A). These three Project Basins do not have regional groundwater discharge areas but do receive a significant amount of recharge from precipitation. Groundwater discharge from these basins is in the form of interbasin flow.

The general understanding of groundwater flow in an environment that is typical of the flow systems comprising the Project Basins is illustrated in Figure 2-4. Precipitation on the mountains, mostly in the form of snow, constitutes the source of groundwater recharge to the basins in the flow systems. Groundwater recharge occurs in place through direct infiltration of precipitation on the mountain block or as infiltration of mountain-front runoff on the alluvial aprons and valley bottoms along perennial streams and surface-water drainages. Recharge becomes groundwater and flows through a given basin following one of three paths creating three types of aquifers.



Source: Modified from Welch et al. (2007)

Figure 2-4
Typical Groundwater Flow Patterns in the Project Basins and Neighboring Basins

- Short flow paths occur in local or perched aquifers which generally occur at higher elevations and are disconnected from the other aquifer types. Local aquifers often discharge their water from perched springs and/or localized discharge areas.

- Intermediate-length flow paths start at high elevation and carry recharge water down towards the range front where contact between the mountain block and the basin fill occurs. The discharge occurs along that line in the form of intermediate springs or seeps. Groundwater discharge from intermediate springs may also contain water from the regional aquifer.

- The longest flow paths carry water from recharge areas on the mountain block to discharge areas located on the valley floors of the same basin and/or other basins located downgradient. Groundwater in which these flow paths occur, forms the regional aquifer, in which groundwater moves from basin to basin via interbasin flow.

2.3 Land and Water-Use Status

A brief overview of the current land and water use patterns in the Projects Basins are summarized in this subsection. The details may be found in the expert reports by Holmes et al. (2011) and Stanka (2011).

The population density of the Project Basins is very low, so urban and commercial land uses are very limited. The estimated populations are less than 100 people in Spring Valley, less than 10 people in Cave Valley, and less than five people in Dry Lake Valley, and no residents in Delamar Valley. No cities or towns exist within these valleys. Other than the major highways in Spring, Dry Lake, and Delamar valleys, no paved roads exist within these valleys.

The land ownership and use are as follows:

- Spring Valley extends over an area of approximately 1,066,000 acres. The BLM owns 75 percent of this land, the U.S. Forest Service owns 20 percent, the National Park Service owns 1 percent, the SNWA owns 2 percent, and private parties own the last 2 percent.

- Cave Valley has an area of approximately 229,600 acres. The BLM owns 97 percent of the land. Approximately 5,779 acres (2.5 percent) are privately owned. The remainder includes 192 acres owned by the University of Nevada, Las Vegas (UNLV); and 43 acres owned by a mining company (Holmes et al., 2011).

- Dry Lake Valley has an area of approximately 573,400 acres of land. The BLM owns approximately 571,400 acres, or 99 percent. The remainder is owned by private parties (996 acres), mining companies (1,354 acres), and SNWA (121 acres as part of the El Tejon Ranch) (Holmes et al., 2011).

- Delamar Valley has an approximate area of 231,400 acres. The BLM owns more than 99 percent of it. One abandoned mine is located on BLM land. No private property exists in this valley (Holmes et al., 2011).

Based on an evaluation of water rights in the Project Basins reported by Stanka (2011), water use is as follows:

- Most water use in Spring Valley is from surface water. Annual groundwater use in Spring Valley was estimated at approximately 13,000 afy. The largest water use is irrigation. Other manners of use include domestic, irrigation, municipal/quasi-municipal, mining and milling, stockwater and wildlife (Stanka, 2011).

- Water sources in Cave Valley, Dry Lake and Delamar valleys include surface water and groundwater. However, all surface water in these basins is intermittent. In these valleys, manners of use include stockwater, domestic, “other,” municipal/quasi-municipal, and irrigation. Current groundwater-use was estimated at about 50 afy in Cave Valley, 800 afy in Dry Lake Valley and about 9 afy in Delamar Valley (Stanka, 2011).

3.0 PRECIPITATION

Precipitation represents the source of all water to the area of interest. Precipitation data are not only needed to estimate the distribution of natural recharge, but also to estimate groundwater ET. A summary of the approach followed to derive and evaluate precipitation distributions for the Project Basins and vicinity in support of the recharge estimates described in Section 6.0 is presented in this section, followed by descriptions of the selected method and the spatial distributions derived for the Project Basins. The details are provided in Appendix B. The precipitation distributions used to support the estimates of groundwater ET are described in Section 5.0.

3.1 Approach

The approach followed to derive a spatial distribution of precipitation for use in the estimation of recharge that is representative of long-term conditions is summarized as follows:

1. Identify methods available to generate spatial distributions of precipitation and select a method to generate precipitation distributions for use in recharge estimation.

2. Describe the selected precipitation distribution representing long-term mean conditions over the area of interest.

3. Select precipitation stations located within the area of interest for use in the evaluation of the selected precipitation distribution. Derive period-of-record means for selected stations.

4. Compare the selected precipitation distribution to the period-of-record means for selected stations to ensure the spatial precipitation distribution is representative of long-term average conditions

5. Use the period-of-record means of precipitation for Nevada U.S. Climate Divisions to support this evaluation.

The application of this approach, including the station data, is described in detail in Appendix B. Summaries of the selected method, station data, and the distributions derived for the Project Basins are provided in this section.

3.2 Selected Method

Several methods are available to generate spatial distributions of precipitation in Nevada. They include contour maps such as those of Hardman Maps (1936, 1962, 1965), distributions generated using the precipitation-altitude regression method, and the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1994, 1997, 1998, 2008).

The PRISM method, which incorporates important physical processes and uses state-of-the-art spatial methods, was selected. The PRISM method is considered to be the most accurate method because: (1) it incorporates the most updated precipitation and land-surface elevation data sets; and (2) it considers all major processes affecting the spatial distribution of precipitation. The most recent version of the normal 800-m PRISM precipitation grid (Version 3 [PRISM, 2010a]) was used to support the generation of spatial recharge distributions. The detailed analysis of all precipitation data including the precipitation-station data are presented in Appendix B.

3.3 Station Data

Precipitation-station data are needed to assess whether the 800-m PRISM precipitation grid is representative of long-term average conditions. The precipitation-station data available for the Project Basins and vicinity were compiled and reduced, their quality evaluated, and their period-of-record summary statistics generated.

The precipitation-station data were obtained from the National Climatic Data Center (NCDC) (EarthInfo, 2009), the WRCC, the NDWR, the USGS (Nevada District), the NRCS (SNOTEL sites), and the Remote Automated Weather Stations (RAWS) network. The available precipitation-station data were obtained for each station's period of record, through the end of the 2010 calendar year and were combined into a single data set and organized by data source to facilitate subsequent evaluation and analysis.

A total of one hundred and twenty-nine (129) regional precipitation stations are included in the data set. Stations with at least 20 years of "non-zero" years were selected for comparison with the 800-m PRISM grid. A "non-zero" year of reported annual precipitation is a year in which the reported annual precipitation was greater than zero. A total of 52 stations have a minimum of 20 years of available "non-zero" years of data. The selected precipitation stations include all stations qualified as "climate normal" by the NCDC. The selected stations are listed in Table B-1, along with their period-of-record summary statistics. Their locations are shown in Figure B-2 by data source.

The quality of the station precipitation data was evaluated based on data qualifiers assigned by the source agency, data documentation, methods of data collection, and reporting frequency. Station data from all data sources were found to be of good quality, except for the RAWS data which were eliminated from the comparison-data subset.

Period-of-record average annual precipitation values and associated statistics were then either identified or calculated for each "good-quality" station with 20 years of record or more. The method of obtaining a period-of-record mean depended on reporting frequency of the data (i.e., daily, monthly, semi-annually, or annually).

3.4 Evaluation of PRISM Grid

Four evaluations of the 800-m PRISM grid were performed to ensure that it represents long-term mean conditions reasonably well to satisfy the objectives of this assessment:

- In the first evaluation, the 800-m PRISM grid was compared to the normal station data to ensure the two products are consistent as they should be. This comparison revealed an excellent correlation (Figure B-4).

- In the second evaluation, the 800-m PRISM precipitation grid was compared to the station period-of-record means. In addition, the temporal variability of precipitation was evaluated using U.S. Climate Division means. The comparison between the PRISM grid and the divisional data revealed agreement between the two (Figure B-5).

- In the third evaluation, the 800-m PRISM grid was compared to the period-of-record means of a subset of stations located in areas important to recharge for Spring Valley and the WRFS. The results indicate good agreement between the PRISM grid and the station data (Figures B-6 and B-7).

- In the fourth evaluation, the mean precipitation values of the climate divisions (Figures B-8 and B-9) for the 30-year normal period (1971-2000) were compared to those calculated over the historical period of record (1895-2010). The difference was less than 10 percent.

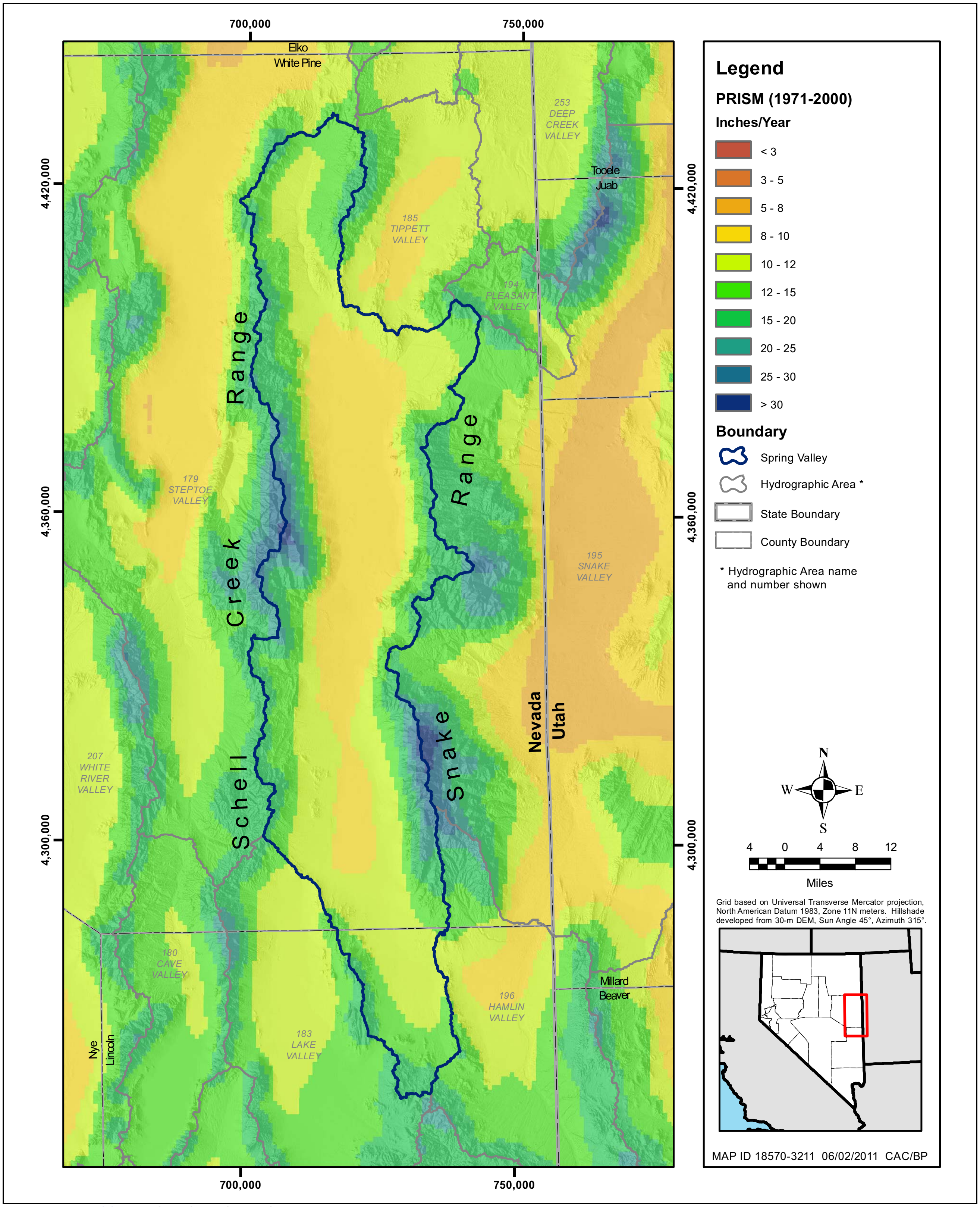
These evaluations demonstrate that the 800-m PRISM precipitation grid represents long-term mean conditions (over the historical period of record) reasonably well, within a margin of error of 10 percent. This is assuming that the period-of-record means for the stations (including the climate division means) represent their true long-term mean values. The precipitation stations' period-of-record means (Table B-1) are themselves known within an average margin error of 11.8 percent at the 95-confidence level, or about 10 percent.

3.5 Spring Valley

The precipitation distribution derived from the 800-m PRISM precipitation grid (Version 3 [PRISM, 2010a]) to support the generation of a spatial recharge distribution for Spring Valley representative of long-term conditions is presented in this section. The estimated annual precipitation volume and a comparison to reported values are presented.

The spatial distribution of annual precipitation extracted from the normal 800-m PRISM precipitation grid (Version 3) for Spring Valley and vicinity is presented in Figure 3-1. This precipitation map indicates that precipitation rates are largest on tops of the mountain ranges surrounding the valley and are lowest on the valley floor. The largest precipitation rates occur on the Snake Range along the eastern boundary of the basin, and on the Schell Creek Range along its western boundary.

The total annual precipitation on Spring Valley as calculated from the 800-m normal PRISM (Version 3) grid is 1,119,700 afy. This volume was compared to estimates previously reported by Scott et al. (1971, p. 37), Nichols (2000, p. C20), Flint and Flint (2007, p. 5), and SNWA (2009a, p. 6-8)



Note: See Table B-1 for Site Information.

Figure 3-1
PRISM 800-m Normal Precipitation Distribution for Spring Valley and Vicinity

(Table 3-1). The volume derived from the 800-m PRISM (Version 3) grid is within the range of previously-reported values (960,000 to 1,141,400 afy). As would be expected, all estimates derived using previous versions of the PRISM normal grid are similar (SNWA, 2009a; Nichols, 2000; Flint and Flint, 2007). The estimate derived by SNWA (2009a), using the 800-m PRISM (Version 2 [PRISM, 2010b]) matches the one derived for this study within less than 4,000 afy. The lowest value, 960,000 afy, reported by Scott et al. (1971), was obtained from the Reconnaissance Report of Rush and Kazmi (1965) and is based on the Hardman map (1936). Rush and Kazmi (1965, p. 20) explain the method they used to derive this estimate: "Hardman (1936) showed that in gross aspect the average annual precipitation in Nevada is related closely to altitude and that it can be estimated with a reasonable degree of accuracy by assigning precipitation rates to various altitude zones." As they state, their method only provides a "gross" estimate of precipitation. See Section 3.8 for a discussion of the limitations of the Hardman maps used in the Reconnaissance Reports.

Table 3-1
Comparison of Spring Valley
Annual Precipitation Volume to Reported Values

Method	Annual Precipitation[a] (afy)	Source
800-m PRISM (Version 3)	1,119,700	This Study
800-m PRISM (Version 2)	1,116,000	SNWA (2009a, p. 6-8)
Hardman maps	960,000	Scott et al. (1971, p. 37)
4-km PRISM	1,141,400	Nichols (2000, p. C20)
Modified 4-km PRISM	1,131,000	Flint and Flint (2007, p. 5)

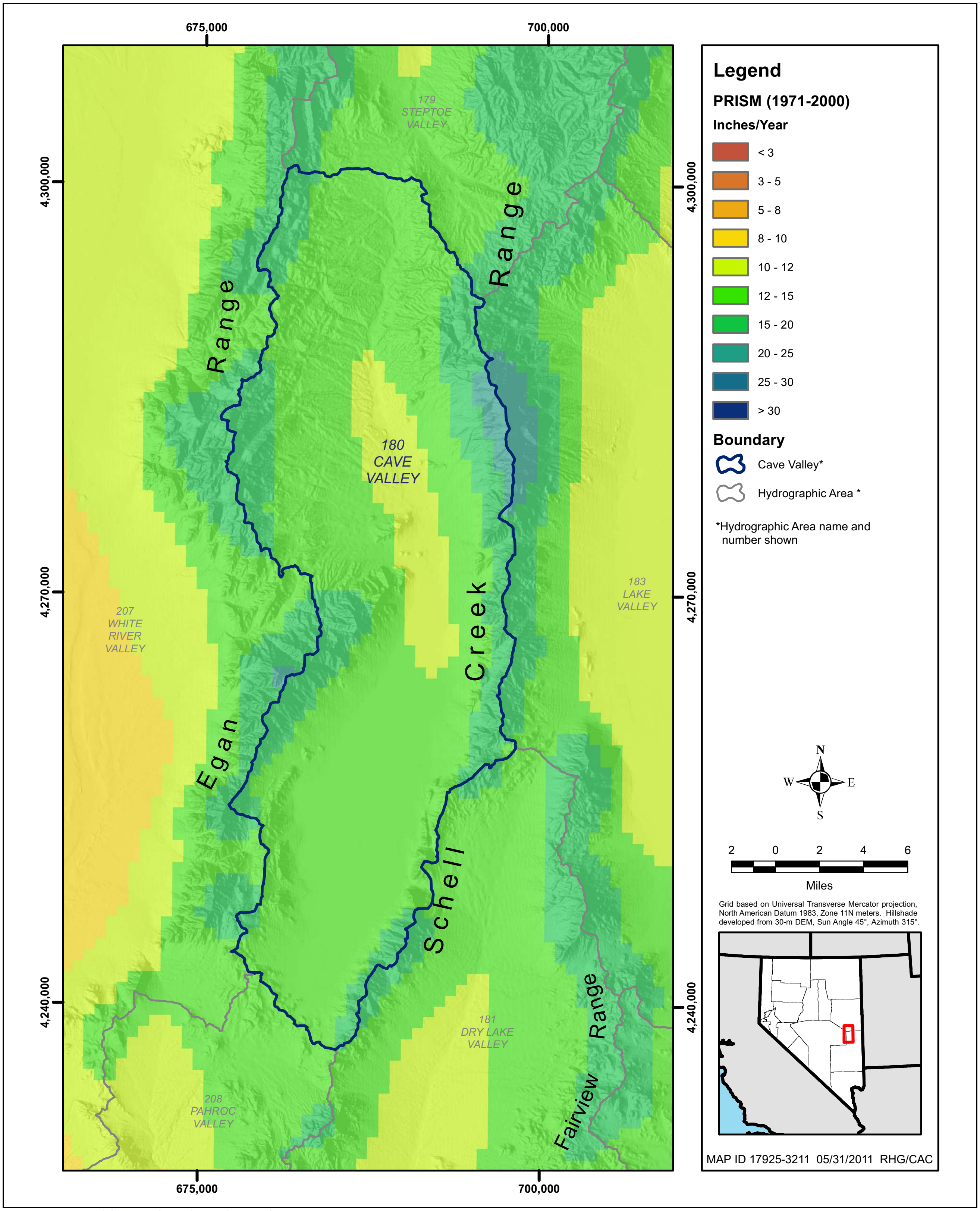
[a] All numbers rounded to nearest 100

3.6 Cave Valley

The precipitation distribution derived from the 800-m PRISM precipitation grid to support the generation of a spatial recharge distribution for Cave Valley is presented in this section. The estimated annual precipitation volume and a comparison to reported values are then presented.

The precipitation distribution extracted from the 800-m PRISM grid for Cave Valley is shown in Figure 3-2. This precipitation map indicates that precipitation rates are largest along the divides of the mountain ranges surrounding the valley and lowest on the valley floor. The largest precipitation rates occur on the northern part of the basin, the Egan Range along the western boundary of the basin, and on the Schell Creek Range along its eastern boundary. Figure 3-2 indicates that precipitation rates are generally lower than in Spring Valley.

The total annual precipitation on Cave Valley as calculated from the 800-m normal PRISM grid is 264,700 afy. This volume was compared to estimates previously reported by Scott et al. (1971, p. 36), LVVWD (2001, p. 4-15), Flint and Flint (2007, p. 5), and SNWA (2009a, p. 6-8) (Table 3-2). The volume derived from the 800-m PRISM grid (Version 3) is within the range of previously reported values (220,000 and 265,000 afy). The lowest estimate also corresponds to that reported by Scott et al. (1971) based on the Hardman map (1962). See Section 3.8 for a discussion of the limitations of the Hardman maps used in the Reconnaissance Reports.



Note: See Table B-1 for Site Information.

Figure 3-2
800-m Normal Precipitation Distribution for Cave Valley and Vicinity

Table 3-2
Comparison of Cave Valley
Annual Precipitation Volume to Reported Values

Method	Annual Precipitation (afy)	Source
800-m PRISM (Version 3)	264,700	This Study
800-m PRISM (Version 2)	265,000	SNWA (2009a, p. 6-8)
Hardman maps	220,000	Scott et al. (1971, p. 36)
Precipitation-altitude regression	258,000	LVVWD (2001, p. 4-15)
Modified 4-km PRISM	245,000	Flint and Flint (2007, p. 5)

3.7 Dry Lake and Delamar Valleys

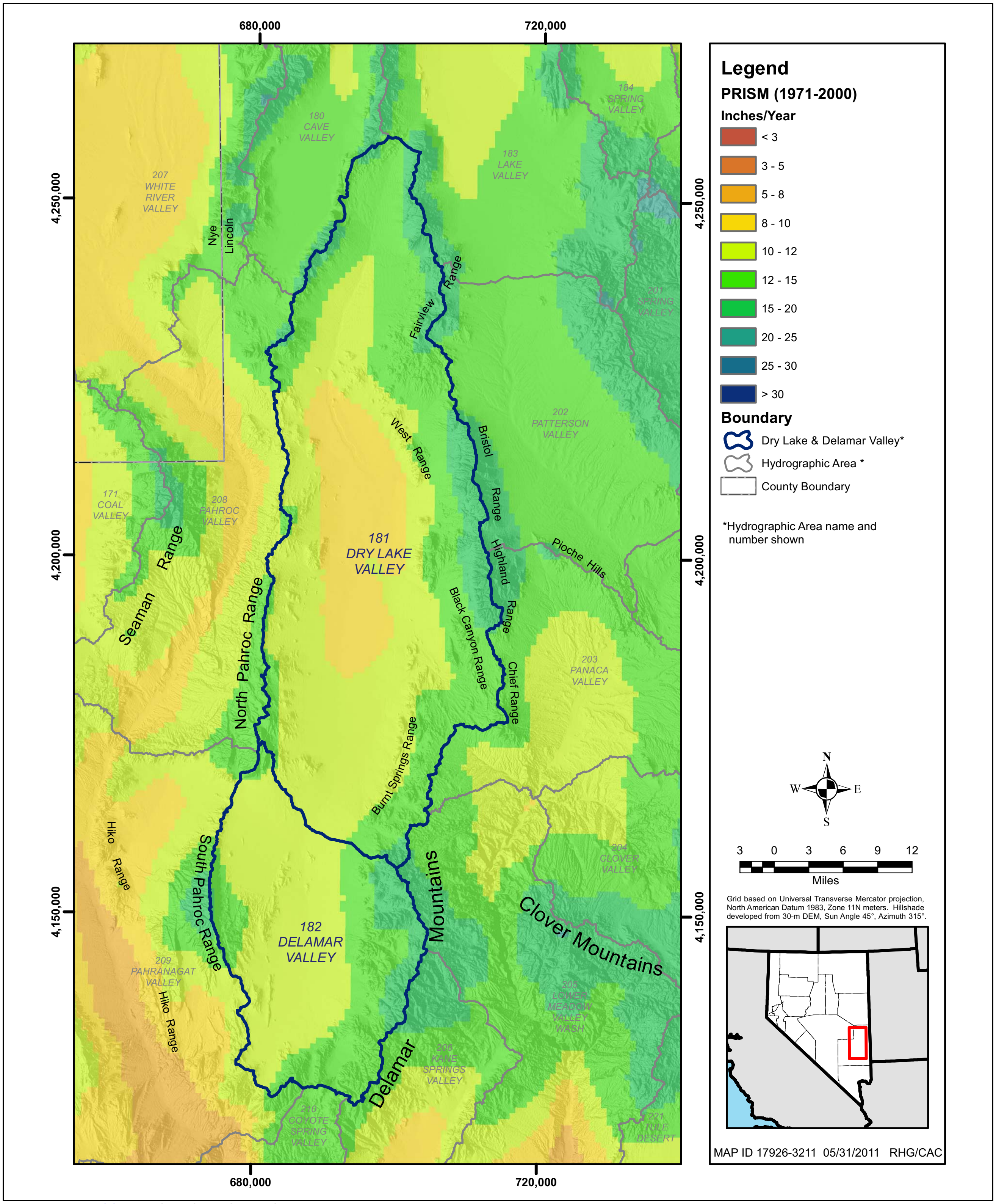
The 800-m PRISM precipitation grid values for Dry Lake and Delamar valleys are presented in this section. The estimated annual precipitation volumes and a comparison to reported values are then presented.

The precipitation distribution extracted from the 800-m PRISM grid for Dry Lake and Delamar valleys and vicinity is shown in Figure 3-3. The map shown in Figure 3-3 indicates that precipitation rates in these basins are also less than in Spring Valley. Precipitation rates are largest on the Bristol Range and Highland Range located along the eastern boundary of Dry Lake Valley. Mountain ranges located along the western boundaries of the two valleys (North and South Pahroc Ranges) receive much less precipitation.

The total annual precipitation volumes for Dry Lake and Delamar valleys as calculated from the 800-m normal PRISM grid (Version 3) are 570,600 and 236,400 afy, respectively. These volumes were compared to estimates previously reported by Scott et al. (1971, p. 36), LVVWD (2001, p. 4-15), and SNWA (2009a, p. 6-8) (Table 3-3). The volume derived from the 800-m PRISM grid is within the range of previously reported values, from 340,000 to 571,000 afy for Dry Lake Valley and from 140,000 to 236,000 afy for Delamar Valley. The lowest values are again associated with those of Scott et al. (1971) which are based on the Hardman map (1962). See Section 3.8 for a discussion of the limitations of the Hardman maps used in the Reconnaissance Reports.

3.8 Limitations of Estimates Reported by Scott et al. (1971)

Although the annual precipitation volumes estimated as part of this study fall within the ranges of reported values, the largest discrepancies are with respect to the estimates reported by Scott et al. (1971). These estimates, which have been used by the NSE, are consistently lower than all others, including the ones used in this study (Table 3-4). The values reported by Scott et al. (1971) are anomalously low, especially for Dry Lake and Delamar valleys, because of the method used to estimate precipitation based on the Hardman maps and elevation contours. This is confirmed by the large differences between the Hardman map (1962) and the PRISM precipitation map, which represents the precipitation-station data to within ten percent in the WRFS as described in Section B.5.3 of Appendix B.



Note: See Table B-1 for Site Information.

Figure 3-3
800-m Normal Precipitation Distribution
for Dry Lake and Delamar Valleys and Vicinity

Table 3-3
Comparison of Dry Lake and Delamar Valleys
Annual Precipitation Volumes to Reported Values

Method	Annual Precipitation (afy)		Source
	Dry Lake Valley	Delamar Valley	
800-m PRISM (Version 3)	569,600	236,400	This Study
800-m PRISM (Version 2)	571,000	236,000	SNWA (2009a, p. 6-8)
Hardman Maps	340,000	140,000	Scott et al. (1971, p. 36)
Precipitation-altitude regression	455,000	176,000	LVVWD (2001, p. 4-15)

Table 3-4
Comparison of Estimated Annual Precipitation
Volume in afy to Values Reported by Scott et al. (1971)

Method	800-m PRISM (Version 3) (This Study)	Hardman (1936; 1962) Maps Scott et al. (1971, p. 36, 37)	Underestimation Value (Percent)
Spring Valley	1,119,700	960,000	14
Cave Valley	264,700	220,000	17
Dry Lake Valley	570,600	340,000	40
Delamar Valley	236,400	140,000	41

3.8.1 Use of Hardman Precipitation Map

Eakin (1962; 1963) and Rush and Kazmi (1965) estimated annual precipitation and recharge volumes in Spring, Cave, Dry Lake, and Delamar valleys using precipitation zones based on the Hardman maps (1936, 1962 and 1965) and an assumed correspondence with land-surface elevation contours (p. 11, p. 16, and p. 20, respectively). As was done in previous Reconnaissance Series reports such as the Spring Valley report (Rush and Kazmi, 1965), it was assumed that selected elevation contours corresponded to the precipitation zones defined by the Hardman (1936) precipitation map. In the case of Cave, Dry Lake and Delamar valleys (Eakin, 1962; 1963), an improved topographical base map (1:250,000 scale topographic map) had been developed and was used to calculate the area for each precipitation zone. Based on this new topographical base and oral communications with Hardman, the following association between precipitation and altitude was assumed:

- Altitudes below 6,000 ft correspond to the less-than-8-in. precipitation zone.
- The 6,000 to 7,000 ft altitude interval corresponds to the 8 to 12 in. precipitation zone.
- The 7,000 to 8,000 ft interval corresponds to the 12 to 15 in. precipitation zone.
- The 8,000 to 9,000 ft interval corresponds to the 15 to 20 in. precipitation zone.
- Altitudes greater than 9,000 ft correspond to the >20 in. precipitation zone.

Revised versions of the Hardman precipitation map were published in 1962 and 1965, in the same time period the Reconnaissance Series Reports for the Project Basins were published by Eakin (1962; 1963). The Hardman (1962) map was used as part of this analysis to evaluate the relationship between precipitation and altitude assumed by Rush and Kazmi (1965) and Eakin (1962; 1963), and is described in the following discussion.

To evaluate the averaging of precipitation by altitude zone and hence the assumed association between precipitation and land surface elevation, the Hardman (1962) precipitation map was geo-referenced and digitized only for the area encompassing Spring, Cave, Dry Lake, and Delamar valleys (Figure 3-4). Using the digitized map and geographic information system (GIS) utilities, the area for each precipitation zone was extracted and multiplied by the average precipitation for the corresponding zone to calculate the volume of precipitation. These estimates are compared in Table 3-5 to the estimates reported by Rush and Kazmi (1965) and Eakin (1962; 1963) using the altitude zones based on the USGS 30-m digital elevation model (DEM).

The summary data listed in Table 3-5 highlights an important difference between the estimates reported by Eakin (1962; 1963) and the estimates derived from the Hardman (1962) precipitation map. The areas calculated for each corresponding precipitation zone are significantly different between the two estimates. This difference is due to the fact that the topographic contours do not correspond to the Hardman (1962) precipitation zones as Eakin (1962; 1963) assumed they would. In some cases, areas representing the 8 to 12 in. precipitation zone are excluded by the 6,000 ft contour, while other areas representing the 12 to 15 in. zone actually fall within the 6,000 to 7,000 ft contour interval. This is illustrated by Figure 3-4 which overlays the elevation contours derived from the USGS 30-m digital elevation model (DEM), onto the digitized version of the Hardman (1962) precipitation map. These elevation contours were compared to the 1:250,000 scale topographic maps used by Eakin (1962; 1963), and only very slight differences between the two were found; therefore, the use of these contours to evaluate the altitude-precipitation assumptions of Eakin (1962; 1963) are appropriate. The inconsistencies between the elevation contours and the Hardman (1962) map are manifested in the estimates of not only precipitation but also recharge, because recharge is primarily dependent on precipitation (see Section 6.0).

3.8.2 Comparison of Hardmap Map and PRISM Grid

A comparison of the digitized version of the Hardman map described in the previous subsection and the PRISM grid used in this study was performed. As described previously, the PRISM precipitation grid is within 10 percent of the precipitation-station data; therefore, it is an appropriate distribution to use to verify the accuracy of the Hardman map.

The comparison results are presented in Table 3-6 and important differences between the two maps, particularly at the higher elevations where the Hardman map greatly underestimates precipitation.

Although the Hardman precipitation maps, the topographic maps, and the vegetation maps available in the 1960s and 1970s were the best maps that could be produced at that time, their level of accuracy is far inferior to similar maps produced today. This is due to two main reasons, which in some cases, are interrelated. The reasons include limited data and technological tools to collect and analyze data.

First and foremost, the number of precipitation stations available in Nevada at the time was much smaller as compared to today. Second, most of the stations at that time were located on the valley floors, whereas, currently, many precipitation stations have been installed at higher altitudes where

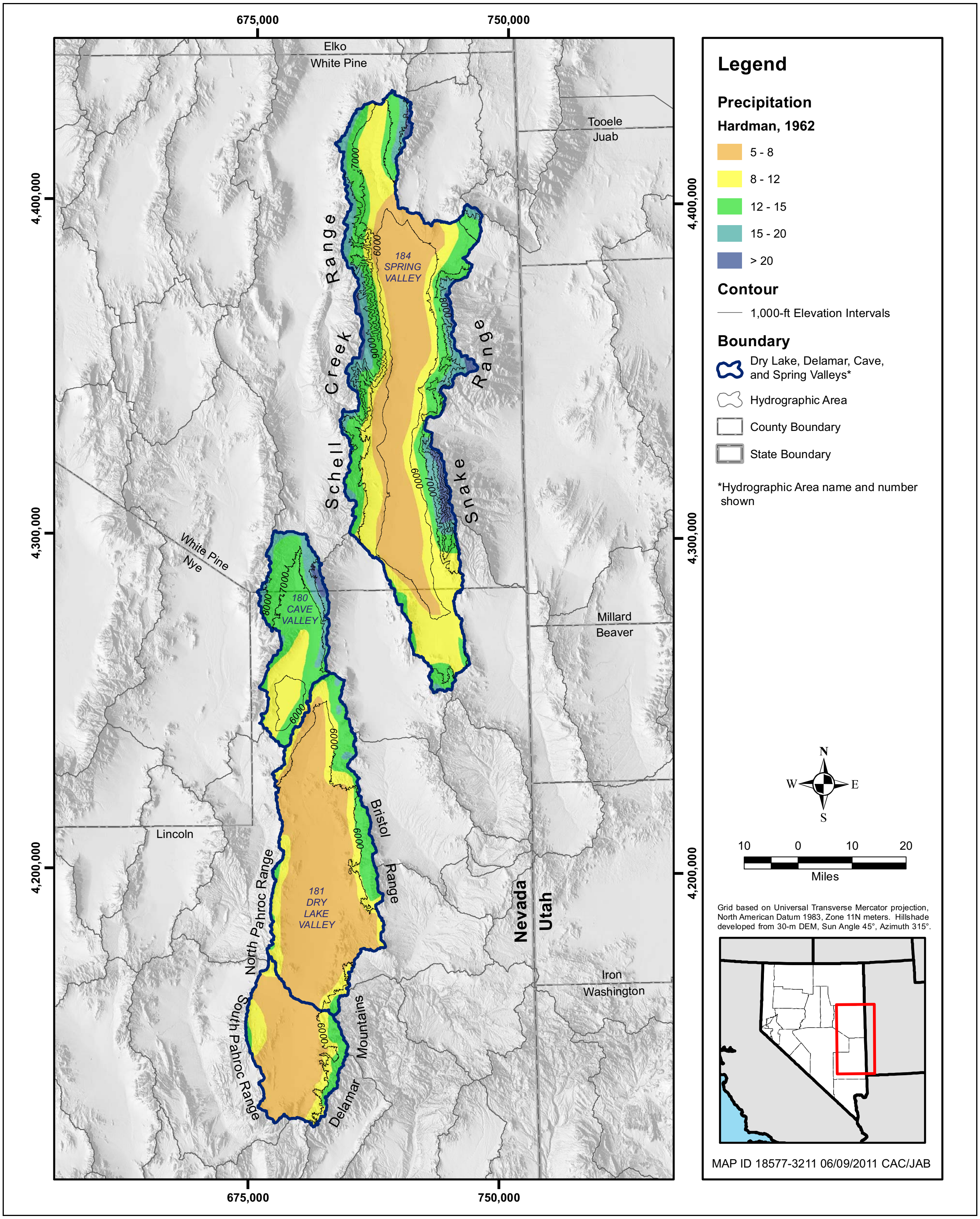


Figure 3-4
Digitized Hardman (1962) Precipitation Map for Spring, Cave, Dry Lake, and Delamar Valleys

Table 3-5
Comparison of Precipitation Estimates Derived by Scott et al. (1971) and from the Hardman Map (1962)

HA Name	Precipitation Zone (in.)	Area (acres)			Precipitation (afy)		
		Eakin(1962; 1963) or Rush and Kazmi (1965)	Digitized Hardman (1962)	Percent Difference	Eakin (1962; 1963) or Rush and Kazmi (1965)	Digitized Hardman (1962)	Percent Difference
Spring Valley	> 20	59,100	31,586	47	103,000	55,275	46
	15 to 20	107,300	114,518	-7	156,000	167,196	-7
	12 to 15	183,500	246,519	-34	206,000	276,101	-34
	8 to 12	393,000	319,887	19	326,000	265,506	19
	< 8	342,000	353,553	-3	171,000	176,777	-3
	Total	**1,084,900**	**1,066,063**	**2**	**962,000**	**940,856**	**2**
Cave Valley	> 20	3,500	4,655	-33	6,125	8,146	-33
	15 to 20	19,500	35,573	-82	28,470	51,937	-82
	12 to 15	69,000	129,990	-88	77,280	145,589	-88
	8 to 12	114,000	58,998	48	94,620	48,968	48
	< 8	29,000	429	99	12,035[a]	178[a]	99
	Total	**235,000**	**229,645**	**2**	**218,530**	**254,818**	**-17**
Dry Lake Valley	> 20	200	NA	NA	350	NA	NA
	15 to 20	3,200	3,380	-6	4,672	4,935	-6
	12 to 15	16,000	74,011	-363	17,920	82,892	-363
	8 to 12	114,000	98,686	13	94,620	81,909	13
	< 8	442,000	397,322	10	221,000[b]	198,661[b]	10
	Total	**575,400**	**573,399**	**0**	**338,562**	**368,397**	**-9**
Delamar Valley	> 20	NA	NA	NA	NA	NA	NA
	15 to 20	NA	NA	NA	NA	NA	NA
	12 to 15	4,000	22,292	-457	4,480	24,967	-457
	8 to12	35,000	45,648	-30	29,050	37,888	-30
	< 8	208,000	163,503	21	104,000[b]	81,752[b]	21
	Total	**247,000**	**231,443**	**6**	**137,530**	**144,607**	**-5**
GRAND TOTAL		**2,142,300**	**2,100,550**	**0**	**1,656,622**	**1,708,678**	**-3**

NA = Not applicable
[a]Precipitation rate used to calculate volume is half of 0.83 ft/yr.
[b]Precipitation rate used to calculate volume is 0.5 ft/yr.

Table 3-6
Comparison of Precipitation Estimates Derived from the Hardman Map and the PRISM Map

HA Name	Precipitation Zone (in.)	Area (acres)			Precipitation (afy)		
		Digitized Hardman (1962)	This Study	Percent Difference	Digitized Hardman (1962)	This Study	Percent Difference
Spring Valley	> 20	31,586	63,654	-102	55,275	125,510	-127
	15 to 20	114,518	146,642	-28	167,196	202,833	-21
	12 to 15	246,519	246,867	0	276,101	274,906	0
	8 to 12	319,887	608,900	-90	265,506	516,424	-95
	< 8	353,553	0	100	176,777	0	100
	Total	**1,066,063**	**1,066,063**	**0**	**940,856**	**1,119,674**	**-19**
Cave Valley	> 20	4,655	3,007	35	8,146	5,408	34
	15 to 20	35,573	46,209	-30	51,937	63,880	-23
	12 to 15	129,990	158,808	-22	145,589	174,719	-20
	8 to 12	58,998	21,621	63	48,968	20,655	58
	< 8	429	0	100	178[a]	0	100
	Total	**229,645**	**229,646**	**0**	**254,818**	**264,663**	**-4**
Dry Lake Valley	> 20	NA	0	NA	NA	0	NA
	15 to 20	3,380	50,338	-1,389	4,935	68,579	-1,290
	12 to 15	74,011	188,575	-155	82,892	209,148	-152
	8 to 12	98,686	334,486	-239	81,909	292,920	-258
	< 8	397,322	0	100	198,661[b]	0	100
	Total	**573,399**	**573,399**	**0**	**368,397**	**570,647**	**-55**
Delamar Valley	> 20	NA	NA	NA	NA	NA	NA
	15 to 20	NA	22,692	NA	NA	30,456	NA
	12 to 15	22,292	74,919	-236	24,967	83,434	-234
	8 to12	45,648	133,833	-193	37,888	122,494	-223
	< 8	163,503	0	100	81,752[b]	0	100
	Total	**231,443**	**231,443**	**0**	**144,607**	**236,385**	**-63**
GRAND TOTAL		**2,100,550**	**2,100,552**	**0**	**1,708,678**	**2,191,368**	**-28**

NA = Not applicable
[a]Precipitation rate used to calculate volume is half of 0.83 ft/yr.
[b]Precipitation rate used to calculate volume is 0.5 ft/yr.

the highest rates of precipitation occur. An inventory of the COOP stations (http://www.wrcc.dri.edu/inventory/sodnv.html) indicates that there is a total of 478 unique stations in Nevada today (as of August 2010), whereas only 98 stations existed before 1936. In addition to the COOP stations, PRISM also used other sources of precipitation-station data. A description of the data used is provided in the normal precipitation PRISM grid metadata, under “Data_Quality_Information” (http://prism.oregonstate.edu/docs/meta/ppt_30s_meta.htm#1):

> Point estimates of precipitation originated from some or all of the following sources: 1) National Weather Service (NWS) Cooperative (COOP) stations, 2) Natural Resources Conservation Service (NRCS) SNOTEL, 3) United States Forest Service (USFS) and Bureau of Land Management (BLM) RAWS Stations, 4) Bureau of Reclamation (AGRIMET) stations, 5) California Data Exchange Center (CDEC) stations, 6) Storage gages, 7) NRCS Snow course stations, 8) Other State and local station networks, 9) Estimated station data, 10) Canadian stations, 11) Upper air stations, and 12) NWS/Federal Aviation Administration (FAA) Automated surface observation stations (ASOS).

Second, data collection methods including the equipment used have come a long way since the 1960s and 1970s. The use of satellite imagery, analysis methods, and computer programs have revolutionized the acquisition and interpretation of spatial data like land-surface elevation and vegetation allowing for the creation of maps that are far more accurate than the ones generated 40 to 50 years ago. Computer models that not only use numerical contouring algorithms, but also incorporate the major controls on precipitation, are far superior to the hand-contouring methods used to construct the Hardman maps. Therefore, it is concluded that the PRISM precipitation distributions presented in this section are the most appropriate for use in the estimation of recharge distributions for the Project Basins and the WRFS.

4.0 Hydrologic Data

This section describes the hydrologic data compiled for the Project Basins and vicinity, including well and spring data, and also aquifer-test data. Wells and springs can provide indications of groundwater occurrence and movement, including flow directions and quantification of hydraulic gradients. Aquifer-test data provide information on the hydraulic properties of the hydrogeologic framework, and assist in the identification of aquifers and confining units and the quantification of groundwater flow rates. The information available for wells, springs, and aquifer tests in the Project Basins and vicinity was compiled and the data sets are described in Appendix C and provided in electronic form. This section provides a summary of the data compilation and evaluation activities of the data available for the Project Basins.

4.1 Wells

An inventory of the wells located in the Project Basins, for which static water-level measurements were available, was performed. Data were compiled from a variety of sources including published and unpublished reports, and from databases or spreadsheets maintained by different agencies (e.g., USGS, NDWR, and Utah Geological Survey [UGS]). SNWA has augmented these databases through its own hydrologic data collection programs and through funding of third-party data collection.

The purposes of these data-collection programs are to document baseline hydrologic conditions and characterize the natural variation of hydrologic parameters within the Project Basins and vicinity. For select wells in the Project Basins, this has included periodic and continuous water-level measurements, water-chemistry analyses, and aquifer testing. This subsection only describes wells for which static water-levels were measured. Wells which were sampled for water-chemistry analyses are specified in Thomas and Mihevc (2011), and wells for which aquifer-test data are available are specified in Section 4.3. Naturally, some wells were used for more than one purpose and may be part of the three data sets.

4.1.1 Data Compilation

Well data were compiled for Spring, Cave, Dry Lake, Delamar, and surrounding valleys from the NDWR Well Log database, USGS National Water Information System/Groundwater Site Inventory database, published and unpublished reports, and SNWA data-collection activities described in Appendix A. Specific types of well data compiled include:

- Site Information
  - Site identifier
  - Site location
  - Reference-point-elevation

- Depth-to-Water Data
  - Date and time of measurement
  - Depth-to-water measurement
  - Method of depth-to-water measurement

- Well Construction Data
  - Date of well construction
  - Total depth
  - Well depth

The compiled data were evaluated to check for duplication of data, inconsistencies in locations, and data inconsistencies. The resulting data set served as starting point for further data reduction activities.

4.1.2 Data Processing

Prior to the analysis of the compiled water-level data, the data set was processed to calculate water-level elevations from the depth-to-water data, determine an effective open interval of a well, identify outlier water-level measurements, and determine the HGU in which a given well is completed.

4.1.2.1 Water-Level Elevation Calculation

For each individual depth-to-water measurement, the water-level elevation was calculated by subtracting the depth-to-water measurement from the land-surface elevation (or reference-point-elevation) using the following equation:

$$H = LSE - DTW \qquad \text{(Eq. 4-1)}$$

where,

H = Water-level elevation or hydraulic-head value (ft amsl)
LSE = Land-surface elevation (ft amsl)
DTW = Depth-to-water (ft bgs)

The water-level elevations were used to assess potential flow directions and calculate hydraulic gradients.

4.1.2.2 Effective Open Interval

Effective open intervals for wells were assigned based on the well construction information obtained from the data sources listed in Section 4.1.1. The term “effective open interval” refers to the largest interval of a well that is open to the formation. Specific examples of open intervals include well screens, perforated casing, or an open borehole that is left uncased. The process of defining an effective open interval for a well is described as follows.

The well construction information necessary for determining an effective open interval is the top and bottom depths of any open intervals, if available, and the total depth of the well. If the top and bottom depths of an open interval are known, the effective open interval for a well was defined as those top and bottom depths. If open interval information was not available for a given well but the total depth of the well was known, it was assumed that the perforated or open interval for the well was 50 ft bgs to the total depth of the well. This assumption was made because the typical sanitary seal depth of wells based on Nevada state requirements is 50 ft bgs (Turnipseed, 1990), and the total depth provides a lower bound for the interval. If a the total depth of a well was not known and open interval information was not available, then an effective open interval was not defined for that well.

4.1.2.3 Identification of Outlier Water-Level Measurements

The identification of outlier water-level measurements consisted of constructing water-level hydrographs for each well in the compiled data set. The hydrographs were then reviewed to identify outlier measurements. The outlier measurements were then flagged in the compiled data set. For example, individual DTW measurements might be flagged as being "anomalously low," "anomalously high," or as "not representative of the overall trend." Anomalously low or high measurements were defined as the water level being lower or higher in magnitude than equivalent data at the same site. The water-level measurements that were flagged as inconsistent were then excluded from further analysis. Depth-to-water measurements collected during pumping were also excluded from further analysis.

4.1.2.4 Hydrogeologic Unit Assignments

The assignment of HGUs was necessary so that each hydraulic head value could be assigned a specific HGU to facilitate interpretations of flow directions and calculations of hydraulic gradients.

Hydrogeologic units were assigned in the following manner. First, if lithologic or stratigraphic information was available for a given site, the representative HGU was assigned based on the penetrated lithology and total depth of the well. If lithologic information was not available for a well, HGUs were assigned by plotting the well location on a hydrogeologic map and assuming that the HGU at the well's surface location represents the HGU penetrated by the well. It should be noted that a well may penetrate multiple HGUs if it is very deep and contains a large open interval. For the purposes of this report, the following HGUs from Rowley et al. (2011) were grouped together to represent the general site-type classification shown on subsequent water-level elevation maps and plates:

- Basin-fill - Quaternary and Tertiary sediments, older Tertiary sediments
- Volcanic - Quaternary and Tertiary basalt, Tertiary volcanic rocks
- Clastic - Cretaceous to Triassic siliciclastic rocks, Mississippian siliciclastic rocks
- Carbonate - Permian and Pennsylvanian carbonate rocks, Mississippian to Ordovician carbonate rocks, and Cambrian carbonate rocks

4.1.3 Well-Data Analysis

For each well included in the compiled data set, the analysis consisted of selecting a water-level measurement to represent the hydraulic head within the HGU in which the well is completed, and identifying the period of record for the available depth-to-water measurements. These are discussed in the following sections.

The selected water-level measurement was the most-recent water-level elevation that had not been excluded for any of the reasons discussed in Section 4.1.2.3. Typically, this measurement is the last measurement in the period of record for a given well, however, this is not always the case. For example, if the last measurement for a given well had been flagged as "pumping", then the next to last water-level measurement was selected. The dates for the selected water-level measurements ranged from January 1, 1912 to March 13, 2011.

The period of record of each well was derived from the compiled water-level data set, by querying the earliest and latest water-level measurements available for that well. The period of record is an important indicator into the history of a given well. Wells with long periods of record typically have more measurements and, as a result, those wells are likely to be more valuable in terms of investigating long-term trends.

Wells with single water-level measurements are included in the data set, even if the date of the measurement is not available.

The resulting data set of wells for the Project Basins and vicinity is provided in Section C.2.0 of Appendix C and summarized for the Project Basins in this section.

4.1.4 Spring Valley

Based the well data set in Appendix C, there are 219 wells within Spring Valley that are, or were, used for stock watering, irrigation, domestic use, mining and milling, and monitoring purposes. Of these, 206 are completed in the basin-fill materials, while 12 are completed in carbonate bedrock. For wells with construction information, nearly 40 percent of the wells are completed to relatively shallow depths of less than 200 ft. Seventeen wells are completed to depths greater than 900 ft. Most lithologic descriptions reported on the driller's logs contain references to interbedded sands, gravels, and clays. SNWA has constructed 20 wells and 13 piezometers in Spring Valley since 2006; these drilling activities are summarized in Appendix A and in Prieur (2011).

The spatial distribution of well locations in Spring Valley is shown on Figure 4-1. It can be seen from the figure that most wells occur in the middle portion of the valley along its main axis, where the depth to water is minimal. The selected water-level elevation for each well and additional hydrologic data for Spring Valley and vicinity are depicted on Plate 1.

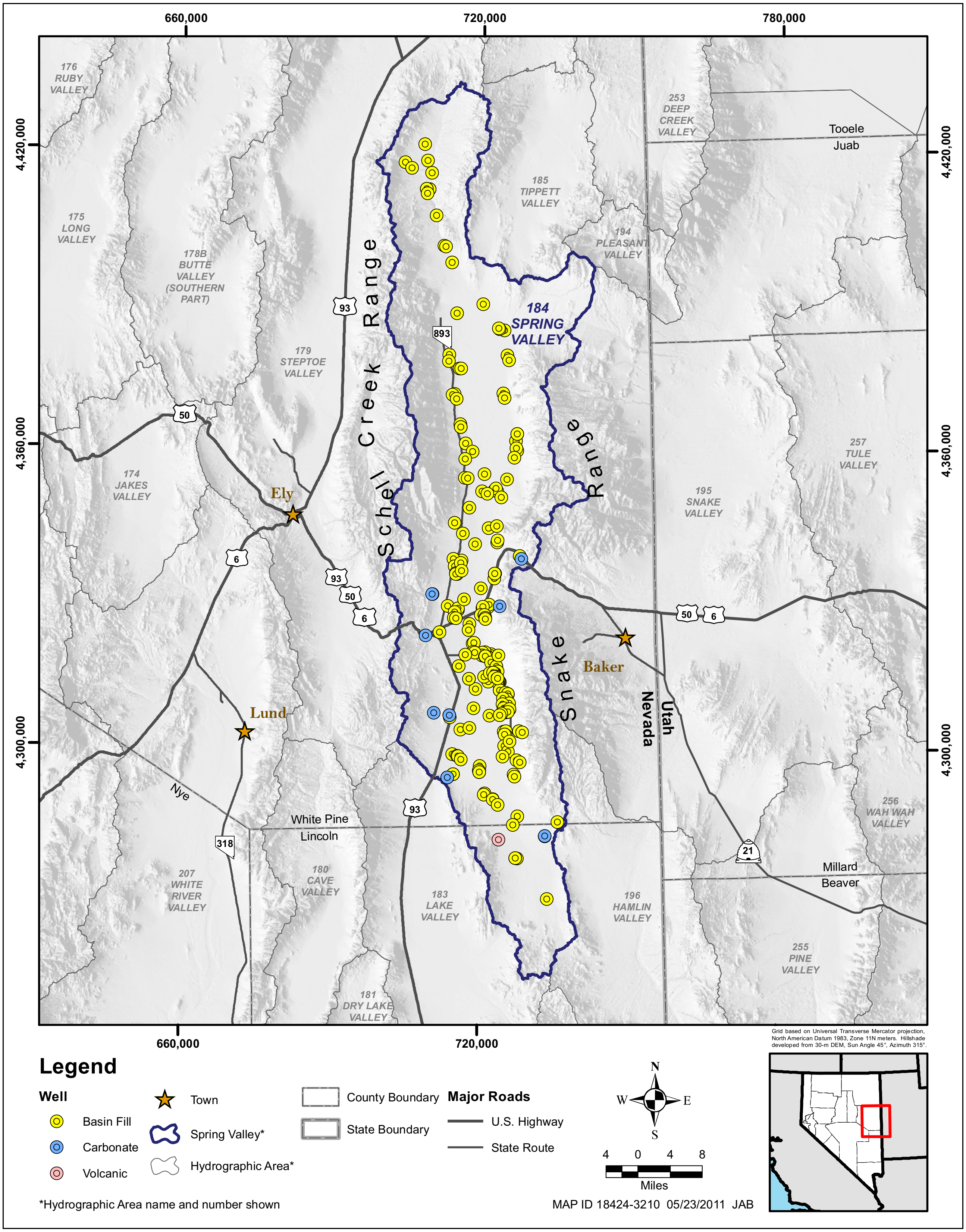


Figure 4-1
Location of Wells in Spring Valley

4.1.5 Cave Valley

Based on the compiled water-level data set, 29 wells were identified in Cave Valley through the site inventory; 22 are completed in the basin fill and 7 are completed in carbonate rocks. Most of the basin-fill wells were drilled for stock watering where depths to water are shallow, and range from 2 to 330 ft bgs. The remaining wells were drilled as part of groundwater exploration and monitoring programs involving the USAF MX-Missile Program or SNWA. NDWR driller's logs for wells in Cave Valley suggest that the basin fill is composed of mostly sand and gravel with significant cemented strata in the northern portion of the valley and interbedded sands and clay in the southern portion of the valley. Petroleum exploration drilling in Cave Valley provides additional geologic information to depths of several thousand feet. SNWA constructed three monitor wells and one test well in Cave Valley in 2005 and 2007; these drilling activities are summarized in Appendix A and in Prieur (2011).

The well locations for Cave Valley can be seen on Figure 4-2. It can be seen from the figure that almost all of the wells in Cave Valley are located along the valley bottom or near the margins of the alluvial fans. The selected water-level elevations for each of the wells, along with additional hydrologic data for Cave Valley and vicinity, are depicted on Plate 2.

4.1.6 Dry Lake and Delamar Valleys

Based on the well-data compilation, 26 wells were identified in Dry Lake and Delamar valleys; 17 are completed in the basin fill, 6 are completed in volcanic rocks, and 3 are completed in carbonate rocks. Like Cave Valley, most of the basin-fill wells were drilled for stock watering where depths to water are relatively shallow. As with Cave Valley, the remaining wells were drilled as part of groundwater exploration and monitoring programs involving the USAF MX-Missile Program or SNWA. Section C.2.0 of Appendix C describes the list of wells compiled for Dry Lake and Delamar valleys. SNWA constructed two monitor wells in Dry Lake Valley and two monitor wells in Delamar Valley in 2005; these drilling activities are summarized in Appendix A and in Prieur (2011). The spatial distribution of the wells in Dry Lake and Delamar valleys can be seen on Figure 4-3. The selected water-level elevation for each site in Dry Lake and Delamar valleys is depicted on Plate 2.

4.2 Springs

An inventory of the springs located within the Project Basins and vicinity was performed by compiling data from various published reports, including USGS topographic maps and publicly-available databases administered by the USGS and DRI. SNWA has augmented these databases through its own hydrologic data collection programs and through funding of third-party data collection.

The purposes of these data-collection programs are to document baseline hydrologic conditions and characterize the natural variation of the spring discharge. For representative springs in the Project Basins, these programs included periodic and continuous discharge measurements, water-chemistry analyses, and descriptions of the physical parameters of the springs. The collected data were evaluated to relate the magnitude, variability and sources of spring discharge, and assess their

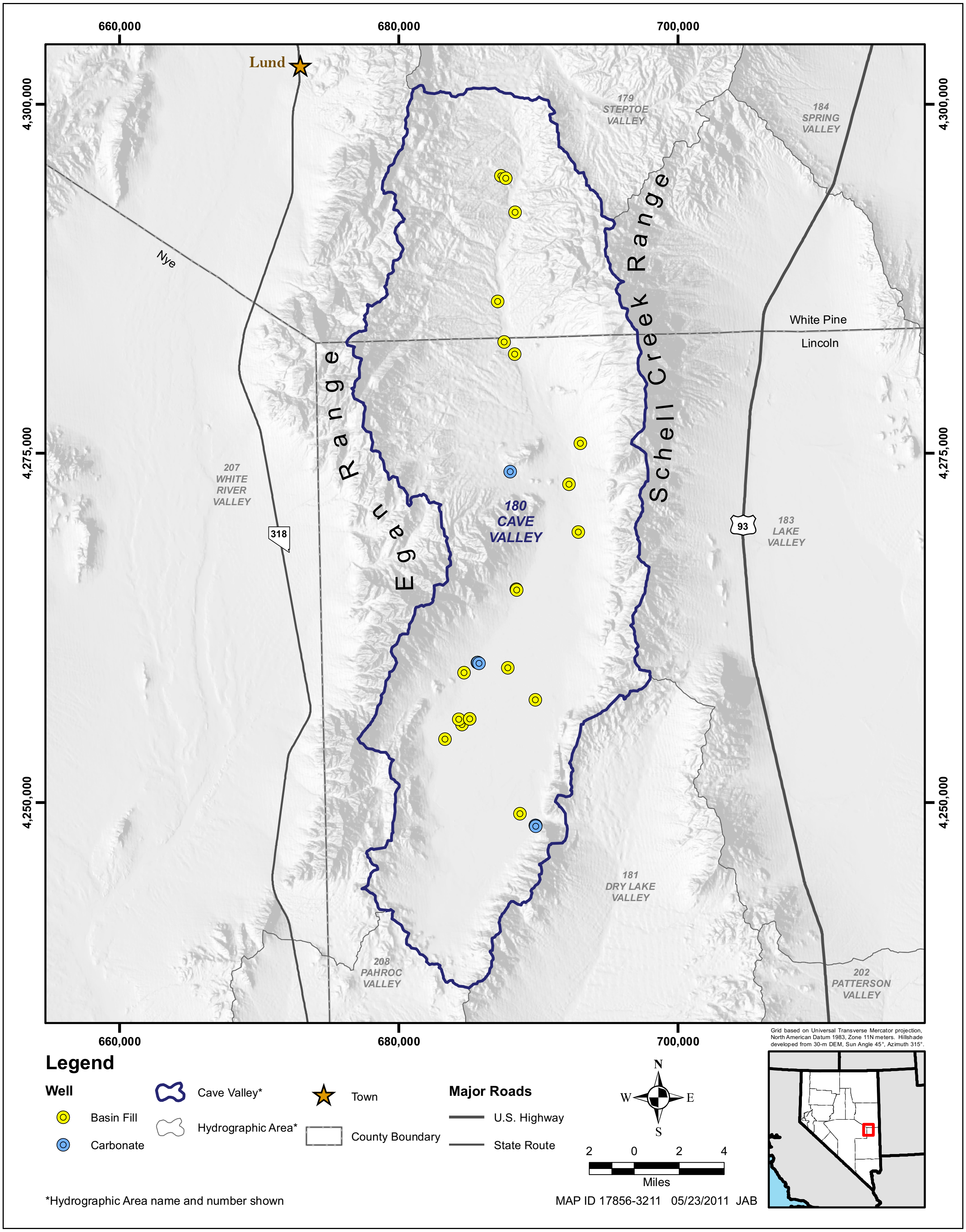


Figure 4-2
Location of Wells in Cave Valley

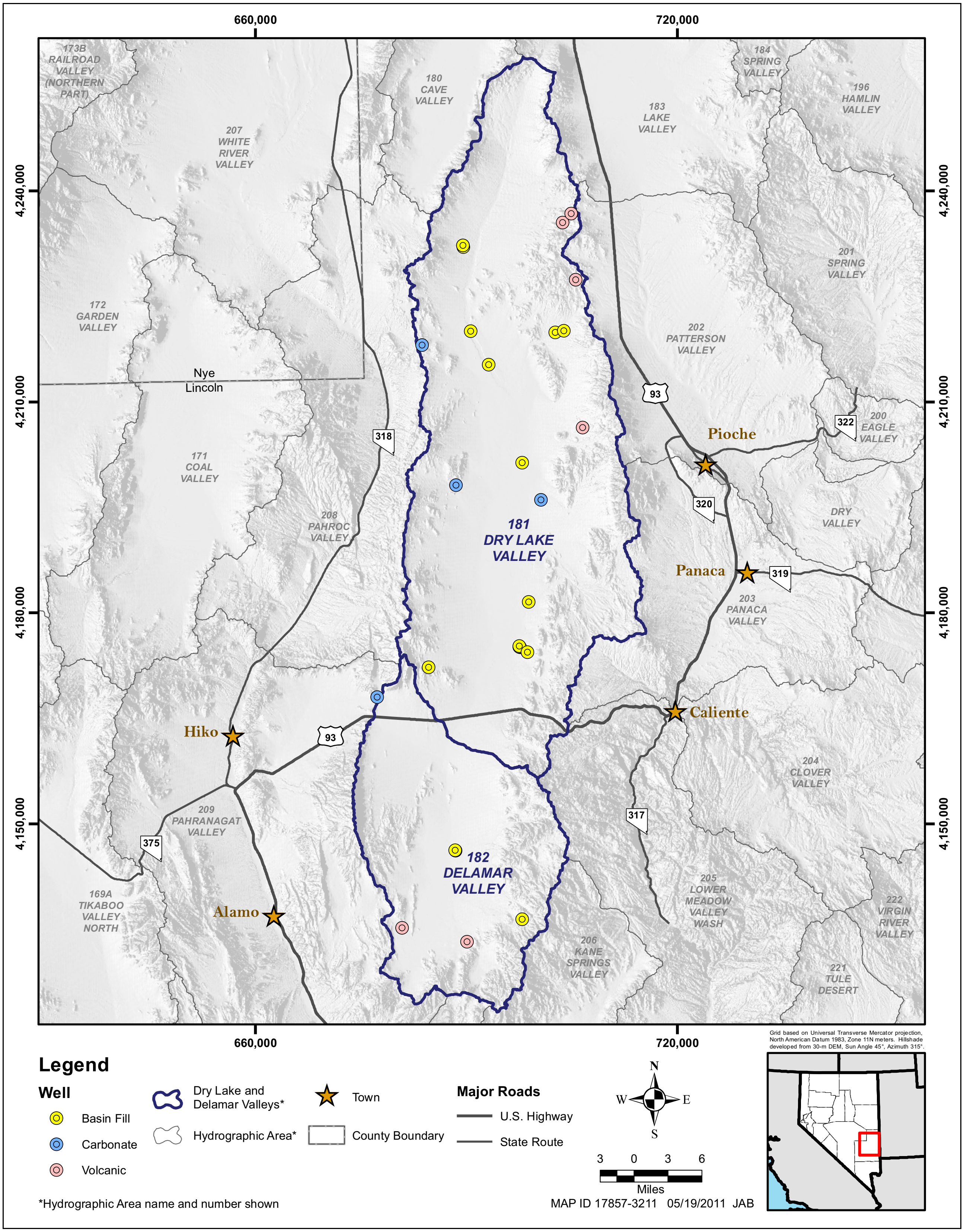


Figure 4-3
Location of Wells in Dry Lake and Delamar Valleys

hydraulic connectivity to regional, intermediate, and/or local flow regimes. In addition, the collected data were used to derive mean annual discharge measurements for springs in the Project Basins and for selected other springs in the adjacent basins. The spring inventory including mean annual discharge measurements for selected springs are provided in Appendix C, and are summarized for the Project Basins in this section.

4.2.1 Spring Classification

The compiled spring data were grouped based on the groundwater system from which they originate (Mifflin, 1968). For this assessment, groundwater systems were defined as having local, intermediate, and regional flow regimes, and the springs were classified as corresponding to one of these systems based on the following criteria:

- Location within the basin
- Water temperature
- Flow rate
- Flow variability
- Geologic and topographic settings
- Geochemical and isotopic data relative to recharge source areas

4.2.1.1 Regional Springs

A regional spring is defined as a spring that discharges from the carbonate-aquifer system. Regional springs have the following characteristics:

- Location on the valley floor
- Water temperatures greater than 68°F (20°C)
- Significant flow rates (greater than 100 gpm [Thomas et al., 1986])
- Perennial flow not reflective of seasonal variation in precipitation
- Evidence of hydraulic connection with the regional carbonate-rock aquifer
- Evidence of long travel times based on geochemical and isotopic data

4.2.1.2 Intermediate Springs

Intermediate springs are also important at the regional scale because they represent a part of the flow system that connects the recharge areas to the regional flow system. Characteristics of intermediate springs are as follows:

- Location on the valley floor or valley margins
- Water temperatures between 55°F and 80°F (13°C and 27°C) (Mifflin, 1968)
- Variable flow rates
- Perennial flow that correlates with seasonal variation in precipitation
- Little or no hydraulic connection with the regional carbonate-rock aquifer
- Evidence of short travel times (basin-scale) based on geochemical and isotopic data

4.2.1.3 Local Springs

Local springs are not important at the regional scale because they represent perched parts of the flow system, which are not hydraulically connected to the main flow system (regional and intermediate). Characteristics of local springs are as follows:

- Location typically on mountain block above the bedrock-basin-fill interface but may reside on valley margins or floors.
- Temperature less than 55°F (13°C) (Mifflin, 1968).
- Small and highly variable flow rates. Spring may be dry at times.

4.2.2 Spring Discharge

Spring discharge records were compiled for springs in the Project Basins and for the following hydrographic areas: White River Valley, Pahranagat Valley, Snake Valley, and the Muddy River Springs Area (MRSA). From the compiled spring discharge data, mean annual discharge volumes were derived. The mean annual discharge volumes for the selected springs are described in Section C.3.0 of Appendix C. In addition, the period of record for the discharge measurements, number of measurements, maximum and minimum discharges, and standard deviations of the average discharges were also derived.

4.2.3 Spring Valley

The springs in Spring Valley derive their source from groundwater recharge in the Schell Creek and Snake ranges and the alluvial fans below the mountain-block/alluvial interface. Most occur within areas where the groundwater table is near or at the ground surface and groundwater is consumed by evapotranspiration. Within these areas, many of the springs consist of depressions in the ground surface that intersect the groundwater table, while others are point sources discharging from one or more orifices. For these springs, all discharge emanates from the basin-fill materials.

All the springs for which temporal data are available exhibit seasonal variations in their flow rates, and some cease flowing during the course of the year. Springs closer to the recharge source exhibit more pronounced responses to seasonal weather patterns. These include springs within the mountain blocks and those located on alluvial fans that encompass the valley bottom. Figure 4-4 depicts the location of SNWA monitored springs in Spring Valley as summarized in Appendix A and Prieur (2011). Based on the criteria outlined in Section 4.2.1, all springs in Spring Valley are classified as either intermediate or local springs. The mean annual discharges of the springs in Spring Valley range from 0 to 1.3 cfs. Only two springs (i.e., South Millick Spring and Minerva Spring) have mean annual discharges exceeding 1 cfs. The discharge of the springs is ultimately consumed within the basin by evaporation and/or by ET from natural vegetation and irrigated crops. Details regarding the spring inventory are provided in Section C.3.0 of Appendix C.

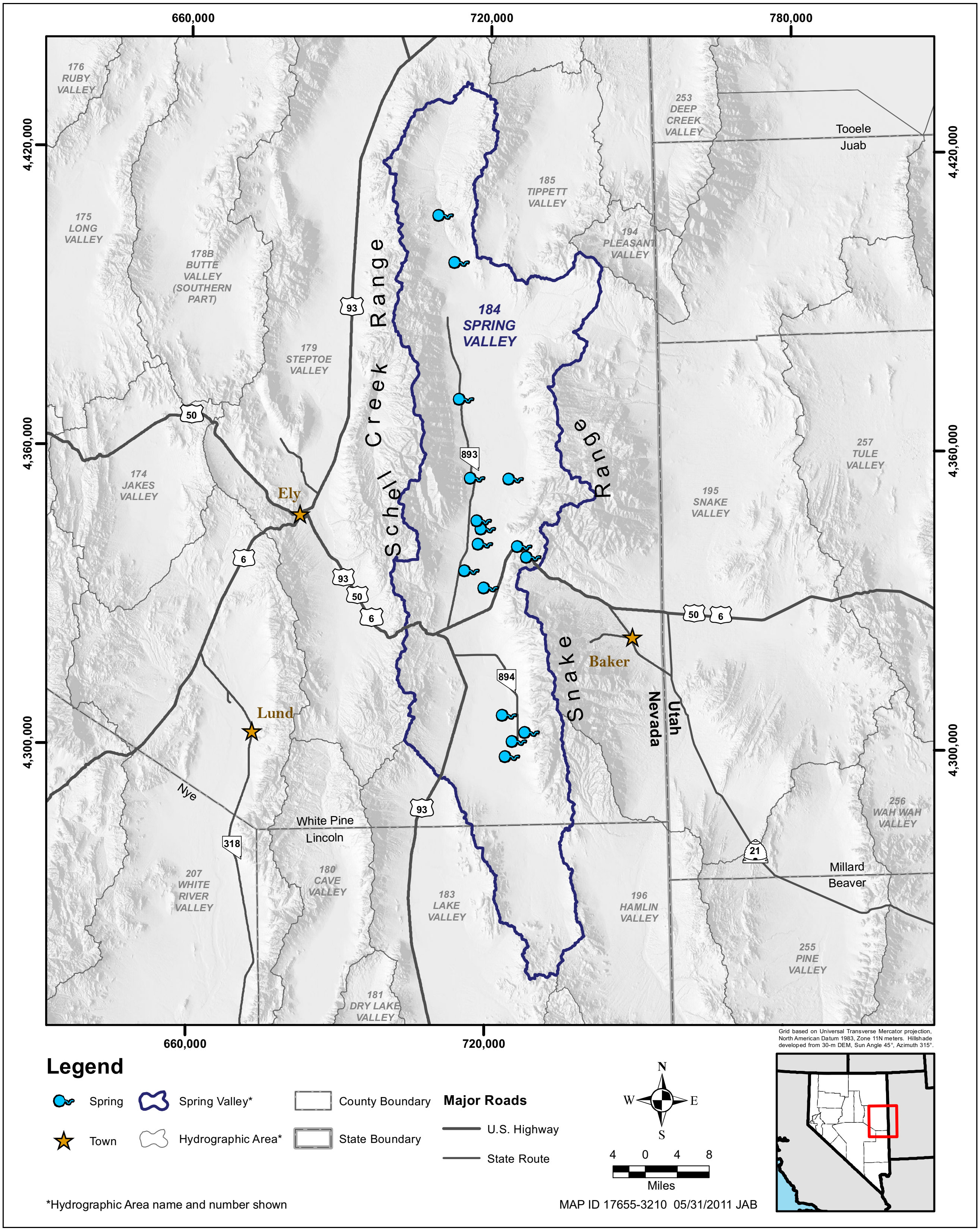


Figure 4-4
Locations of Representative Springs Monitored by SNWA in Spring Valley

4.2.4 Cave Valley

Springs in Cave Valley derive their source from groundwater recharge in the Egan and Schell Creek ranges, and occur mostly in the northern half of the basin and principally within the mountain blocks. Figure 4-5 depicts the location of SNWA monitored springs in Cave Valley as summarized in Appendix A and Prieur (2011). All springs in Cave Valley were classified as local springs based on the criteria outlined in Section 4.2.1.

The most prominent spring is Cave Spring located on the east side of the valley. Discharge from this spring emanates from limestone rocks underlain by older and less permeable shales. Discharge from Cave Spring is highly variable, with the highest flows occurring during the spring snowmelt and lowest flows in the late summer and fall. Measured flows have ranged from 3.9 cfs in late spring to no flow during the late summer and fall months.

The remaining springs all occur within, or in very close proximity to, the mountain blocks, and their discharge is primarily used for stock watering. Section C.3.0 of Appendix C provides a summary of the springs for which data have been collected, including their physical attributes and those monitored by SNWA.

4.2.5 Dry Lake and Delamar Valleys

All springs in Dry Lake and Delamar valleys occur within, or in very close proximity to, the mountain blocks of the surrounding ranges. Most springs in the spring inventory occur in the northern half of Dry Lake Valley. When flowing, these springs have small magnitude flows that are typically used for stockwatering. Meloy Spring has the largest mean annual discharge of 0.13 cfs. All springs were classified as local springs based on the criteria outlined in Section 4.2.1. Figure 4-6 depicts the location of SNWA monitored springs in Dry Lake and Delamar valleys as summarized in Appendix A and Prieur (2011). Section C.3.0 of Appendix C provides a summary of the springs for which data have been collected, including their physical attributes and those monitored by SNWA.

4.3 Aquifer-Test Data

The available information associated with aquifer tests conducted within the Project Basins was compiled, evaluated, and is presented in this section. The data set is included with other aquifer-property data for wells located in adjacent basins, which are described in Section C.4.0 of Appendix C and provided in electronic form.

4.3.1 Data Sources

Major data sources of aquifer-property data for the Project Basins are the MX Missile-Siting Investigation–Water Resources Program Study, the White Pine Power Project, and the SNWA. Others include NDWR's driller's logs and modeling projects such as the Death Valley Model and the Regional Nevada Test Site Model.

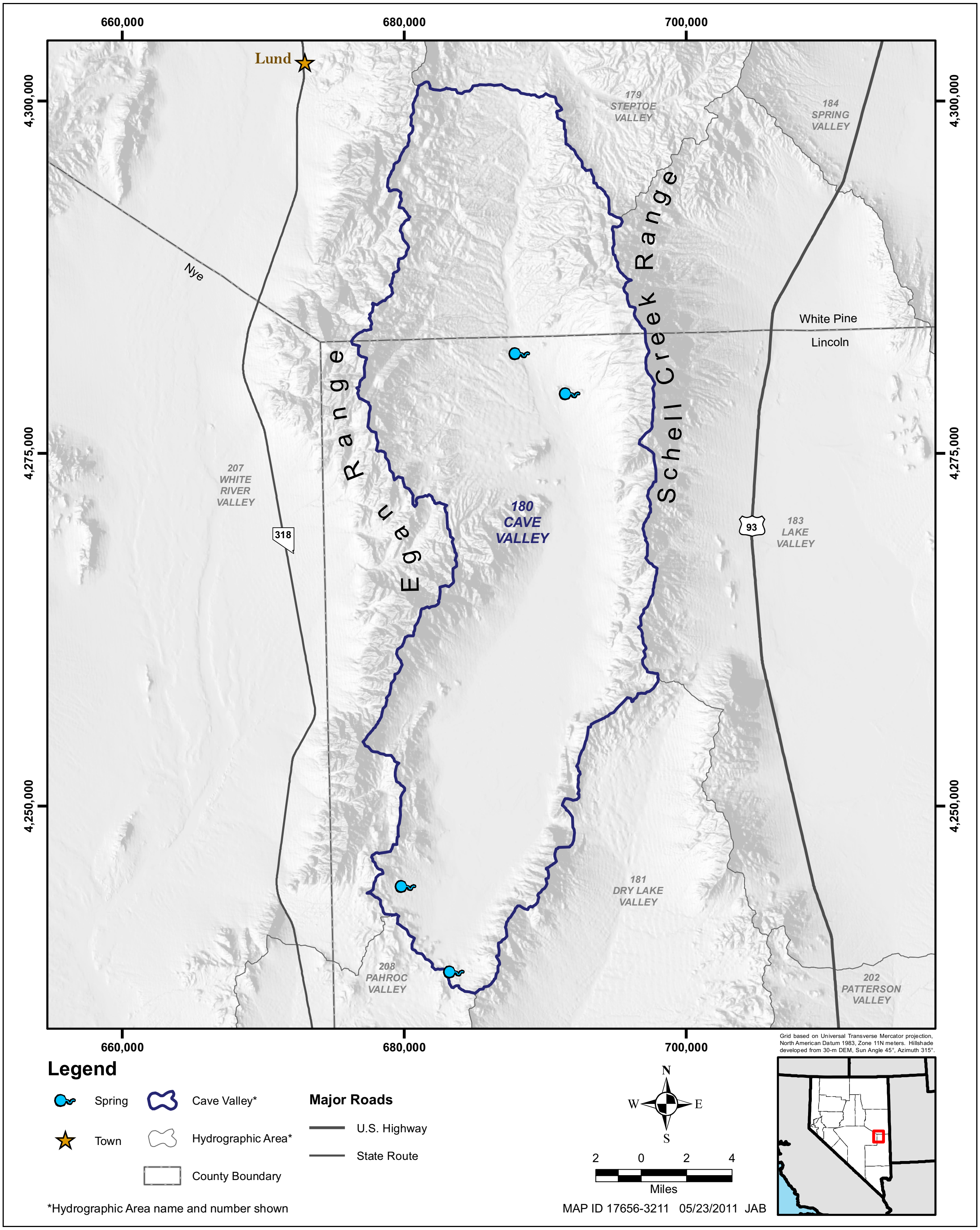


Figure 4-5
Locations of Representative Springs Monitored by SNWA in Cave Valley

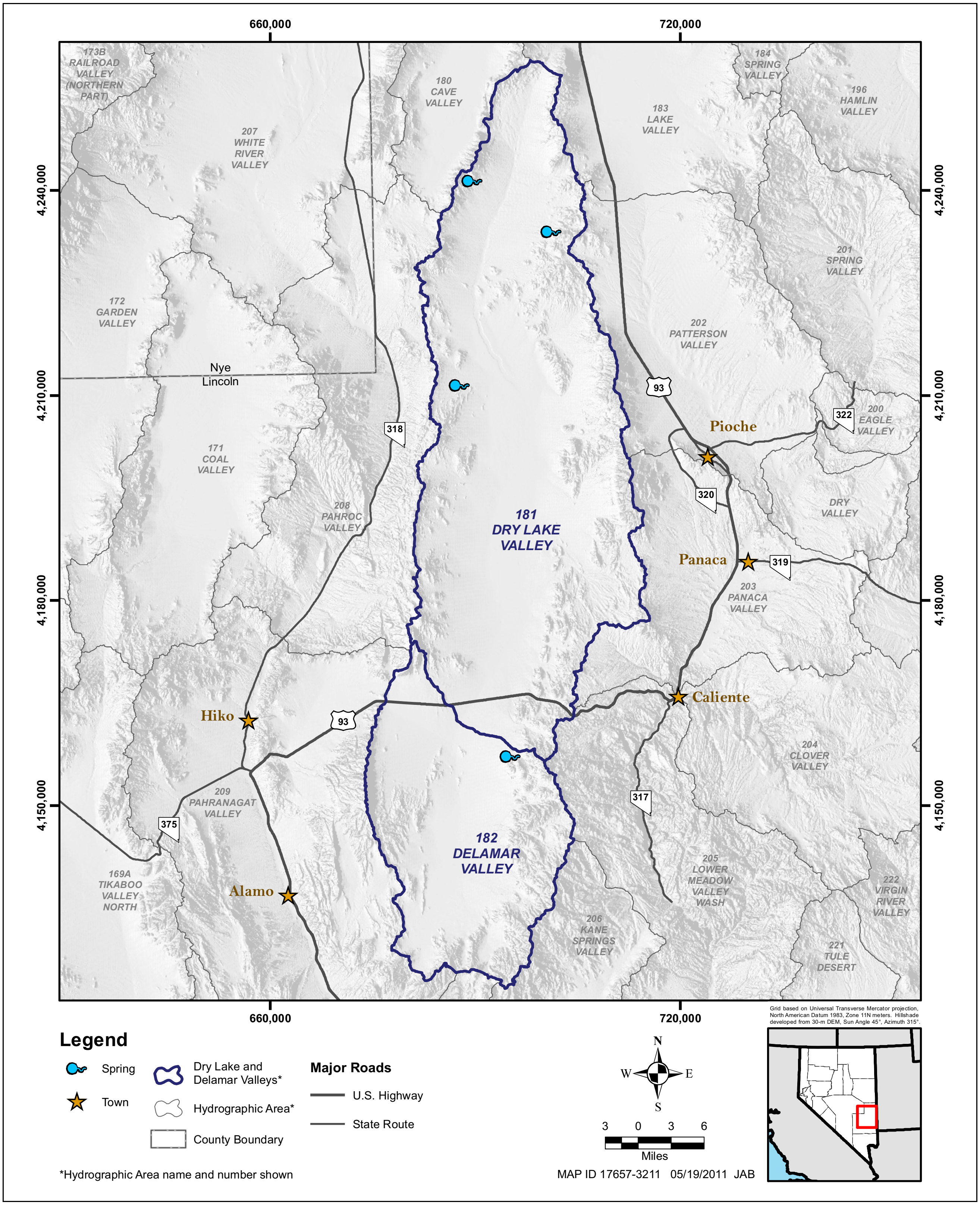


Figure 4-6
Locations of Representative Springs Monitored by SNWA in Dry Lake and Delamar Valleys

The data collected from tests performed under the USAF MX Missile-Siting Investigation–Water Resources Program are described in reports by Ertec Western, Inc. (1981 a through c) which were summarized by Bunch and Harrill (1984). The area of investigation for this project extends over Nevada and Utah and includes all four Project Basins. A number of wells were constructed and tested in 1980 and 1981. Most tests were single-well constant-rate tests that were conducted in the basin-fill aquifer with a few tests conducted in the carbonate aquifer.

The data collected from tests associated with the White Pine Power Project are documented in Leeds, Hill and Jewett, Inc., (1981b, 1983). Aquifer-property data were derived from step-drawdown and constant-rate pumping tests. Several wells in White Pine County, including Spring Valley, were completed in the valley-fill and carbonate aquifers and tested.

In support of its water-rights applications, SNWA has installed and tested several monitor and test wells within the Project Basins and neighboring basins (Appendix A). Several aquifer tests have been performed as part of the hydrologic data collection effort in Cave and Spring valleys. The data analyses of the tests are documented in Prieur et al. (2009, 2010a, b, c, 2011a, b, and c).

The NDWR maintains an online database of driller's logs for many wells in Nevada (NDWR, 2011), which is a source of extensive well information. In addition to location and well-construction information, driller's logs contain lithology and occasionally specific-capacity data, which may be used to derive estimates of transmissivity for limited portions of the aquifer located around the well.

The aquifer-property data associated with the Death Valley Regional Model and the NTS Regional Model were included in reports by Belcher et al. (2001) and IT Corporation (1996), respectively. Both reports (Belcher et al., 2001; IT Corporation, 1996) contained comprehensive aquifer-property data sets compiled from existing databases and the literature to support the regional models documented by Belcher (2004) and IT Corporation (1996), respectively. These data sets contain much of the aquifer-property data available at the time of the studies, including the data from the MX investigation (Ertec, 1981a and b) and the WPPP investigation.

The aquifer-property data set included in this document is limited to information obtained from original sources to avoid duplication. Aquifer-test results reported by Bunch and Harrill (1984), Belcher et al. (2001) and IT Corporation (1996) are not included in the data set, specific-capacity data (NDWR, 2011) are not included either.

4.3.2 Data Types

Generally, the main types of hydraulic properties that may be derived from well and aquifer tests are as follows:

- Hydraulic conductivity or transmissivity
- Storage coefficient/specific storage or specific yield

Other properties such as anisotropy ratios and hydraulic conductivity with depth require tests designed for this purpose.

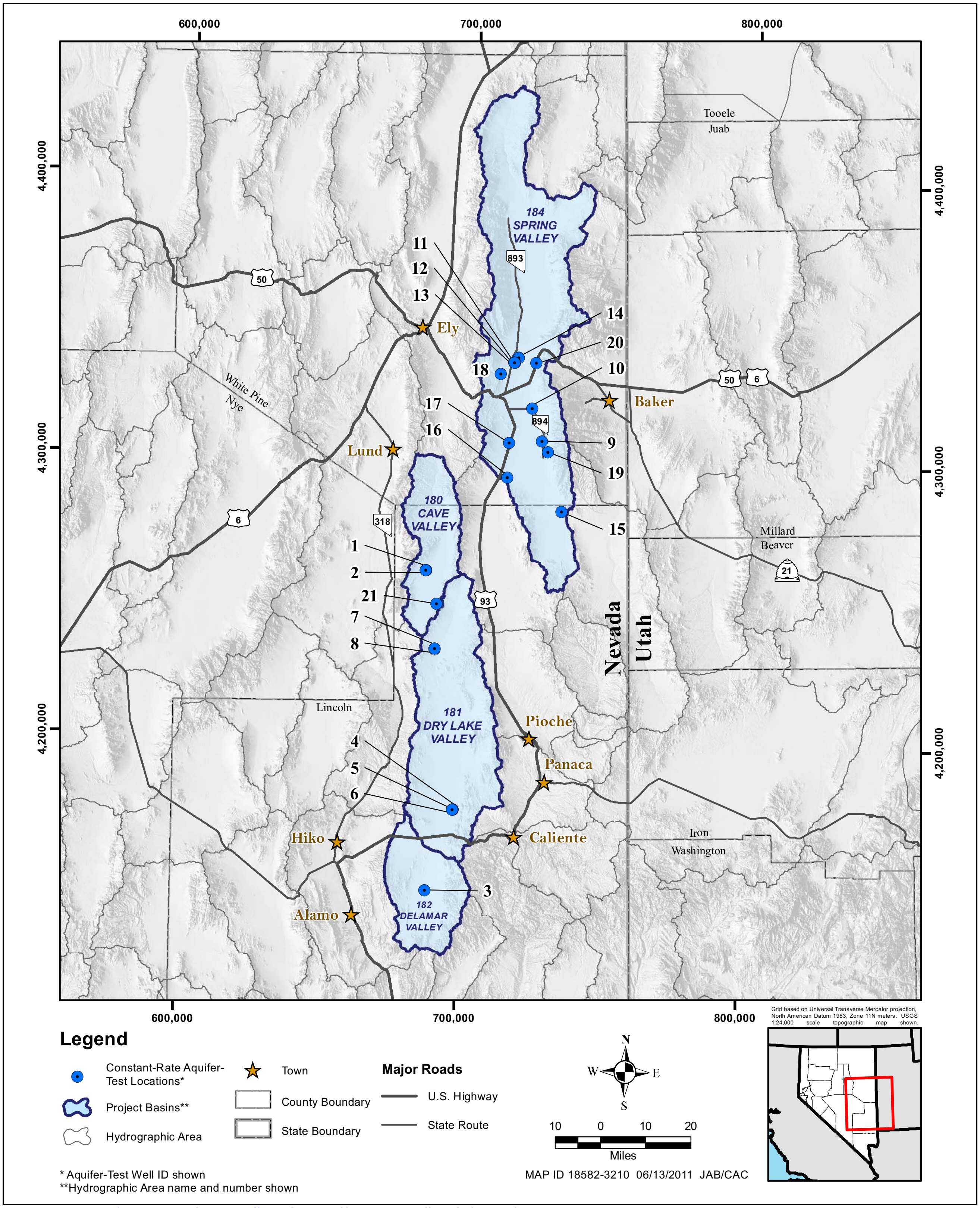
Specific capacity, which may be obtained with short pumping tests in single wells, may be used to derive approximate estimates of transmissivity for the area located in the vicinity of the well. These values of transmissivity are, therefore, approximate estimates of this property for small volumes of the media surrounding the well.

Data presented for the Project Basins in this report only include hydraulic conductivity and/or transmissivity and storage properties obtained from constant-rate pumping tests. Supporting data consisting of site information, including well names and coordinates, and the specifics of the test, including the HGU tested and test date were also obtained. A detailed description of the data set are provided in Section C.4.0 of Appendix C.

4.3.3 Project Basin Data Description

Based on the compilation of aquifer-test data described in Appendix C., 42 records associated with 21 wells or tests were identified for the Project Basins (Figure 4-7). In some cases, aquifer-test analysis results were reported for each well included in the test. In others cases, results were reported for the test as a whole and assigned to the pumping well only. Observation wells associated with such tests are not shown on the map (Figure 4-7).

The number of records is larger than the number of wells, because test data for some wells were analyzed for the pumping and recovery phases of the test, and some tests were analyzed using more than one method. The well locations, shown in Figure 4-7, are as follows: (1) two MX wells and one SNWA well located in Cave Valley; (2) five MX wells located in Dry Lake Valley; (3) one MX well located in Delamar Valley; and (4) twelve wells located in Spring Valley, of which six are associated with the White Pine County Project (Leeds, Hills and Jewett, Inc., 1981a and b) and six with the SNWA investigation (Prieur et al., 2009, 2010a, b and c, 2011b and c). Except for four tests conducted in the carbonate aquifer, and one in both the basin fill and carbonate aquifer, all other tests were conducted in the basin fill. The carbonate-aquifer tests were conducted by SNWA in Spring Valley (Prieur et al. 2009, 2010a, b, and 2011b). The basin-fill/carbonate-aquifer test was conducted by SNWA in Cave Valley (Prieur et al. 2011a).



Note: See Section C.4.2 of Appendix C for Aquifer-Test Well ID information.

Figure 4-7
Project Basin Aquifer Test Locations

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5.0 GROUNDWATER ET ESTIMATES

Groundwater discharge from the four Project Basins occurs as interbasin groundwater flow to adjacent downgradient basins and/or by groundwater ET. The only significant occurrences of groundwater ET is within Spring Valley and, to a much lesser amount, Cave Valley. No groundwater ET occurs in Dry Lake and Delamar valleys. The estimates of groundwater ET derived for Spring and Cave valleys are summarized in this section.

5.1 Objective

The objective of the analysis described in this section is to derive predevelopment estimates of the mean-annual groundwater-ET distributions and volumes for Spring and Cave valleys. Predevelopment conditions are defined as the current conditions with agricultural croplands removed or replaced by interpreted distributions of natural vegetation.

5.2 General Approach

The general approach followed to estimate groundwater ET is based on the simplifying assumption that for a given time period and groundwater discharge area, the volume of groundwater ET is equal to the volume of total ET reduced by the volume of precipitation on the area, expressed by:

$$ET_{gw} = ET_T - P \qquad \text{(Eq. 5-1)}$$

where,

ET_{gw} = Volume of groundwater ET
ET_T = Volume of total ET
P = Volume of precipitation

The implicit simplifying assumptions are (1) the vegetation within a potential groundwater discharge area uses both groundwater and soil moisture (from precipitation) as sources, (2) on average, 100 percent of the precipitation is effectively transpired by vegetation or evaporates and, (3) ET of perched groundwater resulting from direct in-place precipitation is not considered groundwater ET.

This general approach was applied to Spring and Cave valleys, albeit the specific analysis steps were different. The details regarding the specific analysis steps, including the methods and assumptions, are presented in the following sections.

5.3 Spring Valley

Spring Valley is principally a closed groundwater basin; consequently, the primary mechanism of groundwater discharge is by ET. Groundwater ET occurs on the valley floor, which is characteristically flat, and where depth to groundwater is minimal, springs occur, and abundant phreatophytic vegetation is present. This section describes the extent of this area and provides an estimate of the mean annual groundwater ET.

5.3.1 Approach

The general approach described in Section 5.2 was followed to estimate groundwater ET volumes in Spring Valley. The extent of groundwater-ET includes two areas: a main discharge area located along the central axis of the valley, and a smaller discharge area located in the northern part of the basin (defined in Section 5.3.2). Details regarding the specific approaches followed to estimate the distribution of groundwater ET from these two areas are described in this section.

The potential groundwater-ET extent boundary was delineated using information from previous mapping efforts, satellite imagery and field reconnaissance. The land cover within the extent boundary was classified using remote sensing and the Normalized Difference Vegetation Index (NDVI). Details regarding the mapping associated with delineating the potential groundwater-ET extent and the land-cover classes within its boundary are provided in Section 5.3.2 and Appendix D. The process was identical for both the main and the northern groundwater discharge areas, except for the delineation of open-water areas in the main discharge area which changed annually based on the 2006-2010 satellite imagery documented in Fenstermaker et al. (2011).

Groundwater-ET volumes were estimated following different analysis steps for the two groundwater discharge areas. For the main groundwater discharge area, remotely-sensed data and an empirical relationship between NDVI and annual total ET were used to derive spatial distributions of annual total ET and groundwater ET. The specific analysis steps are as follows, with details presented in Section 5.3.3, Section 5.3.4 and Appendix D:

1. Estimating annual precipitation distributions based on annual PRISM precipitation grids.

2. Estimating annual distributions of total ET by applying an empirical relationship between footprint-weighted growing-season average NDVI and annual total ET to growing-season average NDVI grids.

3. Estimating annual distributions of groundwater ET and total volumes by:

   - Calculating the annual distributions of groundwater ET as differences between the annual total-ET and precipitation grids.

   - Calculating the annual volumes of groundwater ET from the annual distributions of groundwater ET.

A different approach was applied to the northern groundwater discharge area because the 2006-to-2010 remotely-sensed data required to implement the first approach were not acquired for this area. Therefore, the groundwater-ET volumes for land-cover classes comprising the northern area were estimated by multiplying the area of each land-cover class by an average annual groundwater-ET rate derived from ET-measurement data collected at sites of similar land cover within the valley. This approach and the resultant estimate are presented in Section 5.3.4.2.

5.3.2 Extent of Potential Groundwater-ET Area

The extent of the potential groundwater-ET area of Spring Valley was initially delineated using previous mapping by Rush and Kazmi (1965, Plate 1), Woodward-Clyde Consultants et al. (1994, p. 42, Figure 3-10 and Table 3-1), and Nichols (2000, Table C17, p. C44). Satellite imagery and field investigations were subsequently used to refine and verify the extent boundaries based on the presence of phreatophytic vegetation and consideration of the depth to groundwater.

Within the extent boundaries, distributions of the six land-cover classes listed in Table 5-1 were delineated using the NDVI method. Field investigations were performed to verify the classification boundaries. A map depicting the groundwater-ET extent and land-cover distributions within the extent boundary is presented in Figure 5-1, which also identifies the main and northern groundwater discharge areas. Additional details regarding the mapping are presented in Section D.3.0 of Appendix D.

Table 5-1
Land-Cover Classification

ET Class	Classification	Description	DTW Range[a] (ft bgs)
1	Open Water	Bodies of open water fed by groundwater sources (direct hydraulic connection, springs, seeps, etc.)	Above ground surface
2	Bare Soil/Low Density Vegetation	Shrubland less than or equal to 20% plant cover - Areas dominated by bare soil and low- to moderate-density desert shrubland, including greasewood, rabbit brush, and other phreatophytic species	Mostly 10 to <60
3	Phreatophytic/ Medium Density Vegetation	Shrubland with plant cover greater than 20% - Areas dominated by desert shrubland, including mixed stands of medium-density greasewood, rabbit brush, and other phreatophytic species	2 to 60
4	Wetland/Meadow	Area of shallow groundwater near bodies of open water consisting of wetland vegetation, marshland, woodland, and dense meadows - additionally includes riparian corridors in the southern part of study area, consisting of saltcedar, desert willows, cottonwood, and mesquite trees with underlying shrubs and grasses	0 to 20
5	Agriculture	Areas where crops are grown and harvested (i.e. alfalfa, hay, etc.), but not grassland/meadowland areas	NA
6	Playa	Bare-soil flat areas located in the bottoms of some basins. Classified as potential groundwater ET areas in basins where the water table is within 10 ft of the land surface	0 to 10

[a]SNWA (2009a; Table E-2, p. E-9)
NA = Not applicable

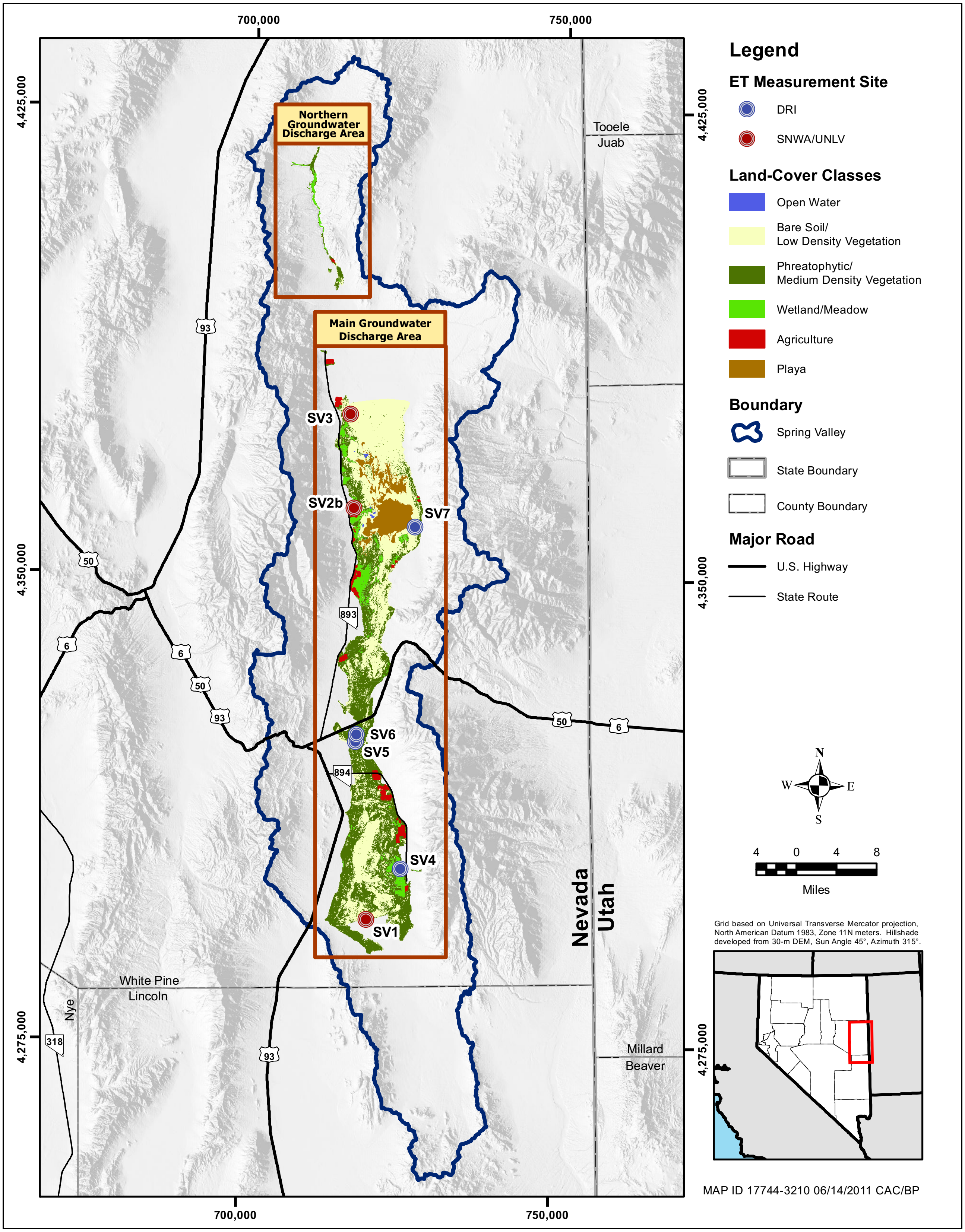

Figure 5-1
Spring Valley Groundwater-ET Extent Map and Location of ET-Measurement Sites

Based on this mapping, the total area within the groundwater-ET extent boundary is 172,605 acres. This total is very similar to that estimated by Rush and Kazmi (1965, p. 22) and Nichols (2000, p. C44) who estimated the area to be 186,000 acres and 168,236 acres, respectively. This similarity is expected, because mapping from these investigations was used to identify the initial boundaries for the area delineated in this study. The total area and extent are also comparable to those estimated by Smith et al. (2007, p. 15) and Welch et al. (2007, Appendix A) for the BARCASS, and by SNWA (2009a, p. 7-14); 177,698 acres and 172,100 acres, respectively.

5.3.3 Annual Total-ET and Precipitation Distributions within the Main Groundwater Discharge Area

This section presents the methods, assumptions, and data used to derive annual distributions of precipitation, total ET, and groundwater ET for the main groundwater discharge area of Spring Valley depicted in Figure 5-1. Annual distributions were derived for each year of the period 2006-2010 which coincides with the period of data collection at ET-measurement sites and precipitation gages located in the valley. Additional details regarding derivation of these distributions are provided in Appendix D.

5.3.3.1 Annual Precipitation Distribution

The annual precipitation distributions within the main groundwater discharge area of Spring Valley were estimated by adjusting annual PRISM precipitation grids to local conditions using precipitation data collected within the area during the period 2006 through 2010.

Precipitation gages were installed at UNLV, DRI, SNWA, and USGS ET-measurement sites located within the groundwater discharge areas of Spring Valley. The locations of these gages and their annual totals are presented in Figure D-2 and listed in Table D-3 of Appendix D, respectively. These data were used to evaluate the accuracy of, and adjust the annual PRISM 4-km precipitation grids which were used to estimate the precipitation distribution within the main groundwater discharge area.

To evaluate the accuracy of the annual PRISM precipitation grids, grid-cell values at the location of the precipitation gages were extracted and compared to measured values. For each year a record of annual precipitation was available, the difference between the measured value and the PRISM grid value was calculated. These values are listed in Table D-4 of Appendix D, and indicate that a significant overestimation bias is associated with the PRISM grids. For the period of record, 26 of the 28 measurements were less than the PRISM value, and the differences ranged from -4.19 to -0.20 in. This bias is best illustrated by a scatter plot of the measured and PRISM-derived precipitation values (Figure D-5; Appendix D). If the PRISM grids were unbiased, data points would plot randomly about the 1:1 line depicted in the charts, and if PRISM perfectly modeled precipitation the values would plot on the 1:1 line. The overestimation bias is illustrated by the fact that nearly all of the data points plot above the 1:1 line, indicating that the PRISM values are consistently greater than measured values. Therefore, the PRISM grids do not accurately represent the precipitation rates within the discharge areas and require adjusting to remove the overestimation bias.

To adjust each annual PRISM precipitation grid, the average difference (measured - PRISM) for each year, was calculated and then added to each grid-cell value of the corresponding PRISM grid. This effectively removed the overestimation bias as illustrated by comparing the charts presented in Figures D-5 and D-6 of Appendix D. The removal of the overestimation bias is further demonstrated by calculating the average differences between measured values and values extracted from the adjusted-PRISM grid, which were zero for all years. Implicit in these adjustments is the assumption that all grid-cell values comprising unadjusted-PRISM distributions overestimate precipitation. The gage data appear to validate this assumption because they are well distributed throughout the extent of the groundwater ET area (Figure D-2; Appendix D), and PRISM overestimates all but two of the 28 records. A comparison of the annual volume of precipitation derived from the PRISM grids and the adjusted-PRISM grids is presented in Table D-5 of Appendix D.

5.3.3.2 Annual Total-ET Distribution

Spatial distributions of annual total ET within the main groundwater discharge area were estimated using an empirically-derived relationship between annual total ET and footprint-weighted growing-season average NDVI as reported in Fenstermaker et al. (2011). The relationship was defined by a linear equation derived through regression analysis using the two variables, and was then applied to growing-season average NDVI grids to derive the annual total-ET distributions. The growing- season average NDVI grids were available from Fenstermaker et al. (2011) only for the main groundwater discharge area depicted in Figure 5-1. The annual total-ET distribution for the northern groundwater discharge area was, therefore, derived separately (see Section 5.3.4.2).

Annual ET data used in the regression analysis were measured at ET-measurement sites located in White River (1), Spring (7), and Snake (2) valleys. These sites were maintained and operated by UNLV, DRI, and SNWA during the period of record, and the data are reported in Fenstermaker et al. (2011) and Shanahan et al. (2011). Satellite imagery was processed and used to derive growing-season average NDVI grids from which footprint-weighted average NDVI values were computed for each ET-measurement site and corresponding year (Fenstermaker et al., 2011). In total, 31 annual ET/footprint-weighted growing-season average NDVI data points were used in the regression analysis, with an additional seven data points reserved to perform an accuracy assessment of the regression model (Fenstermaker et al., 2011).

The regression model was applied to growing-season average NDVI grids to derive annual total-ET distributions for areas delineated as the wetland/meadow, phreatophyte/medium vegetation, and the bare soil/low vegetation land-cover classes (Table 5-1). The equation was not applied to the agriculture, open-water, and playa land-cover classes because no data points representing these classes were used in the regression analysis. Further, the NDVI values in the agricultural areas cannot be used to represent natural conditions and NDVI values cannot be correlated to evaporation rates from open water and playas, as NDVI only identifies the greenness of the vegetation cover. For areas delineated by these classes, the annual ET was estimated by the following:

- For the agricultural croplands, it was assumed that the croplands replaced natural vegetation of the land-cover class currently encompassing them. To remove the effects of this development, the grid cells within agricultural cropland areas were assigned values equivalent to the nearest ET-rates representing natural vegetation (i.e., phreatophytes) using a search radius of 90 m.

- For areas of open-water, a consumptive-use rate of 4.70 ft/yr was assigned based on Huntington and Allen (2010, Appendix 14, p. 246).

- For playa areas, grid-cell values were assigned null values which were subsequently assigned groundwater consumptive-use rates during the derivation of the groundwater-ET distribution described in Section 5.3.4.

For each year, an annual distribution of total ET was derived by applying the processing steps described in this section and Appendix D. The resultant distributions consist of 30×30 m grids of annual total ET, except for the areas delineated as playa, whose grid-cell values remained null. The annual grids were then converted from mm to ft by multiplying the values by a conversion factor of 0.003281 ft/mm. Each grid was then queried to identify grid-cell values exceeding the average annual reference ET (ET_{ref}) in Spring Valley, which was defined as the average annual ET_{ref} measured by the UNLV, DRI, and SNWA Eddy Covariance (EC) stations, or 4.2 ft (Shanahan et al., 2011). For these cells, the values were replaced with the average annual ET_{ref}. During the 5-year period, the percentage of cells that exceeded this value ranged from 0.62 to 3.40 percent, with an annual average of 2.12 percent. The final annual distributions of total ET are presented in Figures D-7 through D-16 of Appendix D. These grids were used to compute the annual total ET for each year by summing the products of each grid-cell area and annual total ET. The annual totals for the period of record and the period of record average are listed in Table 5-2.

Table 5-2
Annual Total-ET Estimates for the Main Groundwater Discharge Area of Spring Valley (afy)

2006	2007	2008	2009	2010	Period of Record Average
184,900	162,900	153,500	186,600	184,700	174,500

Totals were derived from annual total ET grids and exclude ET on playa areas.

5.3.4 Annual Groundwater-ET Estimates

Groundwater-ET volumes were estimated following different analysis steps for the main and northern groundwater discharge areas of Spring Valley. The total volume is the sum of groundwater ET for the two areas.

5.3.4.1 Groundwater-ET in the Main Groundwater Discharge Area

This section describes the derivation of annual groundwater-ET estimates for the main groundwater discharge area of Spring Valley for the period 2006 through 2010, with a detailed accounting of the methods, assumptions, and analyses provided in Appendix D. Annual groundwater-ET estimates were calculated as the differences between spatial distributions of annual total-ET and adjusted-PRISM precipitation using Equation 5-1. The general activities performed and data required to derive these distributions are listed below:

- Estimating the annual distributions of groundwater-ET by calculating the differences between the annual total ET and adjusted-PRISM precipitation grids.
- Calculating the annual volumes of groundwater ET from the groundwater-ET distributions

Descriptions of the specific steps follow. First, the annual 4 km adjusted-PRISM precipitation grids were resampled to the same resolution and origin as the annual total-ET grid, and converted from inches to feet. Next, the groundwater-ET grids were derived using grid operations to subtract the adjusted-PRISM precipitation grids from the annual total-ET grids. Finally, the grid cells within the playa areas of the groundwater-ET grids were assigned an annual groundwater-evaporation rate of 0.09 ft based on Deverel et al. (2005, p. 14). The resultant groundwater-ET distributions are presented in Figures D-7 through D-16 of Appendix D.

The groundwater-ET grids were used to derive groundwater-ET estimates for the main groundwater discharge area and for each year by summing the products of each grid-cell area and corresponding annual groundwater ET. These totals and the period-of-record average are provided in Table 5-3.

Table 5-3
Annual Groundwater-ET Estimates for
the Main Groundwater Discharge Area of Spring Valley (afy)

2006	2007	2008	2009	2010	Period of Record Average
104,400	99,700	104,700	92,000	56,700	91,500

Totals were derived from annual groundwater-ET grids

5.3.4.2 Groundwater ET in the Northern Groundwater Discharge Area

The spatial coverage of the growing-season average NDVI grids (2005-2010) did not include the small groundwater discharge area in northern Spring Valley; therefore, a separate analysis was performed to estimate the groundwater ET for this area. The general activities performed as part of this analysis included the following:

- Using the groundwater-ET extent and land-cover classification map to derive the acreages for each land-cover class present within the northern groundwater discharge area.
- Estimating the average annual groundwater ET for each land-cover class using annual ET-rate and precipitation data for ET-measurement sites in Spring Valley.

The average annual groundwater-ET rates for the northern groundwater discharge area were derived for the land-cover classes from ET-rates measured at sites in Spring Valley by UNLV, DRI, SNWA, and USGS. These data are listed in Table D-7 of Appendix D. The average annual groundwater ET for each class was calculated by multiplying the area by the corresponding average-annual groundwater-ET rate. The acreages, average-annual groundwater-ET rates, and resultant groundwater-ET estimates are listed in Table D-8. The average annual groundwater ET for the northern groundwater discharge area is estimated to be about 3,300 afy. Although this estimate was not derived the same way as the one for the main groundwater-ET area, the groundwater ET rates used in the calculations are representative of the 2006-2010 period of record. Therefore, the estimated groundwater volume estimated for the northern groundwater discharge area is representative of this same period of record.

5.3.4.3 Total Groundwater ET

The period of record average-annual groundwater ET is estimated as the sum of the estimates for the main groundwater discharge area, 91,500 afy, and the northern groundwater discharge area, 3,300 afy, or 94,800 afy.

The period-of-record average annual groundwater ET derived in this study, 94,800 afy, is conservatively low due to the low estimate of 2010 for the main groundwater discharge area, and falls within the range of estimates previously-reported by Rush and Kazmi (1965), Nichols (2000), Welch et al. (2007), and SNWA (2009a). Rush and Kazmi (1965, Table 7, p. 23) provided a reconnaissance-level estimate of average annual groundwater ET of 70,000 afy. Nichols (2000, Table C-17, p. C44) reported groundwater-ET estimates of 102,000 afy and 77,500 afy for 1985 and 1989, respectively. Welch et al. (2007, Appendix A) estimated the average annual groundwater ET for Spring Valley to be 75,615 afy. SNWA (2009a, Table 7-4, p. 7-17) estimated a total of 72,100 afy. These estimates define a range of 70,000 afy to 102,000 afy. The estimate derived by this study is, however, believed to be the best estimate to date because it is the only estimate to explicitly rely on observed vegetation, ET-rate, and precipitation data collected in Spring Valley for a record spanning several years.

5.3.5 Summary and Conclusions for Spring Valley

The period-of-record average groundwater ET estimated for Spring Valley, 94,800 afy, is within the range of previously-reported estimates. However, this value is somewhat skewed by the low estimate for 2010 derived for the main groundwater discharge area. This value is anomalously low as a result of the simplifying assumption related to what is assumed to be effective precipitation, and the extraordinary precipitation that occurred in the basin during 2010. The simplifying assumption is that 100 percent of the precipitation is effectively consumed by ET. This assumption is valid during years of normal and below-normal precipitation, but likely invalid during years of significantly above-normal precipitation because the total ET demand within the groundwater discharge area cannot exceed the available water. In this case, the available precipitation is not 100 percent effectively consumed by ET. For years of significantly above-normal precipitation, the precipitation is likely less than 100 percent effective. Precipitation that is not effectively consumed by ET is either stored in the soil or travels past the root zone to the water table. For 2010, the total ET was estimated to be 184,700 afy, which is about 105 percent of the period of record average. However, the precipitation during that year, based on the adjusted-PRISM grid, was 139,200 afy, or 160 percent of the period of record average. The fact that the total ET did not appreciably increase from the period of record average during a year of extraordinary precipitation suggests that, for that year, the effective precipitation is significantly less than 100 percent. If the percentage was assumed to be lower (e.g., 75 percent), then the groundwater-ET estimate would be higher, as would the period of record average.

5.4 Cave Valley

Cave Valley discharges most of its groundwater by subsurface outflow to adjacent downgradient basins. ET occurs only in a limited discharge area on the valley floor where the DTW is minimal, intermittent springs and streams occur, and phreatophytic vegetation is present. This section describes the extent of this area and provides an estimate of the mean annual groundwater ET volume.

5.4.1 Approach

The groundwater ET estimate for Cave Valley was obtained from the conceptual model report developed for the Project EIS by SNWA (2009a). The estimates of groundwater ET presented in that report were developed for basins of the WRFS and other neighboring flow systems using two methods. Method 1 was developed by SNWA (2009a). Method 2 was a combination of Method 1 and the method used in the BARCASS (Welch et al., 2007). As a result, for basins common to the two studies, such as Cave Valley, SNWA (2009a) reports two estimates of groundwater ET. The estimate derived using Method 1 is used in this groundwater assessment of Cave Valley, and it follows the general approach described in Section 5.2. The specific steps were as follows:

1. The preliminary extent and land-cover classes of the potential groundwater-ET area was delineated.

2. Total-ET rates were derived for each land-cover class listed in Table 5-1 and present in the basin. These rates were multiplied by the corresponding areas for each land-cover class to calculate the total ET volume.

3. The groundwater-ET volume for each land-cover class was derived by subtracting the precipitation volume estimated to fall on each area from the corresponding total-ET volume.

4. The final extent of the potential groundwater-ET area was delineated by revising the preliminary extent map to include only areas where the volume estimates of total ET were greater than those of precipitation.

The details of this approach as it was applied to Cave Valley are presented in the following sections.

5.4.2 Preliminary Extent of Potential Groundwater ET Areas

The process by which the preliminary extent of the potential groundwater-ET areas in Cave Valley were delineated is the same as was used for Spring Valley, which is described in Section D.3.0 of Appendix D. Additional details regarding Cave Valley are provided in SNWA (2009a, p. F-6). The initial extent of the potential groundwater ET area for Cave Valley was based on the previous mapping of Eakin (1962) and LVVWD (2001). As described in Appendix D for Spring and White River Valleys, the initial extent was refined based on satellite imagery from 2002 and field-mapping, and the land-cover classes listed in Table 5-1 were delineated using the NDVI. Of the six land-cover classes listed in Table 5-1, only the bare soil/low vegetation, phreatophyte/medium vegetation, and wetland/meadow classes occur in Cave Valley, and their corresponding acreages are listed in Table 5-4 and their spatial distributions are presented in Figure 5-2.

Table 5-4
Acreages of Land-Cover Classes within the Cave Valley Potential Groundwater-ET Extent Boundary

Land-Cover Class	Area (acres)
Bare Soil/Low Density Vegetation	5,914
Phreatophytic/Medium Density Vegetation	9,651
Wetland/Meadow	1,084
Basin Total	**16,649**

There are two primary areas of potential groundwater ET within Cave Valley, one located in the northern part of the basin along the main surface-water drainage channel, and a second one located on the valley floor in the southern part of the basin.

The potential groundwater ET area is very similar to the areas reported by Smith et al. (2007, p. 15) and Welch et al. (2007, Plate 4 and Appendix A) as part of the BARCASS, who estimated the area to be 13,347 acres. This similarity is expected, because both mapping efforts utilized similar information and mapping methods, including satellite imagery, in their respective studies. In the Reconnaissance Report, Eakin (1962, p. 12; 13) described the groundwater-ET area "to be confined to the area located along the main drainage channel in the valley fill in T. 9 and 10 N, adjacent tributary channels, and along channels in the upper parts of the alluvial apron where the water table is at shallow depth, such as in the vicinity of stock wells 9/62-1a1 and 10/63-25a1, and to the spring areas in sec. 9, T.9N, R.64E, and near Gardner Ranch." This description approximately matches the potential groundwater-ET areas identified in the northern part of the basin (Figure 5-2). Eakin (1962) did not consider the area located in the southern part of the basin to be an area of groundwater ET.

5.4.3 Total-ET Rates

ET-measurement data are not available for Cave Valley; therefore, annual ET rates for measurement sites located outside of Cave Valley were used in the calculations of total ET. ET rates for each class were selected based on the similarities between the vegetation types and the climate associated with the ET-measurement site and the corresponding class in Cave Valley. The availability of supporting data, such as site coordinates, precipitation, and DTW, was also considered in the selection of the sites. For the bare-soil/low vegetation class, an annual ET rate of 1.00 ft/yr was selected based on the average of the area-weighted average annual ET for the sparse and moderately-dense shrubland ET units reported by Welch et al. (2007, p. 56) as part of BARCASS. For the phreatophyte/medium vegetation class, an annual ET rate of 1.03 ft/yr was used based on the average of annual rates reported by Moreo et al. (2007, p. 20) for BARCASS sites WRV-1, WRV-2, and SPV-2. For the wetland/ meadow class, the annual ET rate of 2.25 ft/yr measured at the BARCASS SPV-3 site (Moreo et al., 2007, p. 20) was scaled by the ratio of the annual potential evapotranspiration (PET)

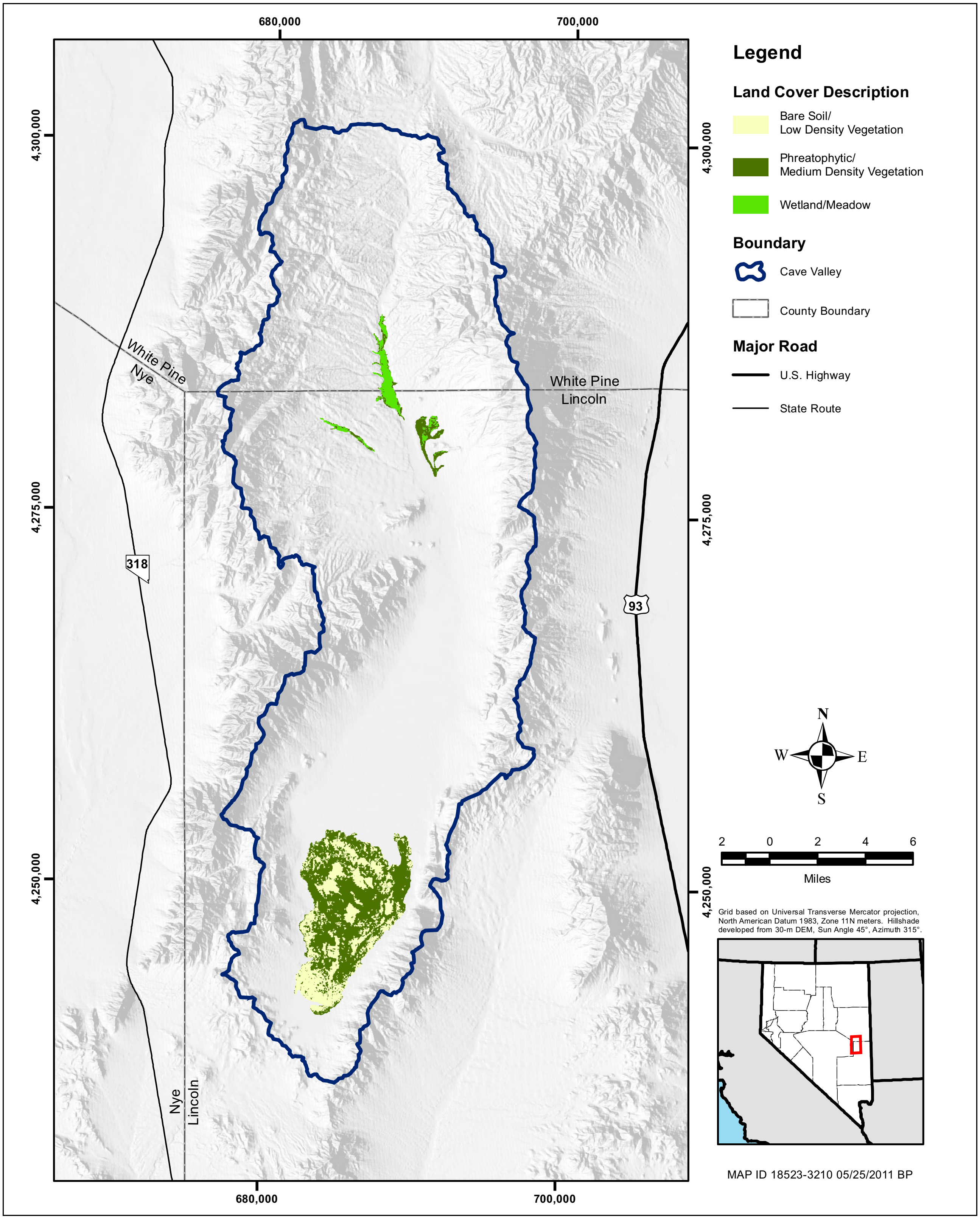

Figure 5-2
Preliminary Extent and Distribution of Land-Cover Classes within the Cave Valley Potential Groundwater-ET Area

rate at the measurement site to the average annual PET rate for the area delineated as wetland/meadow in Cave Valley. The PET rates were extracted from a spatial distribution of PET that was derived by linear-regression analysis of PET-rate data compiled by McCurdy and Albright (2004). Details regarding the derivation of the PET distribution are provided in SNWA (2009a, p. E-9). A PET ratio of 3.86/4.00, or 0.965, was applied to the measured rate of 2.25 ft/yr to derive a PET-adjusted ET rate of 2.17 ft/yr for the wetland/meadow class in Cave Valley. Table 5-5 lists the total-ET rates used to calculate the annual total-ET volume for Cave Valley. The total-ET volumes were calculated by multiplying the area of each land-cover class by their corresponding annual total-ET rate. The areas, total-ET rates and total-ET volumes for each class are presented in Table 5-6.

Table 5-5
Selected Observed ET Rates Used to Estimate ET

ET Class	Selected ET Site	Description of Selected ET Site	Total ET Rate (ft/yr)	Adjusted Total ET Rate (ft/yr)
Bare Soil/Low Density Vegetation	Long-Term Mean Rate/BARCASS Region	Areas within the phreatophytic boundaries exhibiting ground cover densities of less than 20%, considered to be either bare soil or sparse vegetation cover	1.00[a,b]	1.00
Phreatophytic/Medium Density Vegetation	WRV-1, WRV-2, and SPV-2	Medium-density phreatophytes, greasewood and shrubs, such as sagebrush	1.03[c,d]	1.03
Wetland/Meadow	SPV-3	Wetland/meadow land cover surrounding riparian corridors throughout the project area	2.25[c]	2.17

[a]Welch et al. (2007)
[b]Average of the area-weighted average annual ET for the sparse and moderately dense shrubland ET Units reported by Welch et al. (2007)
[c]Moreo et al. (2007)
[d]Average annual ET rate from WRV-1, WRV-2 and SPV-2

5.4.4 Groundwater-ET Volumes

Groundwater-ET volumes for each class were calculated as the difference between the total ET volume and the precipitation volume estimated to fall on the area (Equation 5-1). For each land-cover class, the precipitation volume was calculated by multiplying the corresponding area by the average-annual precipitation rate derived for the area from the PRISM 800-m precipitation grid (SNWA, 2009a, p. F-6). The groundwater-ET volumes were calculated for each class by subtracting the precipitation volume from the corresponding total-ET volume. The groundwater-ET volumes of the classes were then summed to derive the total volume for the basin. The resulting annual groundwater-ET volumes for Cave Valley are presented in Table 5-6.

The total annual volume of groundwater ET is about 1,300 afy. This volume is similar to the 1,550 afy estimated by Welch et al. (2007, Appendix A) for BARCASS. Other available estimates are that of Eakin (1962, p. 13) and LVVWD (2001, p. 4-40), who quantified groundwater ET as “a few hundred acre-feet per year” and 5,000 afy, respectively. The estimates derived by SNWA (2009a)

Table 5-6
Estimated Annual Total ET, Precipitation, and Groundwater-ET Volumes for Land-Cover Classes in Cave Valley

ET Class	Area (acres)	Adjusted ET Rate (ft/yr)	Total ET Volume (afy)	Average Precipitation Rate (ft/yr)	Precipitation Volume (afy)	Groundwater ET Volume (afy)
Bare Soil/Low Density Vegetation	5,914	1.00	5,914	1.06	6,269	0
Phreatophytic/Medium Density Vegetation	9,651	1.03	9,940	1.05	10,134	0
Wetland/Meadow	1,084	2.17	2,352	0.98	1,062	1,290
Basin Total	**16,649**	---	---	---	---	**1,290**

(the 1,300 afy used in this study) and Welch et al. (2007) (1,550 afy) are believed to be the most representative.

5.4.5 Summary and Conclusions for Cave Valley

Based on the groundwater-ET volumes listed in Table 5-6, there is no apparent groundwater ET within the bare soil/low vegetation and phreatophyte/medium vegetation land-cover classes, indicating that precipitation in these areas is larger or equal to the total amount of ET. Groundwater ET occurs only from the wetland/meadow areas located in the northern part of the basin. Therefore, the potential groundwater-ET area was to exclude the other two classes of land cover. As a result, the area located in the southern part of the valley was entirely excluded, as it is concluded here that the vegetation in this area is supplied entirely by local precipitation falling on the area. Therefore, the southern area is not considered to be a groundwater ET area for the purpose of this groundwater resource assessment. The final groundwater-ET areas are presented in Figure 5-3.

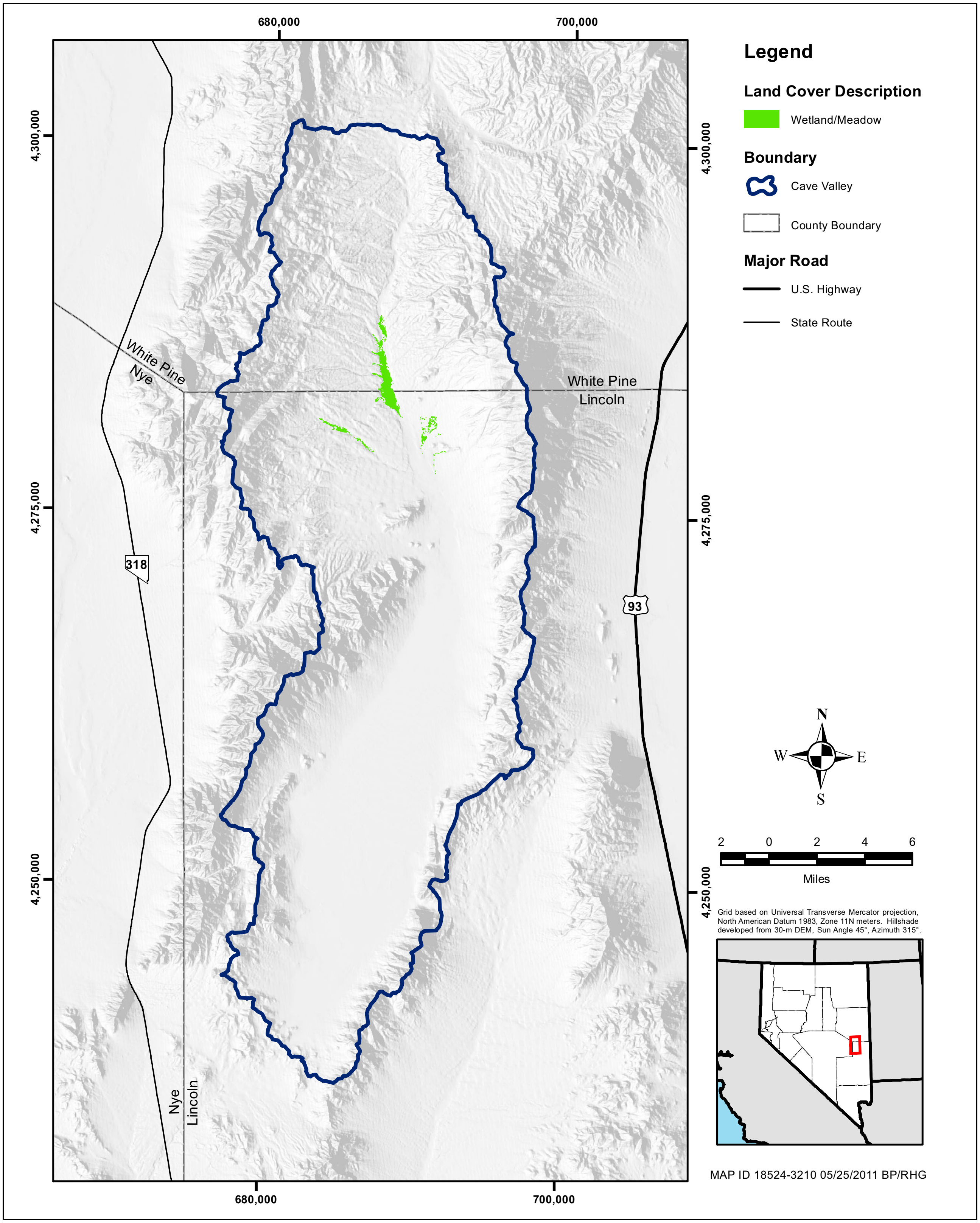

Figure 5-3
Extent and Vegetation Classes of the Final Potential Groundwater-ET Areas in Cave Valley

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6.0 POTENTIAL RECHARGE FOR PROJECT BASINS

Given that precipitation recharge cannot be directly measured for large areas, it must be estimated by some other means. In this section, relevant estimation methods of groundwater recharge, previous estimates, the rationale for method selection, the application of the selected method, and the resulting estimates for the four Project Basins are presented. The estimates of recharge presented in this section are supported by information presented in Section 5.0; and Appendices D, E, F, and G.

6.1 Objective

The objective of the analysis described in this section is to derive estimates of the mean annual recharge distribution and volume for the Project Basins: Spring, Cave, Dry Lake, and Delamar valleys.

6.2 General Approach

The general approach followed to derive recharge estimates for the Project Basins consists of the following steps:

1. Identify relevant methods of estimation.
2. Select method for use in this analysis.
3. Apply method to areas of interest.
4. Describe resulting estimates and compare to previous estimates.

6.3 Review of Relevant Recharge Methods

A review of the available methods of estimation of recharge from precipitation is presented in this subsection. Recharge methods that have been used to estimate basin-scale groundwater recharge in the area of interest and vicinity are based on the law of conservation of mass and may be categorized as follows:

- Groundwater-balance methods
- Soil-water-balance methods
- Chloride mass-balance method

Brief descriptions of the three methods and their implementation by various authors are provided in the following sections.

6.3.1 Groundwater-Balance Methods

The groundwater-balance method is applied to a groundwater basin, usually under estimated predevelopement steady-state conditions, to derive an estimate of the recharge volume for the basin. This volume is calculated as the difference between the total volume of groundwater discharge (i.e., groundwater ET plus subsurface outflow) and the volume of subsurface inflow. A prominent groundwater-balance method developed and applied to basins in Nevada is the Maxey-Eakin method (Maxey and Eakin, 1949). This method and its derivatives are summarized, followed by brief descriptions of other selected groundwater-balance methods used elsewhere.

6.3.1.1 Maxey-Eakin Method and Derivatives

The Maxey-Eakin method (Maxey and Eakin, 1949; Eakin et al., 1951) was designed to estimate groundwater recharge from precipitation for hydrographic areas of Nevada. Estimates of groundwater recharge based on the Maxey-Eakin method were published in the NDWR/USGS Reconnaissance Series from the late-1940s through the mid-1970s. Maxey-Eakin methods include the "standard" method and modified versions.

The standard Maxey-Eakin method (Maxey and Eakin, 1949, p. 40) is based on a precipitation map developed by Hardman (1936). This map delineates six precipitation zones, ranging from 0 to over 20 in. of precipitation per year. Using this map, the five precipitation zones above 8 in. in a given hydrographic area are identified as recharge areas. The acreage for each precipitation zone is then measured and multiplied by its average precipitation rate. The resulting precipitation volume is then multiplied by the recharge efficiency for the zone (i.e., the percentage of precipitation that becomes groundwater recharge). The resulting recharge volumes are then summed to yield an estimate of the total recharge volume from precipitation for that hydrographic area, including recharge by direct infiltration and infiltration of surface-water runoff. The standard Maxey-Eakin efficiencies were derived by balancing the recharge volume to estimates of discharge volume for 13 basins in Nevada (Maxey and Eakin, 1949). The standard Maxey-Eakin method is not designed to provide a realistic spatial distribution of recharge rates. It does, however, provide first-order approximations of basin recharge volumes (Avon and Durbin, 1994).

One major modification of the standard Maxey-Eakin method involves the use of altitude zones on a topographic map to approximate the precipitation zones and calculate their areas. Examples of this variation of the Maxey-Eakin (1949) method are presented by Eakin (1962, p. 11 and 12; 1963, p. 16 and 17) for Cave, Dry Lake, and Delamar valleys. Other investigators used variations of the standard Maxey-Eakin method by modifying the precipitation and the recharge efficiencies (D'Agnese et al., 1997; Berger, 2000; Donovan and Katzer, 2000; LVVWD, 2001; Dixon and Katzer, 2002; Hevesi et al., 2002; and Katzer and Donovan, 2003). Of particular interest are Donovan and Katzer (2000), Hevesi et al. (2002), and Wilson and Guan (2004) who converted the recharge efficiency step function, defined in the standard Maxey-Eakin method over the whole range of precipitation or a portion of it, to similar power functions expressing recharge as a continuous function of precipitation.

6.3.1.2 Other Groundwater-Balance-Based Methods

Other selected methods of estimating recharge from precipitation using power functions to describe the relationship between recharge and precipitation were applied in Idaho (Contor, 2004), India (Kumar and Seethapathi, 2002), and Arizona (Anderson et al., 1992).

In support of the Eastern Snake Plain Aquifer Model Enhancement Project in Idaho, Contor (2004) adapted a relationship used by Rich (1951) to describe a basin's total yield. Contor (2004, p. 3) simplified the relationship to represent recharge on nonirrigated lands as a function of precipitation as follows:

$$\text{Recharge} = K \times \text{Precipitation}^N \qquad \text{(Eq. 6-1)}$$

where,

K = Empirical slope parameter
N = Empirical exponent

Because recharge cannot physically be greater than precipitation, the slope of the recharge-precipitation relationship should never be greater than 1. At the point at which recharge equals precipitation, the exponential relationship is replaced by a straight line with a slope of 1. Furthermore, for a given relationship, the area between the 1:1 straight line extends to zero, and the exponential curve represents the portion of precipitation that does not become recharge. This represents the water that is stored in the soil or lost to ET.

Kumar and Seethapathi (2002) derived an empirical relationship to estimate groundwater recharge from rainfall for the Upper Ganga Canal command area using a seasonal groundwater balance spanning over several seasons during, 1972 to 1973 and 1983 to 1984. They found that recharge increases with rainfall in a nonlinear fashion. The recharge efficiencies they calculated for the monsoon season ranged between 0.05 to 0.19. Kumar and Seethapathi (2002, p. 7) then derived an empirical relationship between recharge and rainfall by fitting the estimated values of recharge and the values of rainfall using the nonlinear regression method. The corresponding equation is as follows:

$$R = 0.63(P - 15.28)^{0.76} \qquad \text{(Eq. 6-2)}$$

where,

R = Groundwater recharge from rainfall in monsoon season (in.)
P = Mean rainfall in monsoon season (in.)

The term 15.28 in. represents the magnitude of rainfall below which recharge does not occur. This equation is similar to that of Contor (2004), except it assumes that recharge only occurs above a certain level of precipitation (15.28 in.).

As part of a RASA study for alluvial basins located in southwest Arizona and vicinity, Anderson et al. (1992, p. B33) developed an equation for estimating mountain-front recharge as a function of precipitation using the water-budget method. Their approach consisted of developing a relationship between the mean annual mountain-front recharge volume and the total annual volume of precipitation for several watersheds when the precipitation is greater than 8 in./yr. They initiated the equation starting with the available data points and adjusted its coefficients until both the individual basin budgets and the total budget for all basins balanced. Their data points included recharge values derived from models and a few basin estimates. Two forms of the equation were developed, one using the total precipitation volume for the basins and one using only the precipitation volume for precipitation rates larger than 8 in. The 8-in. cutoff was arbitrary but yielded better fits to the data and therefore was used to estimate recharge for the study area. The volume of precipitation below 8 in. was attributed to losses to soil-moisture deficits and ET. The resulting equation is as follows:

$$Log\ R = -1.40 + 0.98 \times Log\ P \qquad \text{(Eq. 6-3)}$$

where,

R = Mean direct mountain-front recharge volume (afy)
P = Mean annual precipitation (afy) for $P > 8$ in./yr

Taking the inverse of each side of the equation yields a power function similar to that of Contor (2004):

$$R = 0.040P^{0.98} \qquad \text{(Eq. 6-4)}$$

where,

R = Mean direct mountain-front recharge volume (afy)
P = Mean annual precipitation (afy) for $P > 8$ in./yr

6.3.2 Soil-Water-Balance Methods

The soil-water-balance method focuses on the processes that control net infiltration through the uppermost layers of surficial materials in a given area. These processes include precipitation, snow melt, snow accumulation, and soil-water storage. The soil-water balance must be successively applied to relatively short-time periods for the method to yield reasonable estimates of recharge over long periods of time. This method is used to calculate the amount of water available at each time step, for potential recharge and/or runoff, or water to be carried to the next time step. The soil-water-balance method has been implemented to estimate basin recharge in Nevada using two models: the INFIL code and the Basin Characterization Model (BCM). Brief descriptions of these two models follow.

6.3.2.1 INFIL Code

The INFIL code (Hevesi et al., 2003; USGS, 2008; Scanlon et al., 2006) calculates potential groundwater recharge, including volume and distribution. INFIL uses a 24-hour (daily) time step to allow for an accurate simulation of the snow accumulation and melting processes. INFIL calculates runoff and distributes it to a stream network and simulates recharge through the streambeds. An INFIL model may be calibrated to the available streamflow data or measurements of soil-moisture content. INFIL has been extensively used to estimate recharge for the Yucca Mountain Project (Flint et al., 2002; BSC, 2004). The INFIL code is the most detailed and refined of all the methods discussed here. However, this method requires a tremendous amount of data and intensive computational resources.

6.3.2.2 Basin Characterization Model

BCM is a GIS-based, distributed-parameter, water-balance method of estimating basin recharge using monthly climatic boundary conditions (Flint and Flint, 2007). BCM is, in essence, a simplification of the INFIL code. BCM differs from the INFIL code in that monthly climate data are used, only one soil layer is used, and surface water is not an explicit parameter. BCM simulates total potential recharge, which is a combination of in-place recharge and runoff. One major shortcoming is the exclusion of streams in the code, which renders calibration very difficult, if not impossible. Despite its more simplified form, BCM also requires large amounts of data and significant computational resources. The BCM code has been used by Flint et al. (2004) to derive recharge estimates for basins in the Desert Southwest and by Flint and Flint (2007) for basins in the BARCASS area.

6.3.3 Chloride Mass-Balance Method

The chloride mass-balance method is used to estimate groundwater recharge in arid and semiarid environments. Given estimates of annual precipitation and known chloride concentrations of bulk precipitation (wet and dry deposition of chloride) and groundwater in targeted aquifers, groundwater recharge can be estimated with the following assumptions: (1) atmospheric deposition is the only source for chloride in groundwater in the targeted aquifer; (2) direct runoff to discharge areas is insignificant or is known; and (3) the recharge sources for the basin are correctly delineated (Dettinger, 1989). This method has been used in several studies to derive reconnaissance estimates of natural recharge for desert basins in Nevada, including those by Dettinger (1989), Maurer and Berger (1997), Russell and Minor (2002), and Mizell et al. (2007).

6.4 Selected Method

The groundwater-balance method was selected as the approach for estimating natural recharge for the Project Basins because it provides the best means of deriving a calibrated recharge estimate by incorporating measurable budget components, namely groundwater ET. The groundwater-balance method was applied to Spring Valley and to the WRFS to derive recharge efficiencies, which were then used to derive spatial distributions and annual volumes of recharge for the Project Basins. For Cave, Dry Lake, and Delamar valleys, the groundwater-balance method was applied to the WRFS as a whole. The application of this method to the Projects Basins is described in Section 6.6. The detailed estimation process of the recharge efficiencies for Spring Valley and the WRFS is described in Appendix F.

The rationale for rejecting the other methods is explained in the following paragraphs.

Direct application of the standard Maxey-Eakin efficiencies to the PRISM precipitation distribution was rejected because it would result in an estimate of natural recharge that does not balance with the estimate of natural discharge. As the Maxey-Eakin method is an empirically-derived solution calibrated to the NDWR/USGS Reconnaissance Series estimates of groundwater discharge using the Hardman (1936) precipitation map, it was concluded that the standard Maxey-Eakin recharge efficiencies should only be applied to the Hardman precipitation map (NSE, 2007, p. 12 and 13). Furthermore, the standard Maxey-Eakin recharge efficiencies only apply to the 13 basins and the estimates of groundwater discharge estimates that Maxey and Eakin (1949) used at that time. If new recharge estimates are to be derived based on updated precipitation maps and/or updated groundwater discharge estimates, the appropriate recharge efficiencies should be recalculated using the groundwater-balance method.

Models implementing the soil-water-balance method such as INFIL and BCM offer the best approach for distributing recharge, as they use spatial distributions of the parameter data sets considered in the models. However, the recharge values derived by this method are unconstrained by observed groundwater data. For example, INFIL- and BCM-based models have never been calibrated to the groundwater budget components of a basin. Also, BCM and particularly INFIL require tremendous amounts of data and intensive computational resources, because of their time-step requirements, monthly and daily, respectively. For these reasons, the soil-water-balance method as implemented in INFIL and BCM was not used in this analysis.

The chloride mass-balance method offers an alternative method of deriving recharge estimates. This method yields representative recharge estimates for watersheds for which sufficient chloride-concentration data are available for precipitation and groundwater samples. However, this method does not work well for large areas with sparse data, such is the case for the areas of interest to this study. Thus, the chloride mass-balance method was rejected, as it was concluded that the chloride-concentration observations for precipitation and groundwater are too few to represent the spatial variability of these input parameters for the areas of interest to this study.

6.5 Previous Estimates

Previous investigations reporting estimates of precipitation recharge for the Project Basins are summarized in this subsection.

Reconnaissance Reports and Scott et al. (1971)

Scott et al. (1971) compiled annual recharge estimates derived for Nevada as part of the NDWR/USGS Reconnaissance Series. These estimates are based on the Maxey-Eakin method (Maxey and Eakin, 1949) or one of its variants, such as the use of land-surface elevation zones to approximate precipitation zones (See Section 3.8.1).

Dettinger (1989)

Dettinger (1989) estimated recharge using the chloride mass-balance method. Because it is difficult to find a groundwater system to meet all of the assumptions associated with this method, the resulting recharge estimates are often underestimated for basins with large precipitation volumes and overestimated for basins with small precipitation volumes.

Kirk and Campana (1988 and 1990)

Kirk and Campana (1988 and 1990) estimated recharge for the WRFS using a simple mixing cell model calibrated with the environmentally-stable isotope, deuterium. The simulated total recharge for the WRFS is almost the same as the one estimated by Eakin (1966). However, the resulting spatial recharge distribution is slightly different, especially increasing recharge in Jakes, Dry Lake, Delamar and Coyote Spring valleys. Because the solution of the model is nonunique, the recharge volumes estimated by this method have large uncertainties.

Nichols (2000)

Nichols (2000) estimated recharge from precipitation for several basins of Nevada by deriving new estimates of recharge efficiencies using new estimates of groundwater ET and the PRISM normal precipitation map (1961 to 1990). The recharge efficiencies were calculated using a multiple linear regression model in which recharge for a given basin was expressed as a function of precipitation within discrete zones and net groundwater discharge. The efficiencies derived from the regression model were used to estimate groundwater recharge for the basins in the study area.

LVVWD (2001)

LVVWD (2001) estimated annual recharge from precipitation for hydrographic areas of the WRFS and Meadow Valley Flow System using a modified version of the Maxey-Eakin method (Donovan and Katzer, 2000). The recharge efficiencies were represented as a continuous function of precipitation. The precipitation distribution was derived by linear regression of measured precipitation and altitude data for precipitation stations located within the flow systems and vicinity. Thomas et al. (2001) evaluated the water budget and flow routing derived by LVVWD (2001) using a deuterium mass-balance model and found it to be plausible.

Epstein (2004)

Epstein (2004) used an inverse method to evaluate and find optimal sets of recharge efficiencies for the Maxey-Eakin method and the regression method developed by Nichols (2000). Epstein (2004) also used his method to derive an optimal solution using a set of recharge estimates reported for basins in Nevada. He found that generally the recalculated Maxey-Eakin recharge efficiencies yielded the lowest basin recharge volumes, and the recalculated Nichols (2000) recharge efficiencies yielded the high end of the range.

Flint et al., 2004

Flint et al. (2004) used the BCM code to derive potential recharge estimates for basins in the Desert Southwest, including the Project Basins. His report contained two sets of estimates: a mean-year estimate and a time-series estimate.

Brothers et al. (1993, 1994, 1996)

Brothers et al. (1993, 1994, 1996) are part of the LVVWD CWP report series containing hydrologic assessments and steady-state groundwater flow models of selected basins in Nevada. The data and information used in these models are mainly from the NDWR/USGS Reconnaissance Series and information reported by Harrill et al. (1988). The simulated groundwater budgets are essentially the same as the ones reported in the NDWR/USGS Reconnaissance Series.

Welch et al. (2007)

Welch et al. (2007), as part of BARCASS, reported recharge estimates derived by Flint and Flint (2007) using the BCM code. The precipitation distribution used in this model was based on an adjusted version of the 4-km PRISM (1971 to 2004) grid.

Mizell et al. (2007)

Mizell et al. (2007), also as part of BARCASS, estimated recharge for basins in the BARCASS area using the chloride mass-balance method. The recharge estimates reported by Mizell et al. (2007) carry an uncertainty that is similar to the estimates reported by Dettinger (1989).

SNWA (2009a)

SNWA (2009a) developed estimates of an annual recharge distribution for the Central Carbonate-Rock Province (CCRP) using the groundwater-balance method and the Excel® Solver. The previous 800-m PRISM grid (Version 2 [PRISM, 2010a]) was used for the precipitation distribution. The annual volumes of subsurface inflow and outflow to and from the CCRP flow system were independently estimated. Estimates of groundwater ET derived by Welch et al. (2007) for the BARCAS study were used for the basins common to the two studies. New estimates of groundwater ET derived using satellite imagery and other information were used for the other basins in the study area.

6.6 Method Application

The groundwater-balance method was coupled with an optimization method, implemented in the Excel® Solver, to derive an optimal solution for the relationship between recharge and precipitation, which then was used to estimate recharge efficiencies and potential-recharge distributions for the Project Basins. Estimates of precipitation, groundwater ET, and boundary inflow and outflow were required for the application of this method. The general process is illustrated in Figure 6-1 and the detailed method of derivation of recharge efficiencies is presented in Appendix F.

The recharge-precipitation relationship was expressed using a continuous nonlinear function rather than a linear or a step-wise function such as that defined by the Maxey-Eakin method (Maxey and Eakin, 1949). As described earlier in this section, many investigators had previously used nonlinear relationships between recharge and precipitation. These investigators include Hevesi et al. (2002), Donovan and Katzer (2000), Wilson and Guan (2004), Contor (2004) and Faybishenko (2007). The specific form of the equation is a power function (Equation F-2). When both sides of this equation are divided by precipitation, the resulting equation relates recharge efficiencies to precipitation (Equation F-3). For a given basin or flow system, the method yields a set of recharge efficiencies

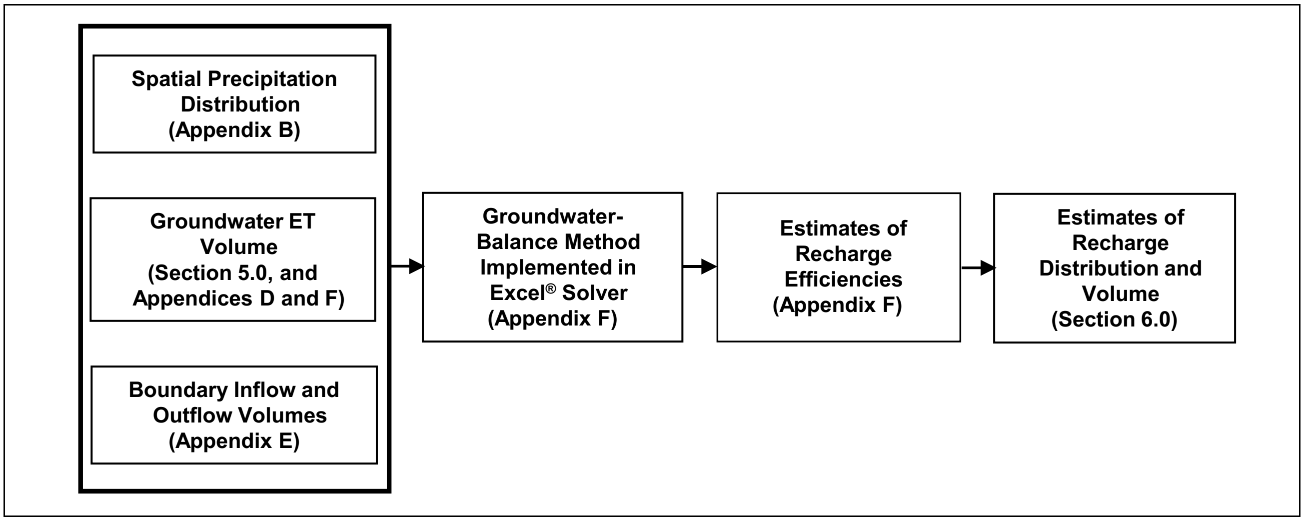

Figure 6-1
Flow Chart Showing Estimation Process of Recharge Distributions and Annual Volumes for Project Basins

while balancing the total annual volume of natural recharge (precipitation recharge + inflow) with the total annual volume of groundwater discharge (ET + outflow). The recharge efficiencies are calculated for a set of 1-in. precipitation intervals with mean precipitation values computed as the average of the PRISM grid cells located within each interval. The average precipitation values of each 1-in. precipitation interval is multiplied by the corresponding recharge efficiency, and areas of no-recharge are excluded. No-recharge areas consist of: (1) areas where precipitation is less or equal to 8 in., (2) groundwater ET areas and, (3) valley bottoms. These areas are removed from the recharge calculations by assigning a zero recharge efficiency to the portions of 1-in. precipitation intervals. The coefficients derived by the optimization process, for the power function (Equation F-3), are used to estimate recharge efficiencies and total recharge volumes that satisfy the groundwater balance for a given basin or flow system. This method and its application in this study are described in detail in Appendix F.

It must be noted that these spatial distributions of potential recharge only account for variations of recharge rates with precipitation which generally is a function of altitude. They do not explicitly account for the geology of the units through which precipitation infiltrates to recharge the groundwater system. The method does not explicitly distribute the recharge from runoff to the actual locations where it occurs. The quantity of recharge from infiltration is, however, implicitly included in the recharge estimated using the groundwater-balance method, which means that the annual volumes of basin recharge are as accurate as the estimates of basin groundwater discharge. Although the recharge distributions generated using this method do not accurately depict the spatial distribution of recharge, they do provide approximate distribution of the potential recharge.

6.7 Recharge Estimates

The annual basin volumes and spatial distributions of recharge in Spring, Cave, Dry Lake, and Delamar valleys were derived using the information provided in Appendix F. The annual recharge volumes for each of the Project Basins were calculated as follows: (1) the volume of precipitation calculated for each 1-in. interval was multiplied by the corresponding recharge efficiency to obtain an annual recharge volume for that interval; (2) the recharge values for all 1 in. intervals were then summed for each Project Basin.

6.7.1 Spring Valley Recharge

The volume of recharge occurring in Spring Valley may be derived using the groundwater balance in two ways, depending on whether a spatial distribution of recharge is desired or not.

Because Spring Valley has relatively negligeable hydraulic connectivity with the surrounding basins, most of its groundwater discharge occurs by ET. Interbasin groundwater flow through its boundaries is relatively small when compared to groundwater discharge by ET. It occurs in the form of outflow to Hamlin Valley and was estimated independently at 4,400 afy, as described in Appendix E. Therefore, the volume of recharge may be calculated directly using the groundwater balance method by equating it to the total discharge (groundwater ET + outflow) as the inflow is estimated to be zero. Groundwater ET was estimated at 94,800 afy (Section 5.0) and the outflow was estimated at 4,400 afy (Appendix E), yielding a basin recharge volume estimate of 99,200 afy.

The volume of recharge occurring in Spring Valley may also be derived from a spatial distribution of recharge derived using the groundwater-balance method summarized in Section 6.6 and detailed in Appendix F. Although the spatial distribution of potential recharge was not needed to estimate the annual recharge volume for Spring Valley, it was generated for mapping purposes. The annual recharge volume for the basin is the same, using either method.

The recharge calculations for Spring Valley are presented in Table 6-1 for the 1-in. precipitation intervals described in Appendix F (Table F-2). Table 6-1 reveals that most of the recharge occurs between precipitation rates of 12 to 20 in./yr. The total basin recharge estimate is 99,200 afy and the mean recharge efficiency for the basin as a whole is 9 percent of the total precipitation.

Comparison of the estimated annual recharge volume to previously- reported values is presented in Table 6-2. The recharge estimate derived for this study, 99,200 afy, falls within the range of previously-reported values, 53,335 afy (Epstein, 2004 – N-Maxey Eakin, p. 136) and 139,194 afy (Epstein, 2004 – N-Nichols, p. 136) (Table 6-2). It is larger than the annual recharge volume of 75,000 afy reported by Scott et al. (1971, p. 48) because of the limitations of the approach used by Rush and Kazmi (1965) to derive this estimate: (1) Rush and Kazmi (1965) estimated the precipitation volumes for the Maxey-Eakin zones using land-surface elevation zones from a topographic map, rather than the Hardman map (1936) (see Section 3.8.1); and (2) the Hardman maps are not accurate (see Section 3.8.2).

The resulting spatial distribution of potential recharge for the basin is presented in Figure 6-2. The map illustrates that calculated groundwater recharge rates are largest on the mountains surrounding the valley. As expected, they are lowest along the margins of the valley (Figure 6-2).

Table 6-1
Recharge Volume Calculations for Spring Valley

1-in. Precipitation Interval	Mean Precipitation Rate (in./yr)	Area (acres)	Precipitation Volume (afy)	Recharge Efficiency (Fraction of Precipitation)	Recharge Volume (afy)
8-9	8.65	4,442	3,203	0.002	5
9-10	9.55	83,615	66,542	0.008	560
10-11	10.55	158,316	139,133	0.020	2,821
11-12	11.46	132,299	126,388	0.034	4,327
12-13	12.49	99,287	103,322	0.052	5,412
13-14	13.49	78,555	88,278	0.072	6,361
14-15	14.48	69,025	83,306	0.093	7,771
15-16	15.48	53,257	68,707	0.116	7,954
16-17	16.54	44,948	61,938	0.141	8,707
17-18	17.52	31,385	45,811	0.164	7,533
18-19	18.56	17,052	26,377	0.191	5,028
19-20	19.65	11,768	19,266	0.218	4,208
20-21	20.53	8,393	14,363	0.242	3,469
21-22	21.69	7,007	12,667	0.272	3,448
22-23	22.74	6,201	11,749	0.300	3,527
23-24	23.49	5,086	9,958	0.321	3,193
24-25	24.83	4,495	9,303	0.357	3,324
25-26	25.65	4,157	8,885	0.380	3,374
26-27	26.52	3,750	8,287	0.404	3,347
27-28	27.64	3,556	8,190	0.435	3,564
28-29	28.72	3,885	9,297	0.465	4,326
29-30	29.63	2,602	6,423	0.491	3,153
30-31	30.29	1,357	3,426	0.510	1,746
31-32	31.52	989	2,599	0.544	1,415
32-33	32.37	393	1,060	0.569	603
33-34	33.47	14	38	0.600	23
				Basin Total Recharge Volume[a]	**99,200**

[a]Rounded to nearest 100 afy.

Table 6-2
Mean Annual Recharge estimated for Spring Valley and Previously-Reported Estimates

Source	Recharge (afy)
This Study	99,200
SNWA (2009a, p. 9-14)	81,339
Reconnaissance Reports and Scott et al. (1971, p. 48)	75,000
Dettinger (1989, p. 69)	61,636
Nichols (2000, p. C25)	104,000
Epstein (2004, p. 136) - Maxey-Eakin Method Evaluation	66,402
Epstein (2004, p. 136) - Nichols-1990-Method Evaluation	93,840
Epstein (2004, p. 136) - BBRM[a]	92,965
Epstein (2004, p. 136) - N-ME[b]	53,335
Epstein (2004, p. 136) - N-N[c]	139,194
Recharge (BCM-Mean Year, Flint et al., 2004, Table 1)	66,987
Recharge (BCM-Time Series, Flint et al., 2004, Table 1)	56,179
Brothers et al. (1994, p. 51)	72,000
Welch et al. (2007, p. 44)	93,000
Mizell et al. (2007, p. 18)	62,000

[a] BBRM: Bootstrap Brute-Force Model
[b] N-ME: Numeric Maxey-Eakin Method Evaluation
[c] N-N: Nichols Method Evaluation

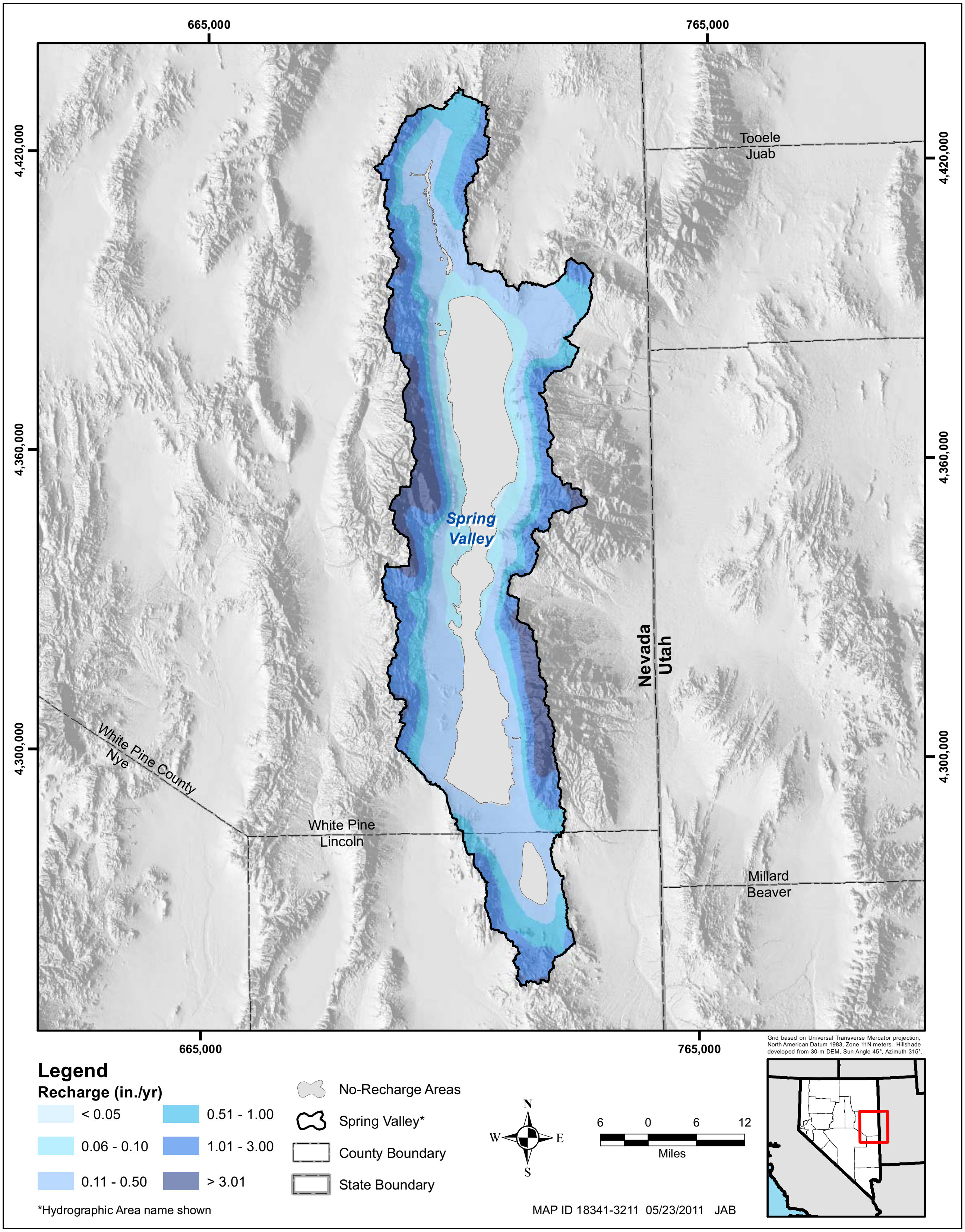

Figure 6-2
Potential Recharge Distribution for Spring Valley

6.7.2 Cave Valley

Both the annual recharge volume estimate and spatial distribution for Cave Valley can only be generated using the groundwater-balance method summarized in Section 6.6 and detailed in Appendix F.

The recharge calculations by 1-in. precipitation intervals for Cave Valley are presented in Table 6-3. The recharge distribution for this basin was derived using the recharge efficiencies of the 1-in. precipitation intervals presented in Table F-3. Table 6-3 also lists the volumes of precipitation and recharge by precipitation interval. Table 6-3 reveals that most of the recharge occurs between precipitation rates of 12 to 20 in./yr. The basin annual recharge volume estimate is 13,700 afy and the recharge efficiency for the basin as a whole is about 5 percent of precipitation.

Table 6-3
Annual Recharge Volume Calculations for Cave Valley

1-in. Precipitation Interval	Mean Precipitation Rate (in./yr)	Area (acres)	Precipitation (afy)	Recharge Efficiency (Fraction of Precipitation)	Recharge Volume (afy)
11-12	11.46	12,790	12,219	0.012	150
12-13	12.49	43,868	45,651	0.023	1,050
13-14	13.49	44,536	50,048	0.037	1,855
14-15	14.48	32,402	39,106	0.055	2,140
15-16	15.48	19,555	25,229	0.076	1,918
16-17	16.54	11,225	15,468	0.102	1,584
17-18	17.52	9,401	13,722	0.131	1,791
18-19	18.56	4,500	6,962	0.164	1,143
19-20	19.65	1,527	2,500	0.203	508
20-21	20.53	1,183	2,025	0.238	482
21-22	21.69	1,013	1,832	0.288	527
22-23	22.74	553	1,047	0.336	352
23-24	23.49	258	504	0.374	188
				Basin Total Recharge Volume[a]	**13,700**

[a]Rounded to nearest 100 afy

A comparison of the estimated annual recharge volume to previously-reported values is presented in Table 6-4. The estimated mean annual recharge volume of 13,700 afy (Table 6-3) falls within the range of reported estimates, 9,380 (BCM-Time Series, Flint et al., 2004, Table 1) and 45,913 afy (Epstein, 2004 - N-Nichols, p. 136) (Table 6-4). The estimate derived by this study is considered to be a better estimate because it is based on new information, particularly, the new estimate of groundwater ET (Section 5.0). An important observation can be made from the estimates listed in Table 6-4, the estimates derived by SNWA form a narrow range that includes the estimates reported by Scott et al. (1971, p. 48).

Table 6-4
Mean Annual Recharge estimated for Cave Valley and Previously-Reported Estimates

Source	Recharge (afy)
This Study	13,700
SNWA (2009a, p. 9-14)	15,044
Reconnaissance Reports and Scott et al. (1971, p. 48)	14,000
Kirk and Campana (1988, p. 26)	11,000-14,000
LVVWD (2001, p. 4-25) and Thomas et al. (2001, p. 6)	20,000
Epstein (2004, p. 136) - Maxey-Eakin Method Evaluation	21,838
Epstein (2004, p. 136) - Nichols-1990-Method Evaluation	32,507
Epstein (2004, p. 136) - BBRM[a]	15,166
Epstein (2004, p. 136) - N-ME[b]	13,592
Epstein (2004, p. 136) - N-N[c]	45,913
Recharge (BCM-Mean Year, Flint et al., 2004, Table 1)	10,264
Recharge (BCM-Time Series, Flint et al., 2004, Table 1)	9,380
Brothers et al. (1993, p. 45)	13,000
Welch et al. (2007, p. 44)	11,000
Mizell et al. (2007, p. 18)	33,000

[a]BBRM: Bootstrap Brute-Force Model
[b]N-ME: Numeric Maxey-Eakin Method Evaluation
[c]N-N: Nichols Method Evaluation

The estimate derived by this study is, however, very similar to the annual recharge volume of 14,000 afy reported by Scott et al. (1971) despite the approach used by Eakin (1962) to derive that estimate, the limitations of which are described in Section 3.8.1 and Section 3.8.2.

The recharge efficiencies (Table 6-3) were used to derive the spatial distribution of potential recharge presented in Figure 6-3. This map shows that groundwater recharge rates are largest on the mountains located along the eastern and western boundaries of the valley. They are lowest along the margins of the valley floor (Figure 6-3).

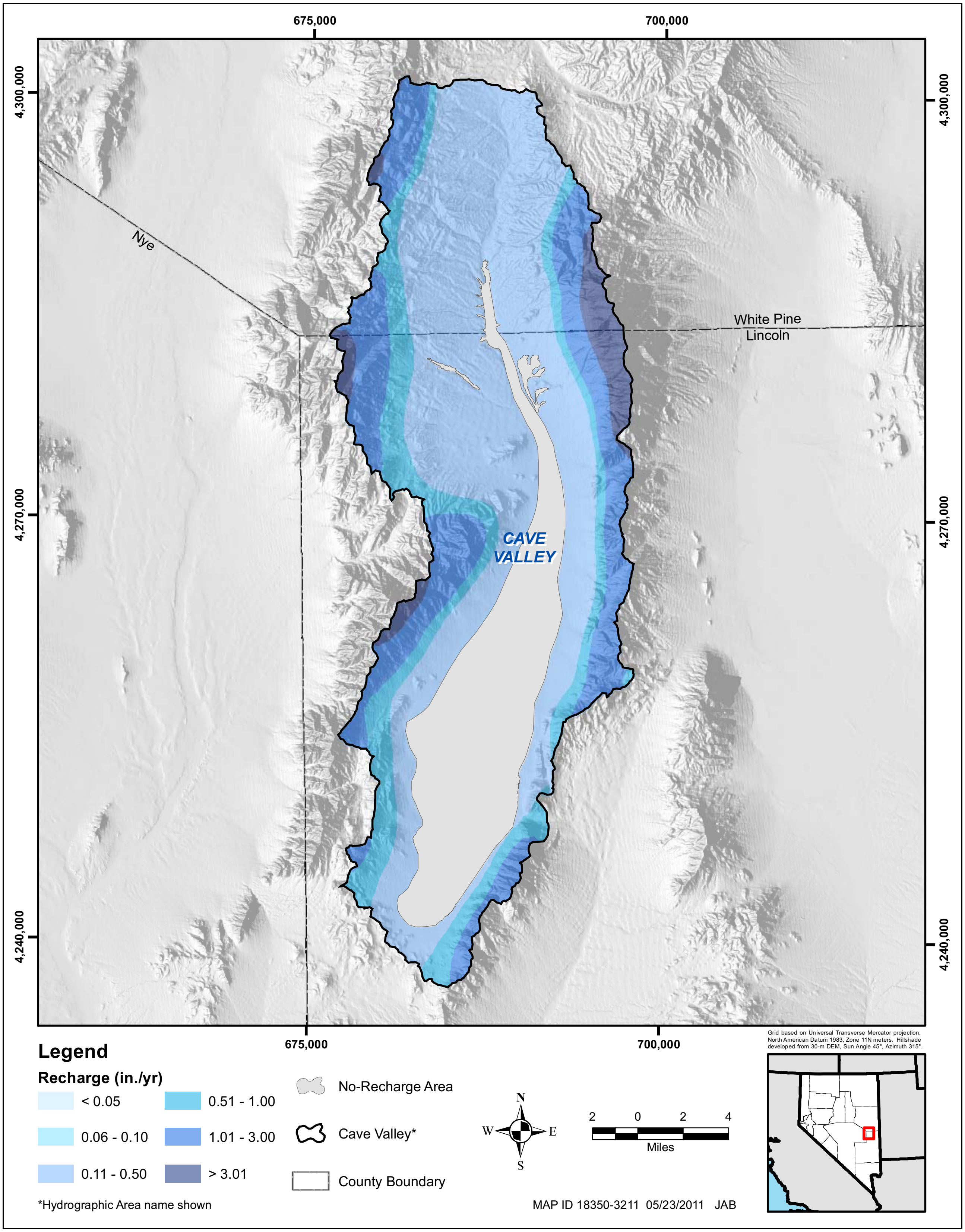

Figure 6-3
Potential Recharge Distribution for Cave Valley

6.7.3 Dry Lake and Delamar Valleys

As was the case for Cave Valley, both the annual volume estimate and spatial distributions of recharge for Dry Lake and Delamar valleys can only be generated using the groundwater-balance method summarized in Section 6.6 and detailed in Appendix F.

The 1-in. interval efficiencies (Table F-3) derived for the WRFS in Appendix F, were used to estimate the volumes of potential recharge for these two Project Basins. The recharge calculations by 1-in. precipitation interval for Dry Lake and Delamar valleys are presented in Table 6-5. The recharge estimates are 16,200 afy for Dry Lake Valley and 6,600 afy for Delamar Valley. The total recharge for these two basins is 22,800 afy, and the average recharge efficiency for the two basins together is 3 percent of the total precipitation.

Table 6-5
Recharge Volume Calculations for Dry Lake and Delamar Valleys

1-in. Precipitation Interval	Mean Precipitation Rate (in./yr)	Area (acres)	Precipitation Volume (afy)	Recharge Efficiency (Fraction of Precipitation)	Recharge Volume (afy)
Dry Lake Valley					
9-10	9.55	42,476	33,804	0.002	54
10-11	10.55	110,032	96,700	0.006	551
11-12	11.46	90,888	86,827	0.012	1,064
12-13	12.49	78,086	81,260	0.023	1,869
13-14	13.48	65,684	73,814	0.037	2,735
14-15	14.48	44,805	54,075	0.055	2,959
15-16	15.48	26,477	34,159	0.076	2,597
16-17	16.54	11,091	15,284	0.102	1,565
17-18	17.52	7,892	11,520	0.131	1,503
18-19	18.56	4,086	6,321	0.164	1,038
19-20	19.65	791	1,295	0.203	263
				Basin Total Recharge Volume[a]	**16,200**
Delamar Valley					
10-11	10.55	20,091	17,657	0.006	101
11-12	11.46	47,070	44,967	0.012	551
12-13	12.49	29,624	30,828	0.023	709
13-14	13.49	24,631	27,679	0.037	1,026
14-15	14.48	20,593	24,854	0.055	1,360
15-16	15.48	11,189	14,436	0.076	1,097
16-17	16.54	9,433	12,999	0.102	1,331
17-18	17.52	2,070	3,021	0.131	394
				Basin Total Recharge Volume[a]	**6,600**
				Dry Lake and Delamar Valleys Total Recharge Volume[a]	**22,800**

[a]Rounded to nearest 100 afy.

The derived recharge volume estimates are compared to previously- reported estimates. The combined estimate of 22,800 afy falls within the range of previously-reported combined estimates of 6,000 afy and 71,831 afy by Scott et al. (1971, p. 48) and Epstein (2004, p. 136), respectively (Table 6-6). The low estimates reported by Scott et al. (1971) are due to the limitations of the method used to estimate precipitation volumes for the Maxey-Eakin recharge-efficiency zones, and the inaccuracies inherent in the Hardman map (see Section 3.8.1 and Section 3.8.2).

Table 6-6
Mean Annual Recharge Estimated for Dry Lake and Delamar Valleys and Previously-Reported Estimates in afy

Source	Dry Lake Valley (HA 181)	Delamar Valley (HA 182)	Total
This Study	16,200	6,600	22,800
SNWA (2009a, p. 9-14)	16,208	6,627	22,835
Reconnaissance Reports and Scott et al. (1971, p. 48)	5,000	1,000	6,000
Kirk and Campana (1988, p. 26)	7,500	2,000	9,500
LVVWD (2001, p. 4-25) and Thomas et al. (2001, p. 6)	13,000	5,000	18,000
Epstein (2004, p. 136) - Maxey-Eakin Method Evaluation	9,159	3,119	12,278
Epstein (2004, p. 136) - Nichols-1990-Method Evaluation	28,559	12,930	41,489
Epstein (2004, p. 136) - BBRM[a]	20,187	10,248	30,435
Epstein (2004, p. 136) - N-ME[b]	8,947	3,567	12,514
Epstein (2004, p. 136) - N-N[c]	50,389	21,442	71,831
Recharge (BCM-Mean Year, Flint et al., 2004, Table 1)	10,627	7,764	18,391
Recharge (BCM-Time Series, Flint et al., 2004, Table 1)	11,298	6,404	17,702
Brothers et al. (1996, p. 45)	5,000	1,000	6,000

[a]BBRM: Bootstrap Brute-Force Model
[b]N-ME: Numeric Maxey-Eakin Method Evaluation
[c]N-N: Nichols Method Evaluation

The recharge efficiencies listed in Table 6-5 were used to derive a spatial distribution of potential recharge for the two basins (Figure 6-4). In Dry Lake Valley, the calculated groundwater recharge rates are largest on the mountains located in the northern tip of the valley and along the eastern boundary. In Delamar, the largest recharge rates occur along the eastern boundary of the basin. As expected, they are lowest at lower elevations, along the alluvial aprons of the basins (Figure 6-4).

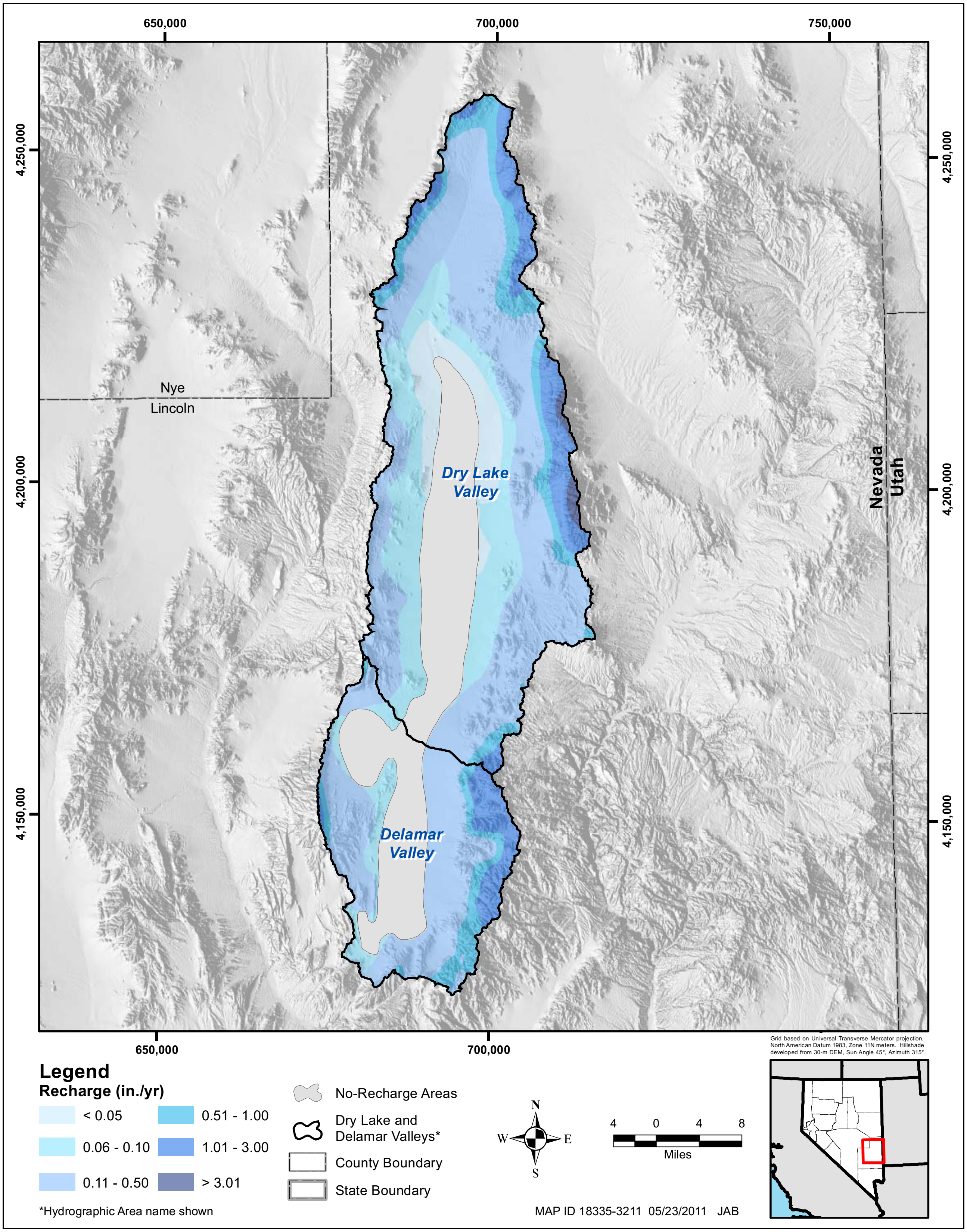

Figure 6-4
Potential Recharge Distribution for Dry Lake and Delamar Valleys

6.8 Summary and Conclusions

Estimates of annual recharge volumes were derived for Spring, Cave, Dry Lake, and Delamar valleys, using the groundwater-balance method coupled with an optimization method implemented in the Excel® Solver (see Appendices F and G for details). The resulting annual recharge volumes are summarized in Table 6-7, along with previously-reported ranges of estimates for comparison. As shown in Table 6-7, all calculated annual recharge volumes fall within the ranges of previous estimates.

Table 6-7
Comparison of Recharge Estimates for Project Basins to Reported Ranges in afy

HA Number	HA Name	This Study	Reported Value		Source
			Minimum	Maximum	
184	Spring Valley	99,200	53,335	139,194	Epstein (2004, p. 136)[a]; Epstein (2004, p. 136)[a]
180	Cave Valley	13,700	9,380	45,913	Flint et al. (2004, Table 1)[b]; Epstein (2004, p. 136)[a]
181	Dry Lake Valley	16,200	5,000	50,389	Scott et al. (1971, p. 48); Epstein (2004, p. 136)[a]
182	Delamar Valley	6,600	1,000	21,442	Scott et al. (1971, p. 48); Epstein (2004, p. 136)[a]

[a]Numeric Nichols Method
[b]BCM-Time Series

In conclusion, the recharge estimates derived as part of this study, are considered the best available because they are based on new and better information, including a more representative spatial distribution of precipitation, new estimates of groundwater ET supported by field data and satellite imagery, new estimates of boundary flow based on the best data available to date, and a numerical solution for the groundwater balance.

7.0 INTERBASIN GROUNDWATER FLOW ESTIMATES

This section presents an evaluation of interbasin groundwater flow at the hydrographic area boundaries of the Project Basins, and provides estimates of such flow through the permeable sections of the boundaries. The evaluation of the basin boundaries and the estimates of boundary fluxes were used to derive the potential groundwater recharge distributions (Section 6.0), describe the source and movement of groundwater across the boundaries (Section 8.0), and define the groundwater budgets for each basin (Section 9.0).

The evaluation relies upon the characterization of the hydrogeologic framework at the boundaries provided by Rowley et al. (2011), and their classification of groundwater flow at the boundaries as "likely," "permissible," or "unlikely." In addition, water-level and aquifer-property data presented in Section 4.0 and Appendix C, respectively, were relied upon to derive estimates of the boundary fluxes using Darcy's Law (Freeze and Cherry, 1979). Details regarding these estimates are provided in Appendix E.

7.1 Spring Valley

Spring Valley is principally a closed groundwater basin with recharge in the surrounding mountain ranges as the source of groundwater, and ET on the valley floor as the primary mechanism of groundwater discharge. Groundwater flow into and out of the basin from adjacent basins is evaluated in this section, and is a much smaller component of the groundwater budget.

The potential for groundwater flow across the hydrographic area boundary was evaluated by Rowley et al. (2011) based on the permeability of rock units occurring at, near, and beneath the boundary, the presence of calderas, the framework geometry, and the orientation and presence of significant fault structures that might enhance or inhibit groundwater movement. Based on this evaluation, interbasin flow is unlikely to occur along the hydrographic boundaries of Spring Valley, except in four locations which are depicted on Figure 7-1. Three of the four permissible-flow boundaries are located in northern Spring Valley; two at the boundary with Tippett Valley, west and east of the Red Hills; and one at the boundary with Snake Valley to the east. A fourth permissible-flow boundary is located in southeastern Spring Valley along the Limestone Hills at the boundary with Hamlin Valley. Each of these boundaries is discussed in the following sections.

7.1.1 Northern Spring Valley and Southern Tippett Valley Boundary

The two permissible flow boundaries at the northern boundary of Spring and Tippett valleys are located on the west and east sides of the Red Hills (Figure 7-1). The presence of north-south trending normal faults at these locations may provide pathways for groundwater flow, but the direction of such flow is inconclusive due to the lack of hydraulic-head data. Due to the prevailing hydrogeologic

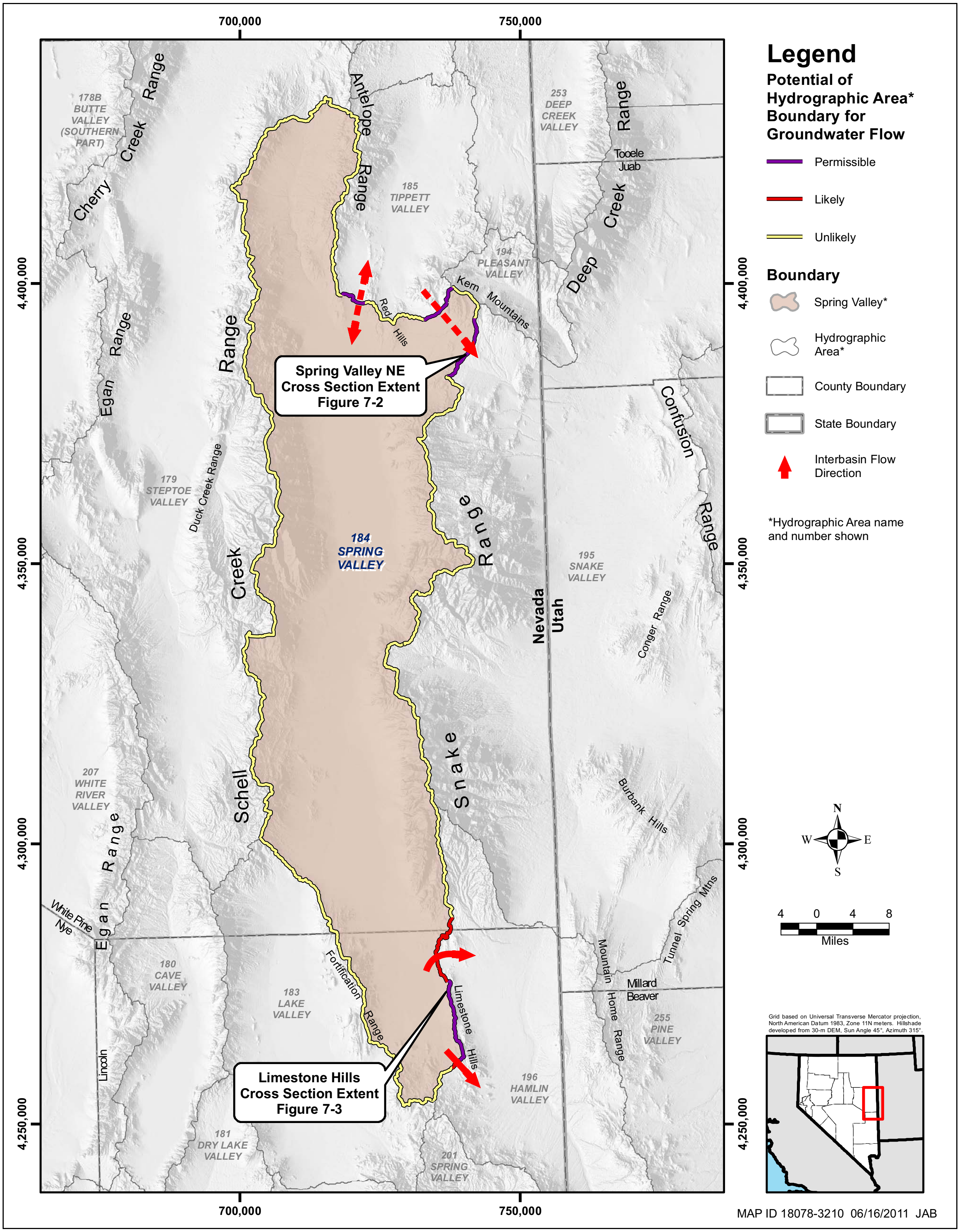

Figure 7-1
Locations of Interbasin Groundwater Flow for Spring Valley

conditions at these locations, and the possible existence of a caldera in southern Tippett Valley, as suggested by the gravity data (Rowley et al., 2011), any groundwater flow across the hydrographic area boundary would be limited. A deep basin in southern Tippett Valley is indicated by the gravity data. This basin is estimated to be as much as 18,000 ft deep, and may be in part underlain by a caldera (Rowley et al., 2011). A caldera at this location would prevent any significant groundwater flow across the boundary.

A review of the limited water-level data for wells in Tippett Valley suggest a hydraulic gradient from the northeast to the southwest. However, this is based primarily on two old BLM wells located in the south part of the valley (Plate 1; Well Map ID 185-1 and 185-3) whose water-level elevations are lower than those to the north (Plate 1; Well Map ID 185-2, 185-4 through 185-8). The uncertainty in the elevation control for these wells, and therefore, the water-level elevations, are such that the hydraulic gradient in Tippett Valley cannot be conclusively determined except for a west to east component due to the groundwater recharge that occurs within the Antelope Range. The hydraulic gradient in northern Spring Valley is north to south, but the wells located in northern Spring Valley near the boundary at the Red Hills have higher hydraulic heads than those in Tippett Valley. The available data coupled with the hydrogeologic framework presented in Rowley et al. (2011), suggest that this area is most likely a groundwater divide.

Previous investigators have differed in their interpretations of groundwater flow across this boundary. Scott et al. (1971), Harrill et al. (1988), and Brothers et al. (1994) estimated a small amount of inflow from Tippett Valley through the underlying carbonate rocks into Spring Valley; 2,000 afy by Scott et al. (1971, p. 48) and Harrill et al. (1988, p. 2), and 1,700 afy by Brothers et al. (1994, p. 55), respectively. Conversely, Welch et al. (2007, p. 84) estimated 2,000 afy of groundwater outflow from Spring Valley to Tippett Valley.

7.1.2 Northeastern Spring Valley and Western Snake Valley Boundary

The area between the southern Kern Mountains and northern Snake Range was evaluated by Rowley et al. (2011) and Mankinen and McKee (2011). The surface hydrogeology of the area and a profile along the hydrographic area boundary is depicted in Figure 7-2. Granitic rocks of the Kern Mountains form the northern extent of the profile, and Precambrian-Cambrian siliciclastic rocks of the lower Snake Range form the southern extent. In between, carbonate rocks separated by the Chainman Shale confining unit are present. Overlying these rocks are Tertiary volcanic rocks and younger sediments. Groundwater flow through the younger sediments (QTs) and along the inferred northwest-southeast trending fault is permissible; however, the presence of north-south trending faults would impede any significant groundwater flow in the west-east direction (Rowley et al., 2011).

Water-level data in this area are inadequate to derive a representative hydraulic gradient and, consequently, an estimate of interbasin groundwater flow was not calculated. The source of groundwater in this area would be derived locally within the northern part of the Snake Range with perhaps some component from the Kern Mountains. Based on the hydrogeologic framework and gravity data, a minor amount of outflow from Tippett Valley might pass through the northeastern part of Spring Valley to this area, but as described in the previous section, this volume would be minor and limited by the caldera in southern Tippett Valley. It is unlikely that flow from eastern Spring Valley

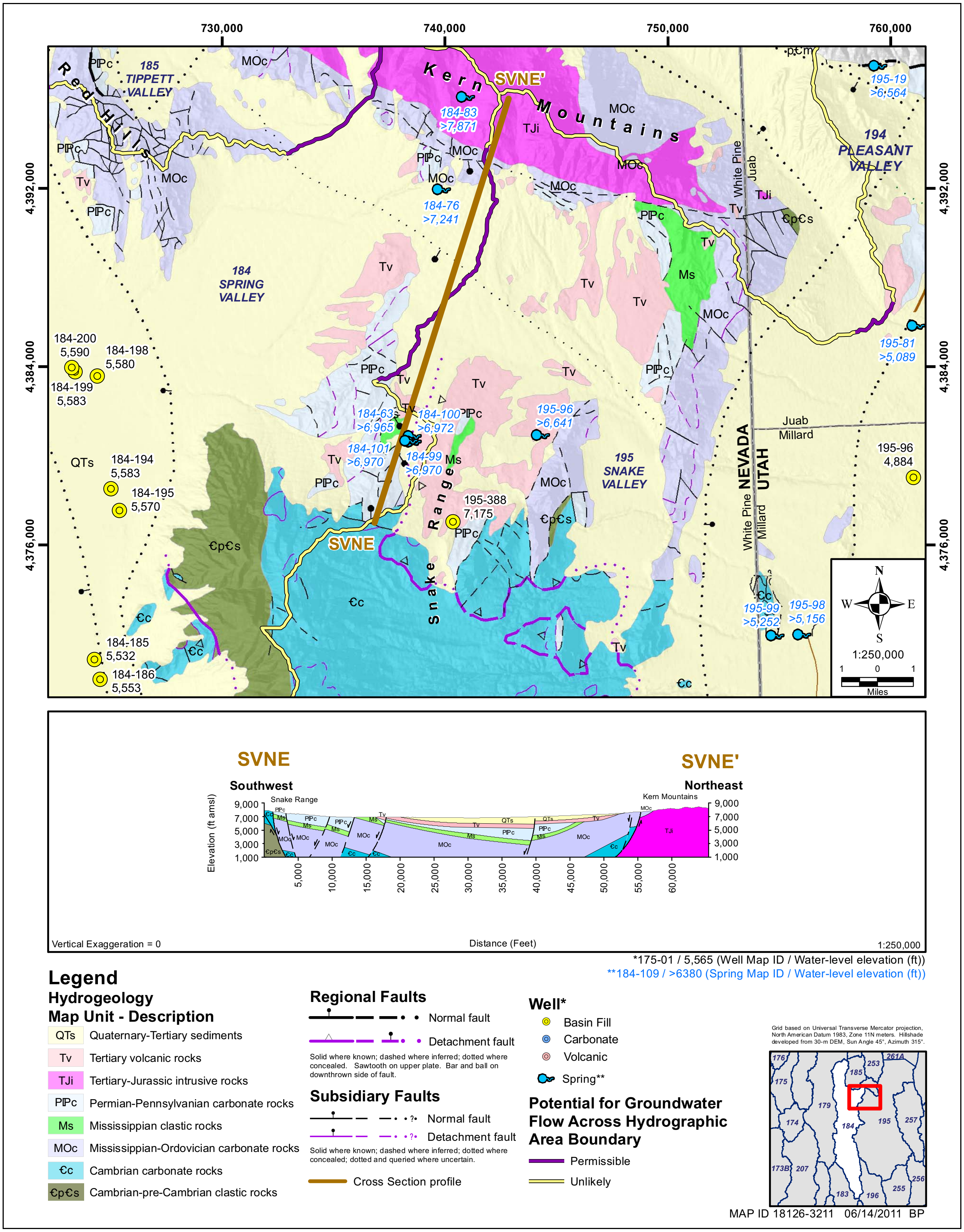

Figure 7-2
Interbasin Groundwater Flow from Spring Valley to Snake Valley

would flow to this area due to the presence of the Precambrian-Cambrian siliciclastic rocks forming the base of the western range front of the Snake Range and the associated range-front fault and subsidiary faults that extend to the north and west of the Red Hills. The gravity data indicate that a buried ridge extending to the southern Red Hills is present along this range-front fault (Mankinen and McKee, 2011, p. 20; Rowley et al., 2011, p. 5-10). Basin-fill water levels indicate a gradient to the south and west, towards the groundwater discharge areas rather than the area between the Kern Mountains and north Snake Range. Therefore, it is concluded here that there is no groundwater flow from Spring Valley to Snake Valley except for possibly some minor amount of flow from Tippett Valley passing through the northeastern part of the Spring Valley to western Snake Valley. This amount is thought to be minor, and the groundwater that occurs in this area is locally derived from the northern Snake Range and possibly the southern Kern Mountains. This is corroborated by Gillespie (2008, p. 37) who analyzed geochemistry data to evaluate the potential for this area to be a groundwater flow path (from Spring Valley to Snake Valley), and determined that such a flow path is unlikely.

Previous investigators have estimated flow through this area as a means to balance their postulated groundwater budgets: Nichols (2000, p. C28) estimated 4,000 afy; Katzer and Donovan (2003, p. 62) estimated 6,000 afy; and Welch et at. (2007, p. 73) estimated 16,000 afy.

7.1.3 Southeastern Spring Valley and Hamlin Valley Boundary

In southeast Spring Valley, groundwater flows across the hydrographic area boundary with Hamlin Valley at the Limestone Hills (Figure 7-1). The hydrogeology of this area was evaluated by Rowley et al. (2011) to assess the possible flow paths connecting Spring and Hamlin valleys, and incorporated new well data, field mapping and geophysical studies. The surface hydrogeology of the area and a profile oriented perpendicular to the presumed flow path are presented in Figure 7-3. The Limestone Hills is a north-south oriented horst of carbonate rocks bounded on each side by range-front and subsidiary faults. Underlying these carbonate rocks are the Precambrian-Cambrian siliciclastic rocks that form the lower confining unit. Based on the line of section presented in Figure 7-3, the thickness of the carbonate rocks is estimated to range between 4,000 and 6,000 ft. In the north, Tertiary volcanic rocks overlie the carbonate rocks. Groundwater flow across the hydrographic area is considered likely at the northern and southern parts of the Limestone Hills, and permissible in between.

Groundwater flow at the north and south ends of the Limestone Hills is likely due to the presence of minor east-west oriented normal faults that cross-cut through the Limestone Hills. The northern location is located at a topographically lower section of the Limestone Hills commonly referred to as “The Troughs”. The southern location is just north of the intersection of the Limestone Hills with the boundary of the Indian Peak Caldera Complex. Groundwater flow through the Limestone Hills, between the north and south areas of likely flow, is permissible given the presence of carbonate rocks; however, this flow is significantly limited by the bounding range-front faults on each side of the Limestone Hills, and the low hydraulic conductivity of the carbonate rocks that comprise them. The hydraulic conductivity of the bulk properties of the carbonate rocks comprising the Limestone Hills is likely orders of magnitude smaller than the faulted and fractured carbonate rocks of the north and south boundaries.

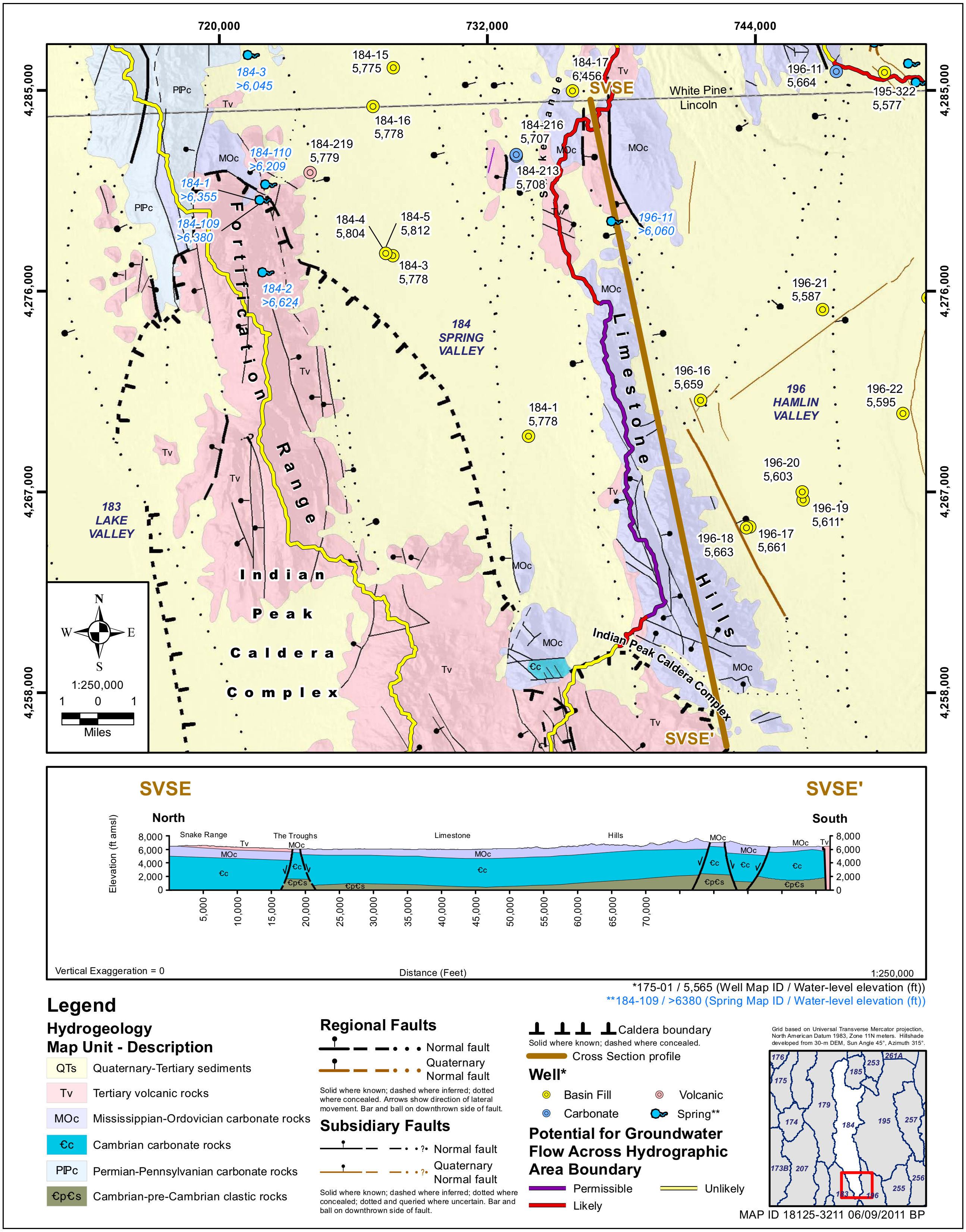

Figure 7-3
Interbasin Groundwater Flow from Spring to Hamlin Valley

The rates of groundwater outflow through the north and south ends of the Limestone Hills were calculated using Darcy's law (Equation E-1), as described in Appendix E. Data requirements for these calculations consist of estimates of the horizontal hydraulic gradient across the boundary, hydraulic conductivity, and flow section thicknesses and lengths.

The direction of groundwater flow and an estimate of the hydraulic gradient in the carbonate aquifer across the Limestone Hills was derived from the available water-level data. Water-level elevation data are presented in Figure 7-3 and confirm a west to east hydraulic gradient across the Limestone Hills. Basin-fill water levels are approximately 100 to 200 ft higher in Spring Valley than they are in Hamlin Valley. Based on hydraulic heads measured in two carbonate wells on either side of the Limestone Hills (184W502M - Map ID 184-216; and 195 N09HE70 32 BBA 1 Big Spring SW - Map ID 196-11), the potential across the boundary is approximately 43 ft. A hydraulic gradient of 0.0008866 ft/ft for the carbonate aquifer was calculated using the potential defined by the two carbonate wells and the approximate distance between them of 48,500 ft.

Estimates of hydraulic conductivity were derived from hydraulic tests conducted by SNWA in Spring Valley. In 2007, SNWA performed hydraulic testing of test well 184W101 (Map ID 184-213) in the southeast portion of Spring Valley. The test well was completed in carbonate rocks of the same formation as those comprising the Limestone Hills to a depth of approximately 1,749 ft bgs. A hydrogeologic evaluation of the site indicated the presence of a fault structure, the penetration of which was an objective of the well-drilling and hydraulic testing program. The associated observation well (184W502M - Map ID 184-216), located approximately 175 ft from the test well, was drilled to a total depth of 1,828 ft bgs and also penetrated the targeted fault structure, but encountered a higher density of open fractures. The data from a 72-hour constant-rate aquifer test were analyzed using both the Barker Generalized Radial Flow Model (Barker GRFM) dual-porosity and the Cooper-Jacob analytical solutions (Prieur et al., 2010a). The primary solution (Barker GRFM) yielded composite hydraulic conductivity values ranging from 7.6 to 8.0 ft/d using a saturated thickness equal to the length of the saturated interval of the borehole. Based on these results, a rounded value of 8 ft/d was used in the Darcy-flux calculation.

A saturated aquifer thickness of 2,000 ft was used for both boundary segments based on the assumption that the majority of the flow occurs in this section, and that below the equivalent depth of this thickness, the hydraulic conductivity is significantly reduced due to overburden pressure. The length of the northern flow section was estimated to be approximately 30,000 ft based on the orientation and displacement of the east-west faults. The length of the southern flow section was estimated to be approximately 6,500 ft.

Using Darcy's law, as expressed in Appendix E (Equation E-1), boundary fluxes at the northern and southern boundary flow sections of the Limestone Hills were calculated to be 3,600 afy and 800 afy, respectively. The calculations are summarized in Table 7-1.

Groundwater flow through the Limestone Hills between the north and south boundary segments is assumed to be minimal due to the limiting nature of the north-south trending range-front faults and low hydraulic conductivity of the bulk material. Therefore, the estimated flow from Spring Valley to Hamlin Valley is 4,400 afy.

Table 7-1
Spring Valley to Hamlin Valley Interbasin Flow Estimate

Boundary Segment	Hydraulic Conductivity (ft/d)	Flow Section Width (ft)	Aquifer Saturated Thickness (ft)	Hydraulic Gradient (ft/ft)	Groundwater Flow (afy)
North	8	30,000	2,000	0.0008866	3,600
South	8	6,500	2,000	0.0008866	800

Rush and Kazmi (1965, p. 24) estimated groundwater flow through the Limestone Hills at 4,000 afy using an assumed transmissivity and hydraulic gradient for the basin fill. Nichols (2000, p. C34) estimated a flow range of 8,000 to 12,000 afy after concluding the hydraulic conductivity should be 2 to 3 times higher than that implied by the Rush and Kazmi (1965) transmissivity value. An extraordinary flow of 33,000 afy was estimated by Welch et al. (2007, p. 73), and is an artifact of an imbalance in the groundwater budget compiled by BARCASS for Steptoe Valley. The imbalance required that excess recharge be shunted to adjacent basins resulting in 33,000 afy directed through southern Steptoe Valley to northern Lake Valley, through the basin fill and then the Fortification Range, and into southern Spring Valley and through the Limestone Hills.

7.2 Cave Valley

Groundwater outflow from Cave Valley must be significant as there is limited groundwater discharge in the basin, but substantial recharge in the surrounding mountain ranges. The potential for groundwater flow across the hydrographic area boundary was evaluated by Rowley et al. (2011), and two locations where groundwater flow is likely or permissible were identified. The first location is at the boundary with White River Valley at Shingle Pass in the Egan Range on the west side of the basin. The second location is in southern part of the basin at the boundary with Pahroc Valley. These locations are shown in Figure 7-4. Elsewhere, groundwater is confined to the basin by the range-front faults on the east and west sides of the valley, and the impermeable nature of the Mississippian Chainman Shale and Precambrian-Cambrian siliciclastic rock confining units within the Egan and Schell Creek ranges.

Groundwater discharge within Cave Valley is limited to the 1,300 afy of groundwater ET that occurs in the northern half of the basin as described in Section 5.0. Groundwater recharge is estimated to be 13,700 afy as described in Section 6.0, with 1,300 afy of that supplying the groundwater ET. The remaining amount, 12,400 afy, is groundwater outflow to White River Valley to the west and Pahroc Valley to the south. The partitioning of this total outflow is described in the following sections.

7.2.1 Cave Valley and White River Valley Boundary at Shingle Pass

Groundwater outflow from Cave Valley to the southern third of White River Valley occurs through carbonate rocks that have been faulted and fractured by the Shingle Pass fault. The fault is a northeast-trending, oblique-slip fault that cuts through upper Paleozoic carbonate rocks on its north side, and lower Paleozoic rocks on its south side (Rowley et al., 2011). The fractured rocks resulting from the faulting provide a likely flow path along the fault from Cave Valley to White River Valley. The volume of flow was approximated in two ways: (1) by equating it to the downgradient spring

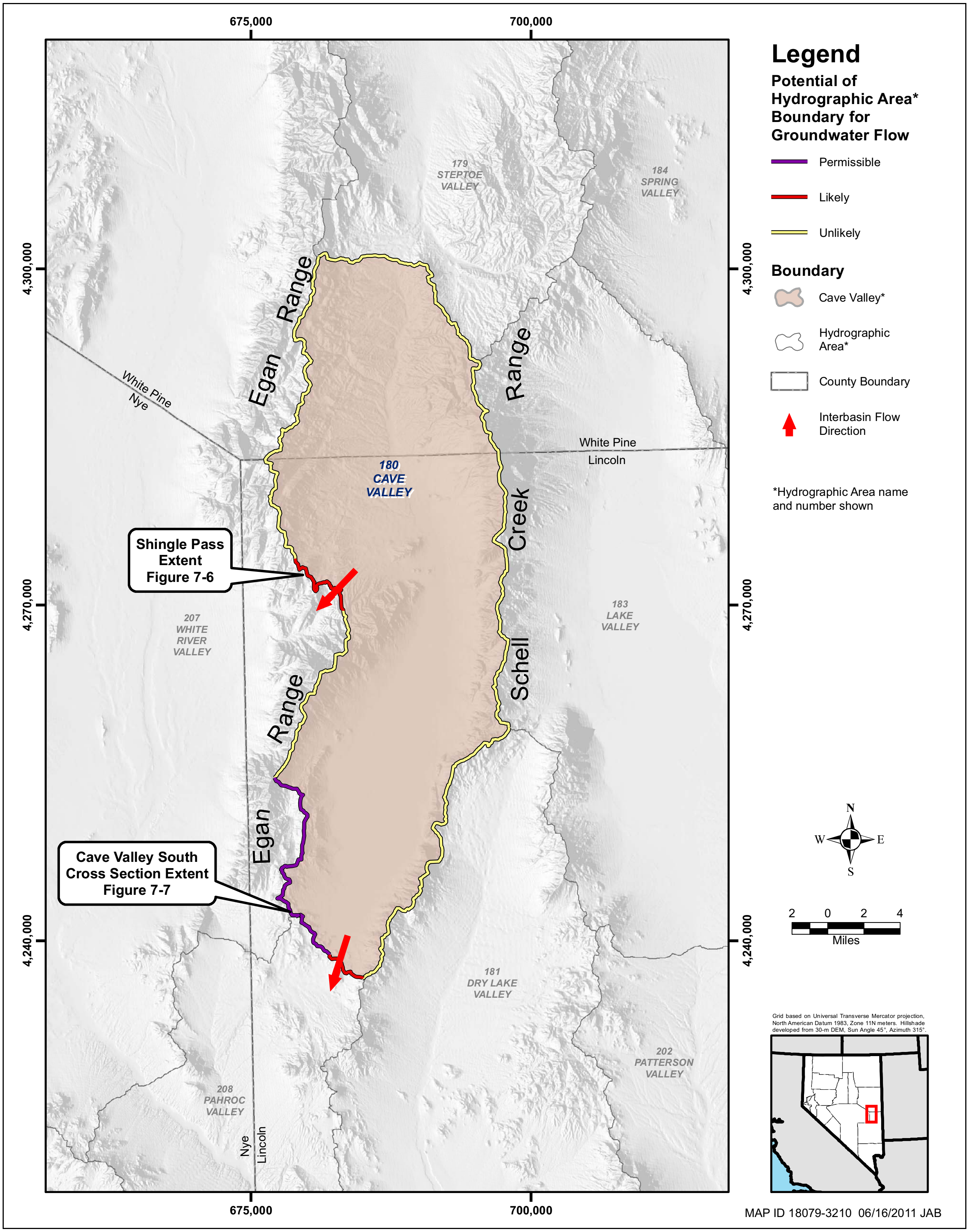

Figure 7-4
Location of Interbasin Groundwater Flow for Cave Valley

discharge minus the recharge from the contributing watersheds in White River Valley and, (2) by estimating the volume of recharge contributing to the flow based on the potential recharge distribution in Cave Valley and features of the hydrogeologic framework affecting its movement.

The springs selected to derive the downgradient spring discharge volume used in the first calculation are listed in Table 7-2 and are depicted in Figure 7-5. These springs were selected because they are cold-water springs (i.e., local springs) and have similar isotopic compositions to springs in the Egan Range and Cave Valley. These are indications that the sources of their respective discharges are derived from local recharge in these areas. The total discharge from these springs is approximately 7,300 afy.

Table 7-2
Discharge Data for Selected Springs in White River Valley

Spring Name	Location[a, b] UTM Easting (m)	Location[a, b] UTM Northing (m)	Elevation[a] (ft amsl)	No. of Measurements[b]	Mean Annual Discharge (cfs)[b]	δD[c] (‰)
Flag Springs 3	672,579	4,254,416	5,294	48	2.2	-105
Flag Springs 2	672,576	4,254,570	5,285	51	2.9	NA
Flag Springs 1	672,719	4,254,696	5,294	44	2.3	NA
Butterfield Spring	673,530	4,256,472	5,324	46	2.7	-105
Shingle Spring	679,925	4,267,716	6,434	4	0.002	-104
				Total	**10.10 (7,312 afy)**	---

[a]Coordinates use the Universal Transverse Mercator (UTM) North American Datum of 1983 (NAD83), Zone 11; elevations use the North American Vertical Datum of 1988 (NAVD88).
[b]Data from Section C.3.2 of Appendix C.
[c]USGS (2011).

Based on the recharge analysis presented in Section 6.0 and Appendix F, the potential recharge of the contributing watersheds in White River Valley was calculated to be about 3,500 afy (Figure 7-5). It is assumed that this estimate of recharge is sufficiently accurate for the purpose for which it is used here. It is acknowledged that the recharge value estimated for this area could be more or less, depending on the accuracy of the precipitation-recharge relationship defined in Appendix F. The outflow from Cave Valley to White River Valley through Shingle Pass, calculated as the difference of the spring discharge and the recharge from the contributing watersheds in White River Valley, is estimated to be approximately 3,800 afy.

In the second calculation, the recharge occurring on the northwestern side of Cave Valley, located just upgradient of Shingle Pass, is assumed to be the source of the outflow to southern White River Valley (Figure 7-5). This assumption is supported by the hydrogeologic framework in which the Shingle Pass fault extends northward and is assimilated into the eastern range-front fault of the north Egan Range. A second fault extending northeast from its intersection with the Shingle Pass fault may also contribute flow from the north-central part of the basin. This area is a shallow graben formed by these two faults, and it is assumed that the recharge occurring in this area contributes to the flow along the faults and through Shingle Pass, and is the source of groundwater ET that occurs there.

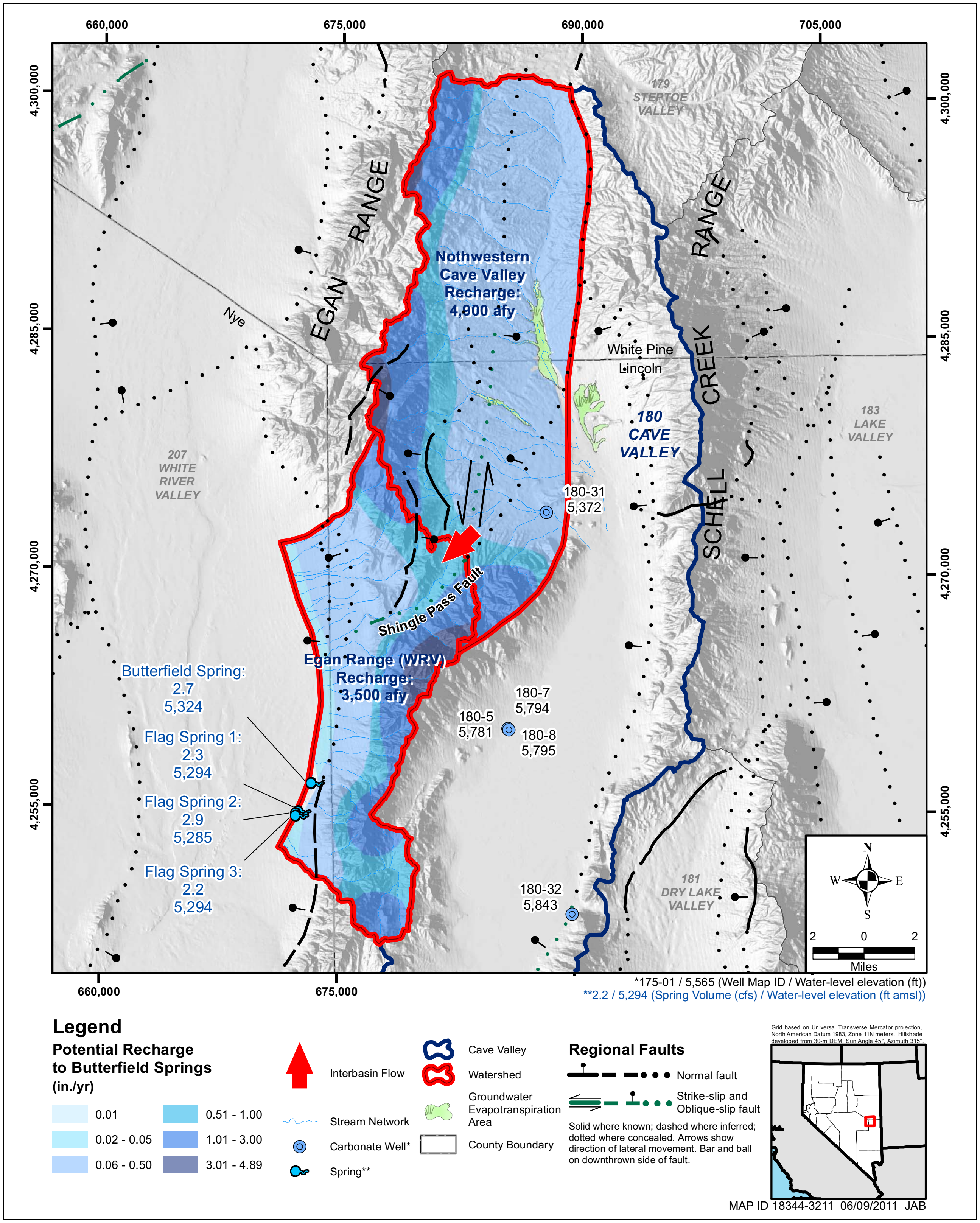

Figure 7-5
Watersheds in Cave and White River Valleys Used to Estimate Outflow through Shingle Pass

The potential recharge distribution derived for Cave Valley (Section 6.0 and Appendix F) was used as the basis to calculate the recharge of the contributing watersheds in the northwestern portion of Cave Valley. The recharge value was calculated to be about 4,900 afy for the watersheds depicted in Figure 7-5. Approximately 1,100 afy of this recharge is consumed by groundwater ET occurring in the northwestern portion of Cave Valley, leaving about 3,800 afy to flow out of Cave Valley through Shingle Pass. This estimate of the outflow is the same as the one previously calculated as the difference between the total discharge of the springs in Table 7-2 and the recharge of the watershed in southern White River Valley depicted in Figure 7-5.

To further check the validity of this estimate, an inverse Darcy flux calculation was performed to derive the corresponding transmissivity value and evaluate its reasonableness using the estimated value of 3,800 afy.

The transmissivity value of the rocks comprising the flow path across Shingle Pass was calculated by using Darcy's law expressed in the following form:

$$T = \frac{Q}{IW} \times \frac{43560}{365} \qquad \text{(Eq. 7-1)}$$

where,

Q = Groundwater flowrate (afy)
T = Transmissivity (ft^2/d)
I = Horizontal hydraulic gradient (ft/ft)
W = Width of flow section (ft)

The horizontal hydraulic gradient was calculated using the following data: (1) the water-level elevation (5,372 ft amsl) of monitor well 180W501M (Figure 7-5 - Well Map ID 180-31), drilled by SNWA and completed in carbonate bedrock just east of Shingle Pass, (2) the elevation of Butterfield Spring (5,324 ft amsl), and (3) the distance between the two locations of about 14 mi or about 74,000 ft. The hydraulic gradient between these two locations was calculated to be 0.00065 ft/ft. The west entrance to Shingle Pass in White River Valley (Figure 7-6) was assumed to be the width of the flow section and was estimated to be about one mile across, or 5,280 ft. Using these values, a transmissivity of 132,139 ft^2/d was calculated. This value falls within the reported range of transmissivity estimates for carbonate wells within the region. The reported estimates range from 5.6 to 1,000,000 ft^2/d with a geometric mean of 2,213 ft^2/d (based on data described in Appendix C). Higher flow values would yield yet higher apparent transmissivities.

Based on these estimates, the volume of local recharge within the White River Valley side of the Egan Range (3,500 afy) plus the estimated groundwater outflow from Cave Valley through Shingle Pass (3,800 afy) is sufficient to supply the spring discharge observed at the downgradient springs in White River Valley that are listed in Table 7-2. The sources of these springs are the recharge areas delineated on Figure 7-5, which is corroborated by the isotopic data presented and analyzed by Thomas and Mihevc (2011, p. 28) and is consistent with the hydrogeologic framework description

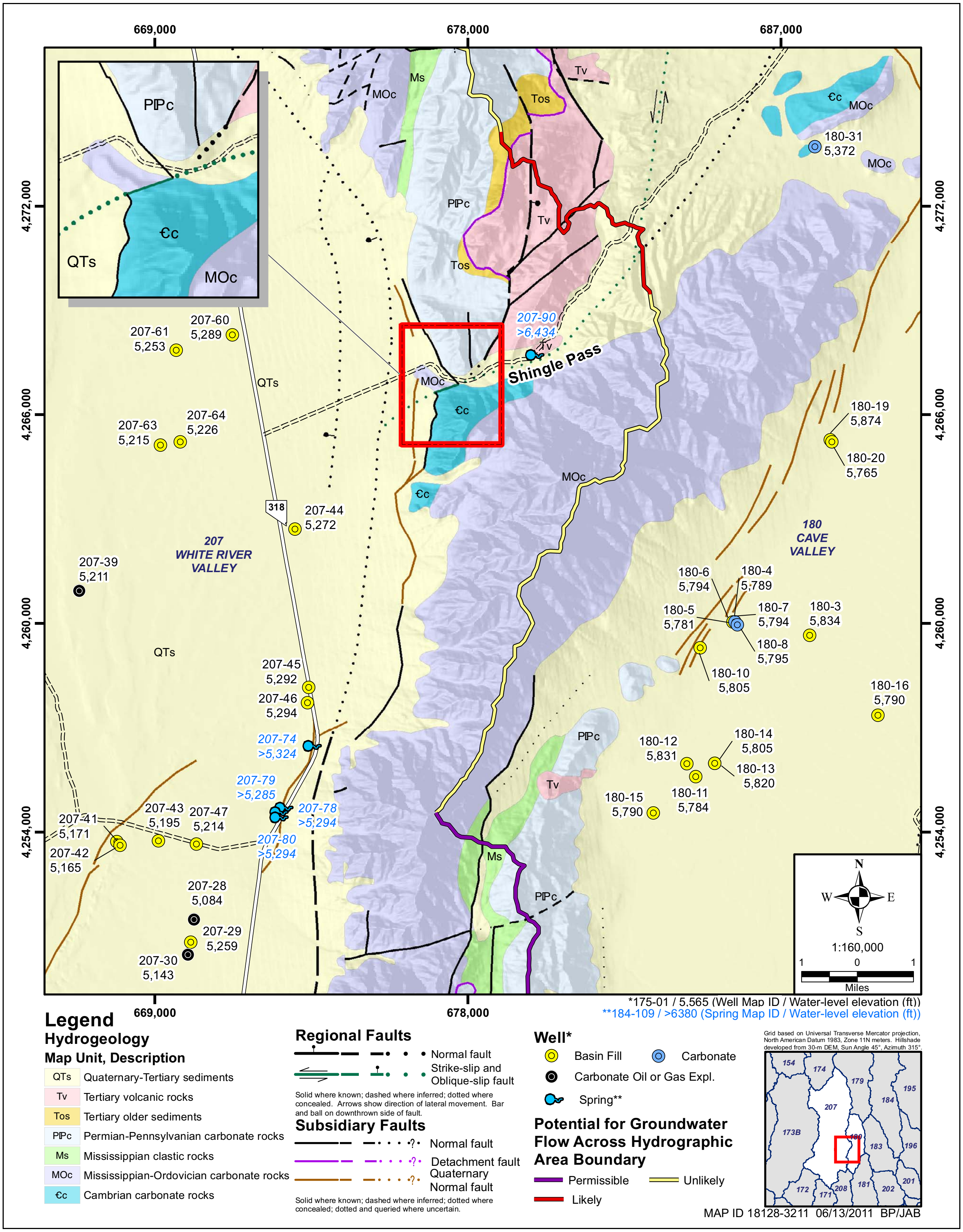

Figure 7-6
Interbasin Groundwater Flow from Cave Valley to White River Valley

presented in Rowley et al. (2011). It is also likely that there is a flow contribution from sources upgradient of these recharge areas, that flows north to south along the prevailing hydraulic gradient.

Previous investigators have recognized the hydrogeologic significance of Shingle Pass and have also estimated groundwater flow through this area or the Egan Range to the south. Eakin (1962, p. 13), Eakin (1966, p. 265), Harrill et al. (1988, p. 2), and Scott et al. (1971, p. 48) all reported 14,000 afy of interbasin flow through Shingle Pass. LVVWD (2001, p. 6-3) reported 15,000 afy of interbasin flow in that location.

7.2.2 Southern Cave Valley and Northern Pahroc Valley Boundary

Outflow from southern Cave Valley to the northeastern portion of Pahroc Valley occurs through fractured carbonate rocks and along fault zones associated with the west range-front fault of the southern Schell Creek Range. The series of north-northeast-trending, left-lateral oblique-slip faults provide likely groundwater flow paths from southern Cave Valley to northern Pahroc Valley (Figure 7-7). Of the 13,700 afy of recharge derived locally within the basin, 1,300 afy is consumed by groundwater ET in the northern half of the basin, 3,800 afy is estimated to flow through Shingle Pass to White River Valley, and the remainder, 8,600 afy, is interbasin flow to northern Pahroc Valley.

The estimated groundwater outflow of approximately 8,600 afy from Cave Valley to Pahroc Valley is close to the low end of the range of reported literature values, but falls outside the range. Kirk and Campana (1988, p. 29-31) reported 11,000 to 14,000 afy of interbasin flow from southern Cave to northern Pahroc Valley.

7.3 Dry Lake and Delamar Valleys

Dry Lake and Delamar valleys can be considered a single basin based on the hydrogeologic framework described in Rowley et al. (2011), the isotopic data and analysis presented in Thomas and Mihevc (2011, p. 22), and an evaluation of the water-level and spring data presented in Section 4.0 and Appendix C. For the following discussion on interbasin flow, the two basins are combined.

The potential for groundwater flow across the hydrographic area boundaries of Dry Lake and Delamar valleys was evaluated by Rowley et al. (2011), and based on this evaluation groundwater flow is unlikely to occur except in the locations depicted on Figure 7-8. Groundwater flow is permissible across the northern boundary of Dry Lake and Lake valleys and a portion of the western boundary of Dry Lake and Pahroc valleys. Groundwater flow is likely across the boundary of Dry Lake and Delamar valleys, and across the southern boundaries of Delamar Valley and northern Coyote Spring and southern Pahranagat valleys.

7.3.1 Northern Dry Lake Valley and Lake Valley Boundary

Rowley et al. (2011) characterize groundwater flow at the northern boundary of Dry Lake and Lake valleys as permissible due to the potential flow paths created by the range-front faults of the Schell Creek and Fairview Ranges that converge at this location. However, groundwater recharge within

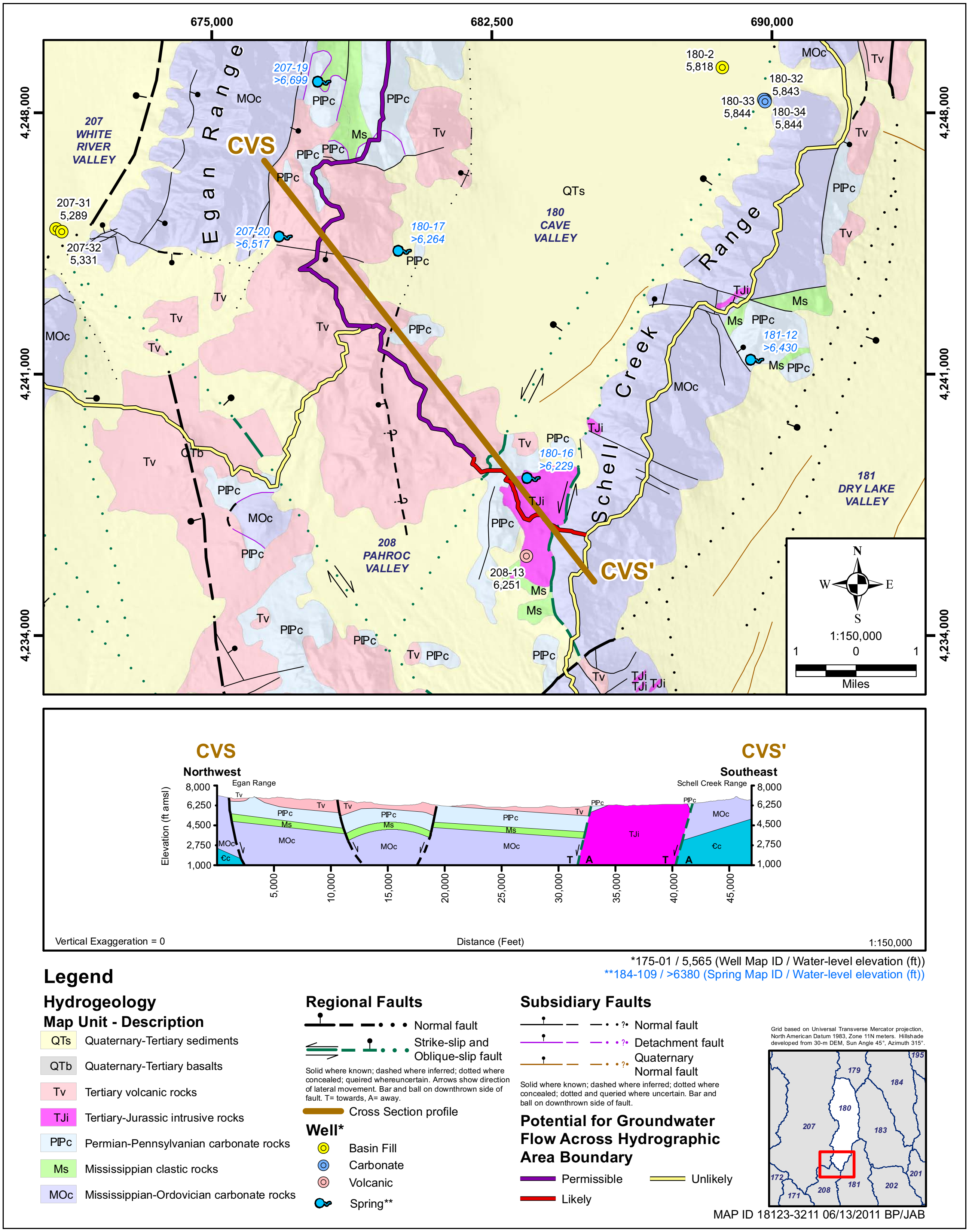

Figure 7-7
Interbasin Groundwater Flow from Cave Valley to Pahroc Valley

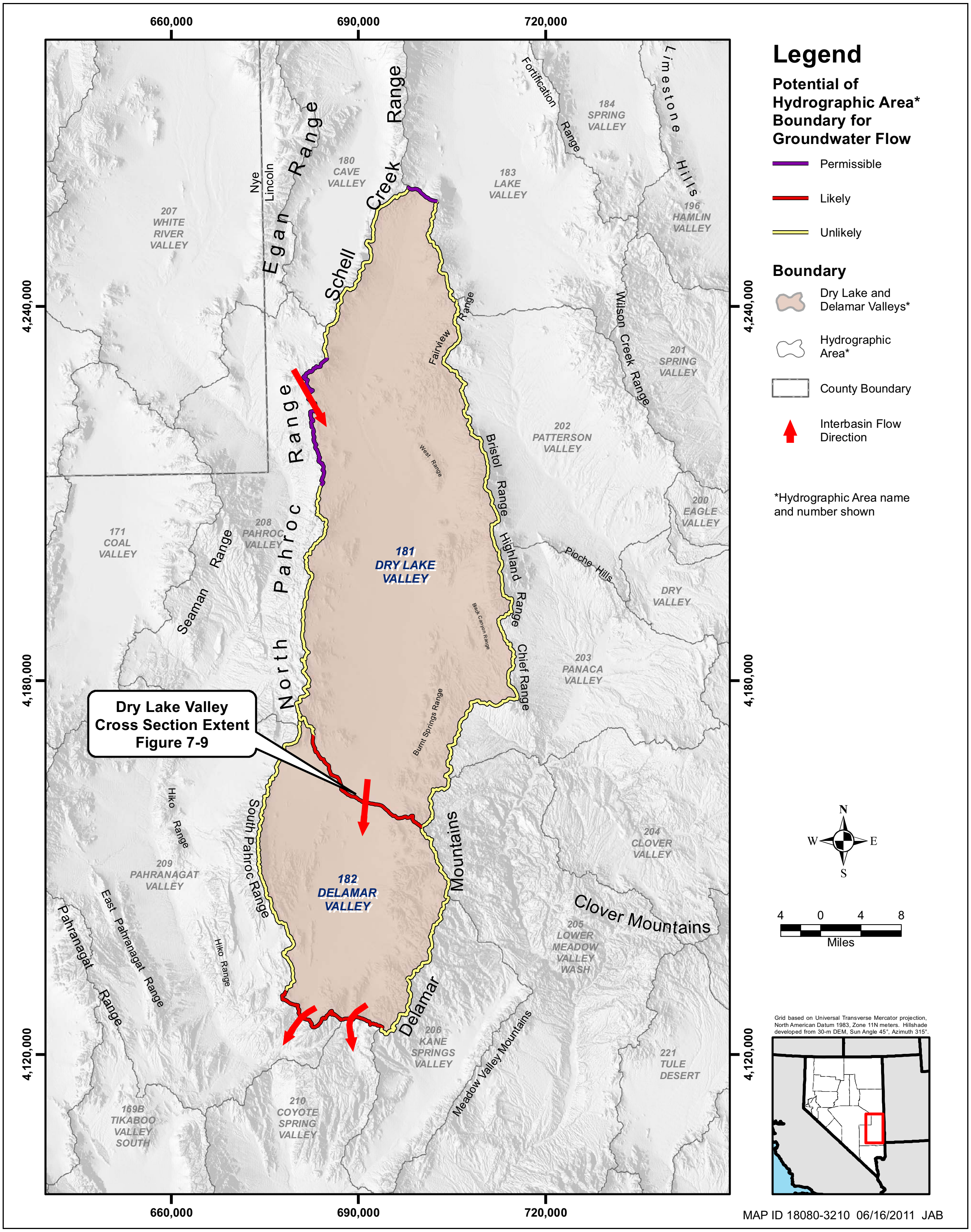

Figure 7-8
Locations of Interbasin Flow for Dry Lake and Delamar Valleys

these ranges coupled with the presence of the Mississippian Chainman Shale confining unit at depth create a groundwater divide that is corroborated by the available water-level data.

7.3.2 Northwestern Dry Lake Valley and Pahroc Valley Boundary

South of Cave Valley, the Egan Range to the west, the Schell Creek Range to the east, and the North Pahroc Range to the south all converge to form the boundary of northern Pahroc and northwestern Dry Lake valleys (Figure 7-8). The geology is comprised Paleozoic carbonate rocks, some of which are covered by volcanic rocks of Tertiary age. This is an area of complex faulting with northeast-trending, left-lateral oblique-slip faults extending from southern Cave Valley to northern Pahroc Valley where they intersect a series of northwest-trending, right-lateral oblique-slip faults. These faults extend from the western range-front fault of the southern Egan Range in White River Valley, to the southeast and into Dry Lake Valley where they are assimilated into the eastern range-front fault of the North Pahroc Range. The extensive faulting in this area likely controls the movement of groundwater by providing flow paths that allow groundwater to flow from southern Cave and southern White River valleys to northern Pahroc Valley, and from northern Pahroc Valley to northwestern Dry Lake Valley.

There are no wells completed in the carbonate rocks in northern Pahroc Valley, but there is a carbonate well, North Dry Lake MX, in northwestern Dry Lake Valley located between the two northwest-trending right-lateral oblique-slip faults. The hydraulic head in this well is less than those in the surrounding wells in southern Cave and White River valleys and northern Pahroc Valley, inferring a regional gradient to the southeast and support for the described flow paths.

Due to the lack of hydraulic-head data for the carbonate aquifer in this area, a boundary flux was not calculated. However, isotopic data reported in Thomas and Mihevc (2011) indicate that some amount of groundwater inflow from northern Pahroc Valley to western Dry Lake Valley must occur. The results of deuterium analyses performed on two groundwater samples collected from the North Dry Lake MX well range from -107.0 to -108 permil. These values are significantly lighter than samples collected from local springs in the area and the carbonate well on the east side of the valley recently drilled by Vidler Water Company, Inc. (Well 181 S01 E65 05DA 1 PW-1 - Well Map ID 181-27). The results of deuterium analyses performed on groundwater samples collected from these sites range from -95 to -101 permil, and reflect groundwater derived from local recharge. Deuterium values for the North Dry Lake MX well reflect a mixture of groundwater from southern Cave Valley and southern White River Valley, where the deuterium values range from -100 to -107.1 and -104 and -120 permil, respectively (Thomas and Mihevc, 2011, Appendix 1).

The hydrogeologic framework, regional hydraulic gradients, and isotopic data all support groundwater flow from northern Pahroc Valley to northwestern Dry Lake Valley. The isotopic signature of this water suggests it is a mixture of groundwater from southern Cave Valley and southern White River Valley, but the amount and the proportion can not be determined given the available data. All things considered, groundwater inflow from Pahroc Valley is estimated to be about 2,000 afy.

7.3.3 Dry Lake Valley and Delamar Valley Boundary

Dry Lake and Delamar valleys are separated by a low alluvial divide, but are geologically and hydrologically connected to essentially form one contiguous basin. Rowley et al. (2011) evaluated this area and concluded that groundwater flow is likely across this boundary through the basin-fill sediments and fractured volcanic and carbonate rocks associated with the range-front faults of the North Pahroc and Burnt Springs ranges (see Figure 7-9). Groundwater flow is enhanced in the north-south direction by these faults and the numerous subsidiary faults and fractures of the same orientation. These same faults are barriers to groundwater flow in the east-west direction (Rowley et al., 2011). Based on water-level elevations for wells located within the basins, there is a north to south gradient, indicating outflow from Dry Lake Valley to Delamar Valley. Because there is no significant groundwater ET in Dry Lake Valley, the outflow is calculated as the locally derived groundwater recharge, 16,200 afy, plus the inflow from northern Pahroc Valley, 2,000 afy. This value is estimated to be about 18,200 afy. Eakin (1966, p. 265), Harrill et al. (1988, p. 2), and Scott et al. (1971, p. 48) all reported 5,000 afy of interbasin flow for that location based on Eakin (1963). In addition, LVVWD (2001, p. 6-2) reported 12,000 afy, and Kirk and Campana (1988, p. 29-31) reported a range of 4,500 to 7,275 afy.

7.3.4 Delamar Valley Boundaries at Southern Pahranagat and Northern Coyote Spring Valleys

Groundwater flow across the hydrographic area boundary of Delamar Valley was evaluated by Rowley et al. (2011) who concluded that groundwater flow is likely across the southern boundaries with southern Pahranagat Valley and northern Coyote Spring Valley. As in Dry Lake Valley, there is no groundwater ET in Delamar Valley; therefore, the outflow is estimated as the sum of the inflow from Dry Lake Valley, 18,200 afy, and the locally derived groundwater recharge, 6,600 afy, or about 24,800 afy. Groundwater flow is prevented across the eastern boundary by the various caldera complexes comprising most of the Delamar Mountains, and across the western boundary by the Tertiary volcanic rocks and range-front fault and numerous subsidiary faults associated with the South Pahroc Range (Figure 7-10).

The majority of flow occurs in the north-south direction along the range-front faults and the northeast extension of the Pahranagat Shear Zone (PSZ), to areas of lower hydraulic head in northern Coyote Spring Valley and possibly the very southern part of Pahranagat Valley. The range-front faults transition into left-lateral shear zones as they pass through southern Pahranagat Valley and become normal faults on the western side of the Sheep Range. Water-level data from the few wells and springs in Delamar Valley and the adjacent areas of southern Pahranagat and northern Coyote Spring valleys indicate a hydraulic gradient to the south and southwest along and across the PSZ and into northern Coyote Spring Valley.

SNWA Monitor Wells 182M-1 (Well Map ID 182-9) and 182W906M (Well Map ID 182-10), drilled to depths of 1,345 and 1,735 ft bgs in southern Delamar Valley, have water-level elevations of 3,771 and 3,481 ft amsl, respectively (Figure 7-10). Both wells are completed in Tertiary volcanic rocks of the Hiko Tuff formation that comprise the basin fill. Monitor well 182M-1 is located north of the PSZ on the southwest side of the valley, while monitor well 182W906M is located near the west range-front fault of the Delamar Mountains and within the trace of the PSZ. Water levels in both

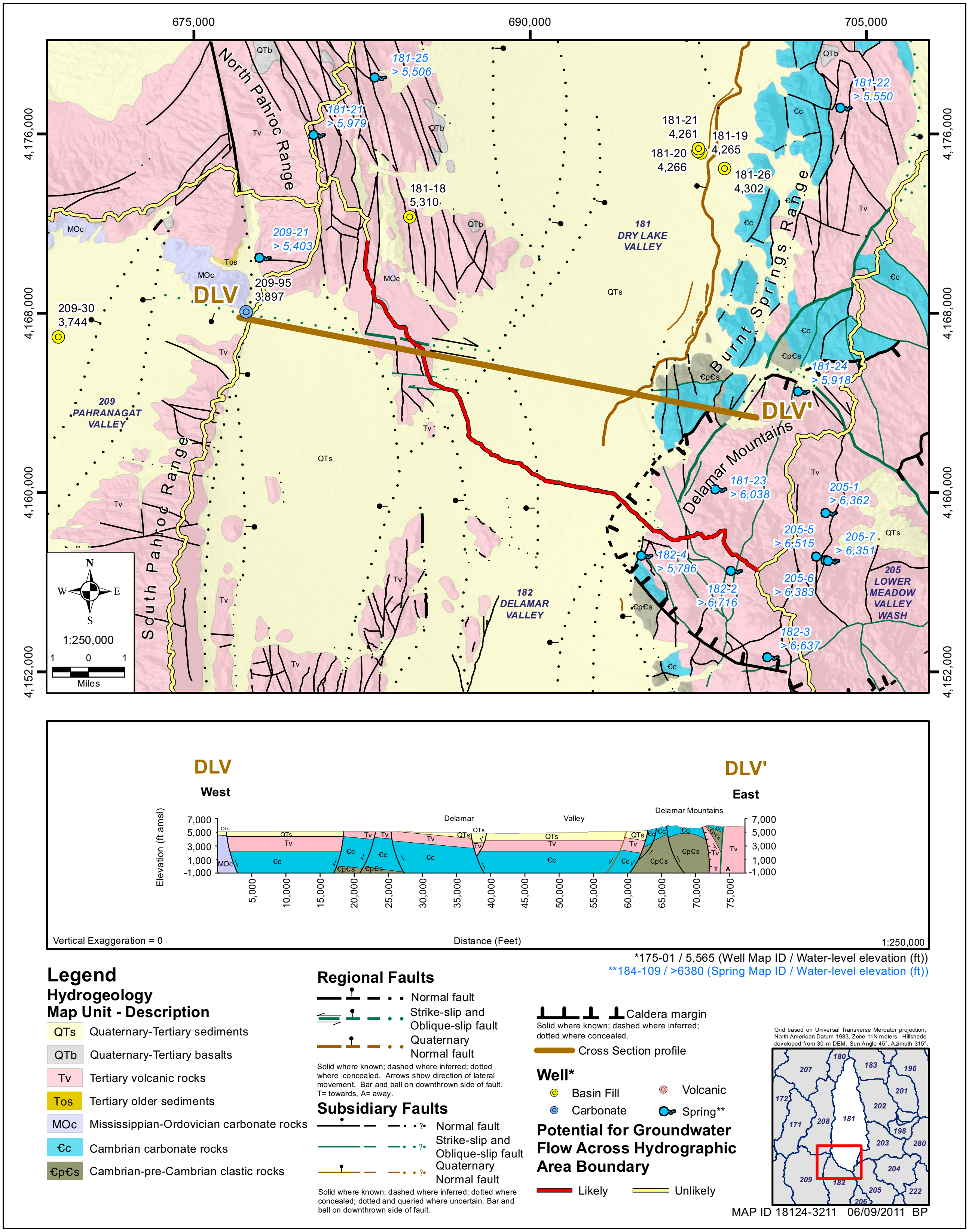

Figure 7-9
Interbasin Groundwater Flow from Dry Lake to Delamar Valley

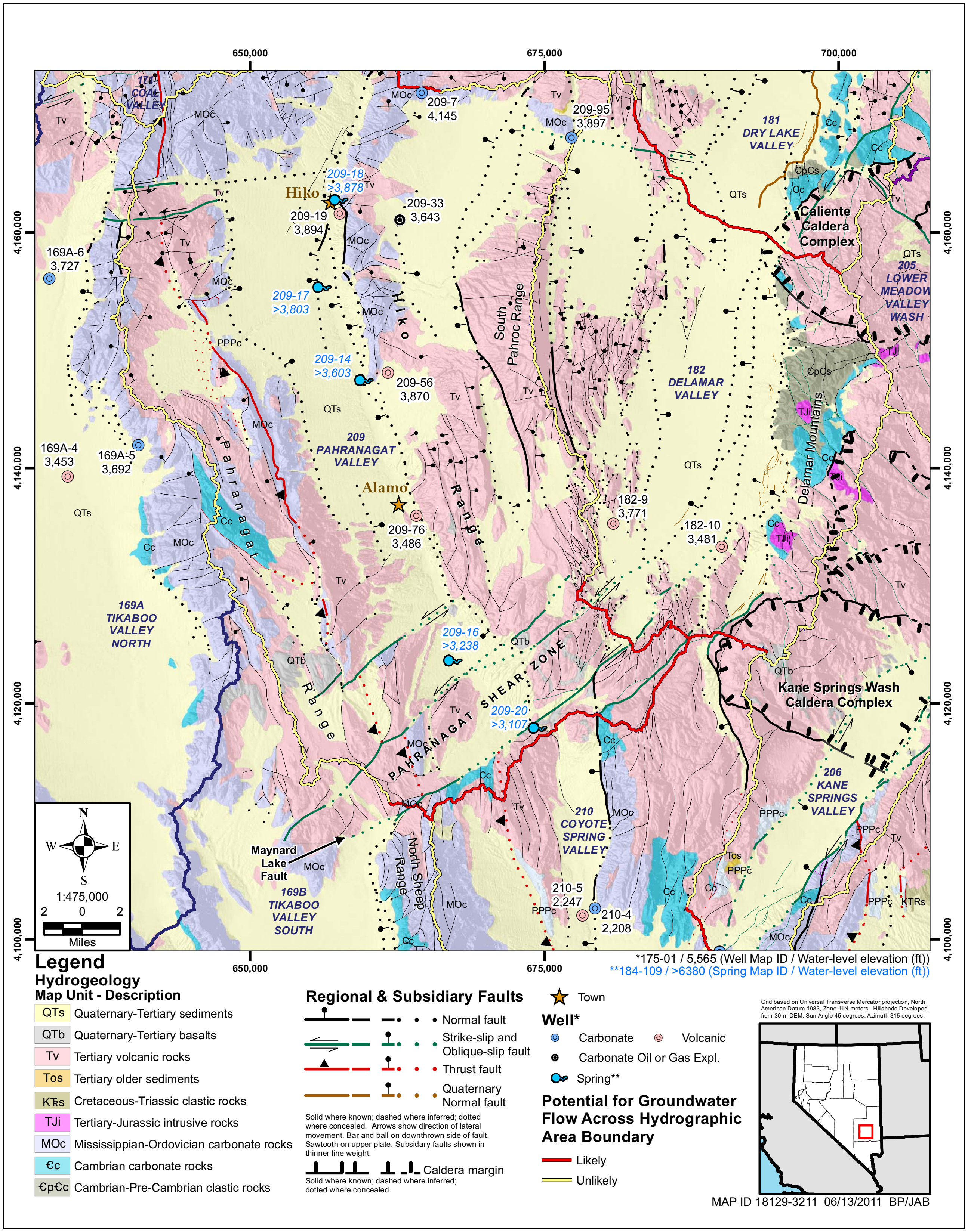

Figure 7-10
Hydrogeology of the Pahranagat Shear Zone and Vicinity

wells are most likely representative of the local groundwater system rather than the regional potential of the carbonate aquifer. A comparison of their water-level elevations with elevations of the springs in southern Pahranagat Valley and wells completed in the carbonate aquifer in Coyote Spring Valley, reveals a significant hydraulic potential between these areas. Spring elevations in southern Pahranagat Valley range in elevation from about 3,238 ft amsl at Solar Panel Spring (Spring Map ID 209-16) to about 3,107 ft amsl at Maynard Spring (Spring Map ID 209-20). This represents a hydraulic potential of at least 350 ft from southern Delamar Valley to southern Pahranagat Valley.

In northern Coyote Spring Valley, SNWA completed a monitor well, CSVM-3 (Well Map ID 210-4), in the carbonate aquifer to a depth of 1,230 ft bgs which has a water-level elevation of 2,208 ft amsl. The nearest location reflecting the potentiometric level the carbonate aquifer is the elevation of Ash Springs (Spring Map ID 209-14), in central Pahranagat Valley, which emerges from carbonate rocks on the north-trending range front. Ash Springs is located at an elevation of 3,603 ft amsl and about 30 mi from monitor well CSVM-3. This represents a hydraulic potential in the carbonate aquifer of about 1,400 ft from central Pahranagat Valley to northern Coyote Spring Valley. When compared to the SNWA monitor wells in Delamar Valley, the potential is even greater, ranging from about 1,550 to 1,280 ft.

Based on the conceptualization of flow and the supporting hydraulic-head data, groundwater flow is to the south and southwest from Delamar Valley along the strike of the PSZ. The large hydraulic-head differences between southern Delamar and Pahranagat valleys and northern Coyote Spring Valley suggest that there is potential for significant flow from these areas and across the shear zone to Coyote Spring Valley. The groundwater flow is controlled principally by the shear zone for which hydraulic properties are unavailable, making an estimate of the flow using Darcy's Law unrealistic.

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8.0 GROUNDWATER OCCURRENCE AND MOVEMENT

Understanding the occurrence and movement of groundwater within a given basin and between hydraulically-connected basins is one of the primary considerations when developing a conceptualization of the groundwater system and the geologic and hydrologic factors affecting it. To develop such an understanding, the hydrogeologic framework presented in Rowley et al. (2011), water-chemistry and isotope data presented in Thomas and Mihevc (2011), and the data and analyses presented in previous sections of this report were evaluated and relied upon in the descriptions of the occurrence, sources, and movement of groundwater within the Project Basins presented in this section. The temporal variations in groundwater levels based on evaluations of water-level hydrographs are also described. The evaluation is supported by maps (Plates 1 and 2) displaying the major features and controls affecting groundwater flow within the Project Basins and their vicinity: well and spring locations and elevations, structural features, recharge and discharge areas, interbasin flow locations, and flow directions.

8.1 Spring Valley

This section discusses the occurrence, sources, and movement of groundwater within Spring Valley. The discussion includes an assessment of the current and recent groundwater levels based on an inventory of the wells and springs located in the valley and adjacent areas. The conceptualization of the groundwater system of Spring Valley is depicted on Plate 1.

8.1.1 Groundwater Occurrence

Groundwater occurrence can be described by available water-level data and spring locations within the basin. These data are presented in Section 4.0, and summarized here for Spring Valley. The locations of the wells and springs are presented on Plate 1 with other attributes of the groundwater system underlying the valley.

Groundwater occurs at shallow depths throughout most of Spring Valley. On the valley floor, groundwater occurs above the ground surface (i.e., flowing wells) or near the ground surface, and becomes progressively deeper towards the valley margins and on the alluvial fans. In the northern part of the valley, at well 184 N24 E66 31CB 1 (Well Map ID 184-212), the DTW is approximately 140 ft bgs (see Appendix C). In the central and south-central portion of the valley, the DTW is shallow, particularly within the groundwater discharge areas where groundwater ET and/or springs occur and significant perennial streamflow reaches the valley floor. Within the groundwater discharge area and to the south, in Baking Powder Flat, the presence of flowing wells is indicative of an upward hydraulic gradient. This gradient is created by the significant recharge that occurs within the Schell Creek and Snake Ranges, and the confining nature of some of the fine-grained surficial deposits (e.g., playa and lake deposits). In the far south, at well 184 N08 E68 14A 1 USBLM (Well Map ID 184-1), the DTW is 407 ft bgs (Plate 1 and Appendix C).

Water-level elevations derived from the well data provide an indication of the hydraulic gradients within Spring Valley and the potential groundwater flow directions (Plate 1 and Appendix C). Because most of the wells are completed within the basin-fill sediments, nearly all of the water-level data are reflective of the basin-fill hydraulic heads. In most instances, the hydraulic heads measured in wells completed in the basin fill are lower than those measured in wells completed in the carbonate aquifer, which are typically located closer to the mountain blocks and recharge sources. An exception is the carbonate well in the southeast portion of the valley at the northern part of the Limestone Hills, whose hydraulic head is approximately 70 ft lower than those measured in the surrounding wells completed in the basin fill. Higher hydraulic heads in carbonate wells is expected because the recharge to the carbonate rocks creates the hydraulic potential driving the groundwater system in the valley. As such, both were used in the following description of the hydraulic-head distribution.

Water-level elevations within the basin range from approximately 6,000 ft amsl in the northernmost portion of the valley to approximately 5,550 ft amsl east and southeast of the Yelland Dry Lake in the north-central part of the valley (Plate 1 and Appendix C). In the southern part of the valley, the lowest water levels are approximately 5,700 ft amsl near the topographic divide with Hamlin Valley, just northwest of the Limestone Hills. As the data indicate and Plate 1 illustrates, there is a water-level gradient of 24 ft/mi (or 0.005 ft/ft) from north to south in the northern portion of the valley, and a gradient of 5.7 ft/mi (or 0.001 ft/ft) from south to north in most of the southern portion of the valley. An apparent groundwater divide exists in the southern part of the valley, and it is coincident with a gravity high that extends from the eastern part of the Fortification Range to the southwestern part of the Snake Range (Figure 8-1) (Rowley et al., 2011). This divide is defined by an approximate water-level elevation of 5,800 ft amsl and water-level data to the north and south ranging from 5,763 ft amsl (SPR7011Z, Well Map ID 184-228) and 5,707 ft amsl (184W502M, Well Map ID 184-216), respectively.

8.1.2 Groundwater Sources

Sources of water for the aquifer system underlying Spring Valley are the significant groundwater recharge areas within the Schell Creek and Snake Ranges, the Antelope Range to the north, and the Fortification Range to the south (Plate 1). The surface geology of Spring Valley is predominantly carbonate rock and coarse alluvial materials whose permeability is such that groundwater recharge is readily accepted. However, potential groundwater recharge in some areas of the Schell Creek Range and southern Snake Range is rejected by mostly impermeable Precambrian-Cambrian siliciclastic rocks exposed at the surface. This rejected potential recharge contributes to perennial streamflow that recharges the basin-fill along alluvial fans and near the valley floor. Groundwater inflow from adjacent basins is another potential groundwater source to the basin; however, this inflow, if it occurs at all, is considered minor due to the prevailing hydrogeologic conditions at the boundaries and the hydraulic gradients defined by the available water-level data within the basin and in adjacent basins (Plate 1). Details regarding interbasin flow of groundwater at the basin boundaries are presented in Section 7.0.

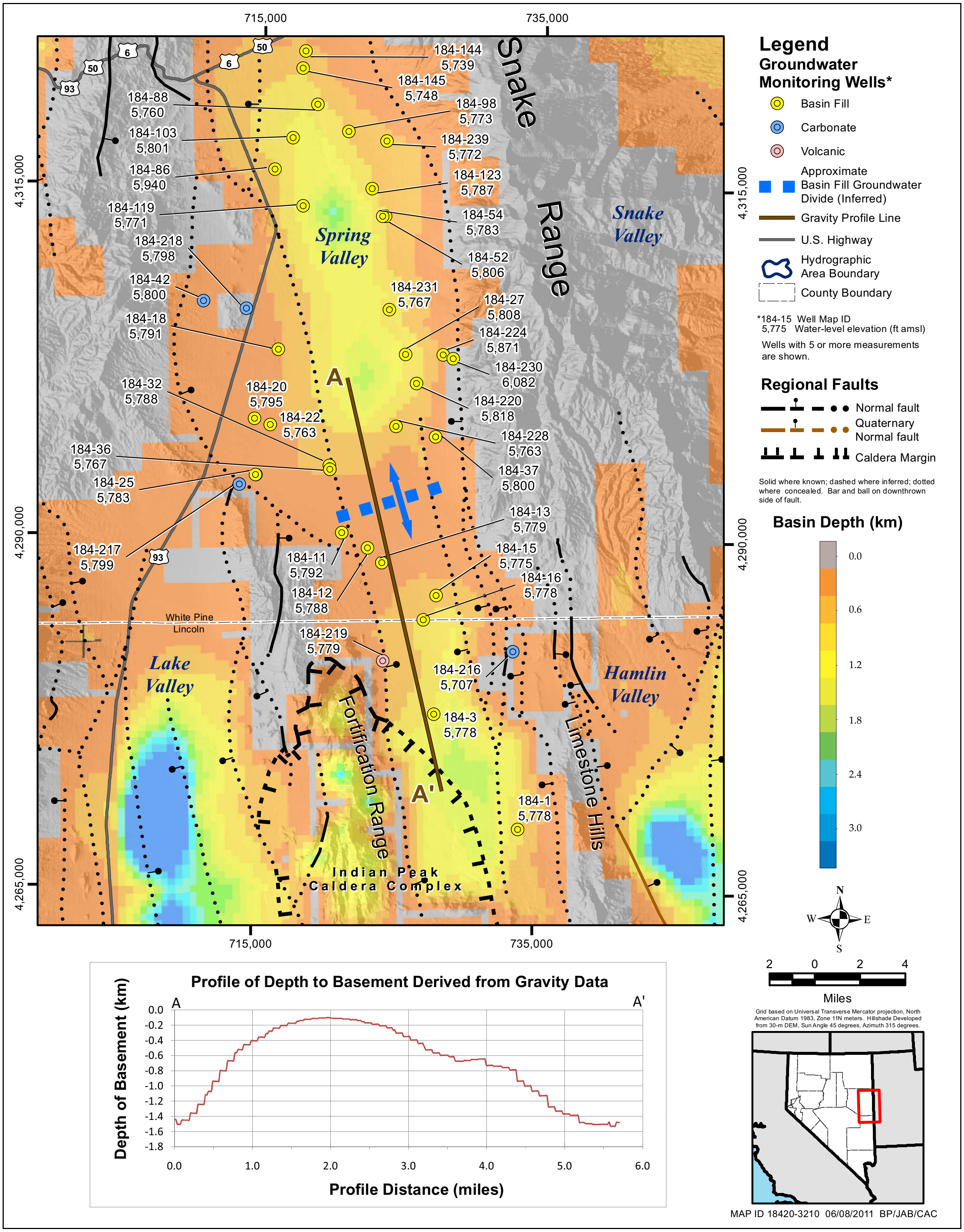

Figure 8-1
Depth to Pre-Cenozoic Basement in Southern Spring Valley and Vicinity

8.1.3 Groundwater Movement

Groundwater moves from the recharge areas within the surrounding mountain ranges, principally the Schell Creek and Snake Ranges, to discharge areas located on the valley floor. The hydraulic-head potential derived from the recharge areas is evident by the numerous springs and seeps located on the valley floor. Nearly all of these springs and seeps are located at the base of alluvial fans or are structurally controlled by the range-front or subsidiary faults. Many are immediately downgradient from the recharge areas. Flowing wells within the valley are another indication of the hydraulic-head potential derived from the recharge areas and suggest that the potentiometric surface of the underlying carbonate-rock aquifer is greater than or equal to that of the basin-fill aquifer (i.e., upward vertical gradient).

In the north, hydraulic gradients indicate groundwater flow southward to groundwater discharge areas in the central part of the valley (Plate 1). In the south, hydraulic gradients indicate groundwater flow northward to groundwater discharge areas in the central part of the valley. At the groundwater divide, groundwater movement on the northern side flows northward to groundwater discharge areas in the central part of the valley. Groundwater movement on the south side is to the southeast towards the Limestone Hills and the basin boundary with Hamlin Valley. At this boundary, the available water-level data indicate a hydraulic gradient across the carbonate-rocks of the Limestone Hills and, therefore, groundwater outflow to Hamlin Valley. Groundwater flow across this boundary is characterized by Rowley et al. (2011) as permissible and locally likely based on the hydrogeologic framework. The source of this outflow is interpreted to be local recharge generated from precipitation, and is estimated to be about 4,400 afy (see Section 7.0).

Groundwater outflow to Snake Valley has been postulated across the northeastern boundary of Spring Valley (Nichols, 2000; Katzer and Donovan, 2003). However, the water-level data between Spring and Snake valleys, south of the Kern Mountains and north of the Snake Range (Plate 1), are inadequate to derive a representative hydraulic gradient and, therefore, an interbasin flow volume that can substantiate the postulated estimates. No groundwater-level data are available for this area, except for what can be inferred from a single stock well completed in 1953 in Snake Valley, in the north Snake Range (i.e., well 195 N19 E69 15C 1, Well Map ID 195-388). This well was completed in the alluvium to a depth of 28 ft bgs, at an elevation of approximately 7,175 ft amsl. The existence and location of this well has not been verified, nor would it be representative of the groundwater system in Spring Valley. An assessment of the potential for interbasin flow at this location is described in Section 7.0, and the results indicate that any outflow to Snake Valley across this boundary would most likely be groundwater originating in Tippett Valley rather than Spring Valley. Groundwater in this part of Spring Valley would more likely flow to the groundwater discharge areas located downgradient in the central part of the valley, as the available water-level data indicate.

8.1.4 Temporal Variation of Water Levels

Several wells with sufficient water-level records are available in Spring Valley to assess the temporal variation in groundwater levels within the basin. The water-level data, however, are highly variable in their frequency of measurement and periods of record. These limitations, coupled with the fact that groundwater production data for most of the valley are limited, make it difficult to attribute observed water-level fluctuations near pumping centers to changes in hydrologic conditions and/or anthropogenic effects.

To evaluate the temporal variation in groundwater levels, hydrographs for wells with significant periods of record were constructed from data collected by SNWA since 1993 and data obtained from the USGS through August 2010. Specifically, hydrographs were created for wells that had 10 or more DTW measurements. The hydrographs are presented in Section C.2.2 of Appendix C. Most of the wells are located in the middle to southern portion of the valley (i.e., south of U.S. Highway 50), and most are completed in the basin-fill based upon the lithologic description of their respective driller's logs. There are hydrographs for several wells completed in the carbonate-rock aquifer that were constructed as part of the SNWA exploratory-drilling program. Other wells were constructed in the early 1980s in support of the USAF MX Missile-Siting Program and, since their construction, there has been intermittent data collection. In 1990, the USGS began quarterly monitoring as part of a joint funding agreement with the LVVWD and NDWR. This joint funding arrangement continues and was expanded in 2005 to include additional wells. As the hydrographs illustrate, the periods of record for most wells are essentially the same, ranging from 1981 to present. The most complete records are for wells monitored by SNWA to satisfy the monitoring requirements associated with the stipulated agreement between SNWA and the U.S. Department of Interior agencies (DOI). These data are provided in Appendix C and are reported in SNWA (2011b, Appendix C).

Temporal variation in water levels for wells completed in basin-fill sediments ranges from 2 to 15 ft for most wells. This variation is most likely related to changes in the hydrologic conditions or measurement accuracy rather than anthropogenic effects. Temporal variation in water levels for wells completed in the carbonate-rock aquifer ranges from 2 to 5 ft. Most wells completed in the carbonate-rock aquifer show small, but consistent, water-level declines from early 2007 to the end of 2010. Several wells, including SPR7005M (Well Map ID 184-221), SPR7005X (Well Map ID 184-222), and SPR7006M (Well Map ID 184-223), however, show seasonal water-level fluctuations with maximum water-level elevations occurring in early spring and minimum water-level elevations occurring in July and August (Section C.2.2). These fluctuations are consistent with seasonal changes in the hydrology (e.g., spring snow melt, summer ET). Groundwater production data for the limited pumping that occurs within Spring Valley are unavailable, so the effects of pumping were not evaluated.

8.2 Cave Valley

This section describes the occurrence, sources, and movement of groundwater within Cave Valley. The conceptualization of the groundwater system underlying Cave Valley is depicted on Plate 2.

8.2.1 Groundwater Occurrence

DTW in Cave Valley ranges from near ground surface in parts of northern Cave Valley (i.e., near Cave Spring and Parker Station) to greater than 200 ft bgs in the southern portion of the valley. DTW in the vicinity of the playa in the southern portion of Cave Valley is in excess of 150 ft bgs, suggesting that the vegetation in this area subsists mainly on precipitation and possibly a perched groundwater source that is disconnected from the groundwater system (Plate 2). Water-level elevations in Cave

Valley range from approximately 6,800 ft amsl in the far northern part of the valley to approximately 5,800 ft amsl in the south (Plate 2). These water-level elevations indicate a north-to-south hydraulic gradient of approximately 50 ft/mi or 0.009 ft/ft along the central axis of the valley.

As described in the hydrogeology report (Rowley et al., 2011), Cave Valley is effectively partitioned into two sub-basins by the northeast-striking oblique-slip Shingle Pass Fault that has displaced a part of the Egan Range, forming an east-dipping tilt block that extends northeast across and underneath Cave Valley where it terminates against the western range-front fault of the Schell Creek Range. At this location, the western range-front fault of the Schell Creek Range has downthrown the footwall block of the second fault, thereby removing its potential for impeding north-south flow at this location. The vertical displacement of the western range-front fault of the Schell Creek range is at least 15,000 ft, which has resulted in a north-south preferential flow path through fractured bedrock associated with this fault and the many subsidiary faults and associated fractures of the same orientation. To the west and on the north side of the tilt block, the associated Shingle Pass fault and presence of the Chainman Shale confining unit within the block appears to have hydraulically isolated the carbonate rocks of this area from those in the northeastern, eastern and southern parts of the valley. This partitioning is reflected by the hydraulic-heads measured in the limited number of wells completed in the carbonate aquifer in the valley.

In the northern sub-basin, a well constructed by SNWA (180W501M, Well Map ID 180-31) and completed in carbonate rocks to a depth of 1,212 ft bgs, has a DTW of about 1,056 ft bgs and water-level elevation of about 5,372 ft amsl (Plate 2). The water-level elevation most likely represents the hydraulic head of the nearby Shingle Pass Fault through which a small amount of interbasin flow from Cave Valley to White River Valley is presumed to occur (see Section 7.0). However, groundwater production from this well was very limited during air-lift development and subsequent pumping to purge the well before water-chemistry sampling, suggesting that the hydraulic connection between the well and fractures associated with the Shingle Pass Fault may also be limited. The hydraulic head measured in this well is about 80 ft higher than the elevation of nearby local springs in adjacent White River Valley.

In the southern sub-basin, wells were completed in the carbonate aquifer at two locations. The first location is on the western margin of the basin and contains a well constructed as part of the USAF MX-Missile Program (Well Map ID 180-8, Plate 2). DTW at this location is about 220 ft bgs with a water-level elevation of about 5,795 ft amsl. The second location is on the western range-front fault of the Schell Creek Range, near Sidehill Pass and contains a monitor well installed by SNWA (i.e., 180W902M, Well Map ID 180-32). The DTW at this location is about 142 ft bgs, with a water-level elevation of about 5,843 ft amsl. Water-level elevations ranging from about 5,840 to 5,790 ft amsl in the southern sub-basin are almost 450 ft higher than the carbonate well in the northern sub-basin.

8.2.2 Groundwater Sources

Sources of water for the aquifer system underlying Cave Valley are the significant groundwater recharge areas within the Egan Range on the west and the Schell Creek Range on the east, and the alluvial fans along their range fronts (Plate 2). The surface geology of these areas is predominantly carbonate-rocks with coarse alluvial material forming the fans. The permeability of these units is such that groundwater recharge is readily accepted, except for an approximate 5 mi section of Precambrian-Cambrian siliciclastic rocks that are exposed in the Schell Creek Range to the east, at and north of Cave Spring. These rocks are considered impermeable except for where they are locally fractured (Rowley et al., 2011), and any precipitation that runs off this area recharges the basin-fill along the alluvial fans and near the valley margins. Local recharge appears to be the sole source of water to the groundwater system, and other sources, such as subsurface inflow from adjacent basins, are precluded by (1) the geometry and nature of the hydrogeologic framework, and (2) the prevailing hydraulic gradients along the basin boundaries. The water-level data within the basin and in adjacent basins (Plate 2) indicate flow out of the basin rather than into it. This is corroborated by the isotopic data and analysis presented by Thomas et al. (2001, p. 6) and Thomas and Mihevc (2011, p. 24).

8.2.3 Groundwater Movement

Groundwater in the basin fill follows the hydraulic gradient from recharge areas of higher potential in the northern part of the basin to the south, along the topographically lower central axis of the valley and surface water drainage. Groundwater flow in the underlying carbonate aquifer is less conclusive based on the limited potentiometric data for the carbonate aquifer. However, the available potentiometric data, when coupled with the description of the hydrogeologic framework (Rowley et al., 2011), groundwater sources, and isotopic data (Thomas and Mihevc, 2011), support groundwater movement in the carbonate aquifer as follows: (1) a significant amount of the groundwater recharged in the Egan Range, north of the tilt block and the Shingle Pass fault, flows south and southwest through fractured carbonate rocks to White River Valley and local springs occurring along the western range-front fault and; (2) groundwater recharged in the higher elevations of the Schell Creek Range and the southern part of the Egan Range (i.e., the tilt block and south) flows southward along preferential flow paths created by the western range-front fault of the Schell Creek Range and the east-dipping bedding planes of the Egan Range to northeastern Pahroc Valley. As described in Section 7.0, outflow from Cave Valley to White River Valley is estimated to be about 3,800 afy, and outflow from southern Cave Valley to the northeastern Pahroc Valley is estimated to be about 8,600 afy. These flow paths are corroborated by the available isotopic data reported in Thomas and Mihevc (2011).

8.2.4 Temporal Variation of Water-Levels

Few wells in Cave Valley have sufficient water-level records to assess the temporal variations in groundwater-levels in the basin. Cave Valley MX well (Well Map ID 180-8), located in the south-central portion of the valley (Plate 2), penetrates approximately the top 200 ft of the carbonate aquifer forming the southern part of the tilt block. A consistently rising water-level trend has been observed, with about a 15-ft increase in the overall water-level elevation since the early 1980s. No seasonal variations can be discerned from the record. Conversely, declining trends in other wells penetrating the carbonate-rock aquifer have been observed (i.e., 180W501M, 180W902M, CAV6002M2, CAV6002X). Each of these wells has a period of record spanning late 2006 to 2010 with declines on the order of 5 to 10 ft. This is a period of below normal precipitation, but whether or not that is the cause of the declining water levels cannot be determined at this time with the limited data available. Observations of water-level elevations for most wells completed in the basin fill have slightly increasing trends similar to that of the Cave Valley MX well (Well Map ID 180-8), for the time period spanning 1980 to 2010. The remainder of the wells have no trends or variability consistent with annual changes in the hydrology.

8.3 Dry Lake Valley and Delamar Valley

This section discusses the occurrence, sources, and movement of groundwater in Dry Lake and Delamar valleys, which for the purposes of this discussion, are considered a single basin based on the hydrogeologic framework and isotopic and hydraulic-head data. The conceptualization of the groundwater system of these two valleys is depicted on Plate 2.

8.3.1 Groundwater Occurrence

The water-level data indicate that the DTW in northern Dry Lake Valley is relatively shallow, ranging from 10 to about 270 ft bgs. The DTW deepens to the south, where it ranges from 3 to about 658 ft bgs in the central and southern portion of Dry Lake Valley, and exceeds 1,300 ft bgs in southeastern Delamar Valley. Water-level elevations range from 6,540 to 5,270 ft amsl in the northern portion of Dry Lake Valley, and from 5,653 to 4,249 ft amsl in the central and southern portion of the valley. Water-level elevations in Delamar Valley range from 3,850 ft amsl in the central portion of the valley to about 3,480 ft amsl in the southeastern portion of the valley.

Three wells in the compiled data set (Appendix C) were identified as penetrating the carbonate aquifer. Two wells are located on the west side of Dry Lake Valley (Plate 2), with water-level elevations ranging from 4,611 to 4,288 ft amsl. Another well drilled in early 2010 by Vidler Water Company, is located on the east side of Dry Lake Valley, near the Ely Springs Ranch. This well was drilled to a total depth of 1,881 ft bgs and has a reported DTW of 406 ft bgs, with a corresponding water-level elevation of 4,366 ft amsl. A monitor well installed by SNWA in Pahranagat Valley on the northwestern margin of Delamar Valley has a water-level elevation of 3,897 ft amsl, which is 370 to 620 ft lower than the water level elevations in the carbonate wells located north of this location in Dry Lake Valley, and about 70 to 440 ft higher than the basin-fill wells in southern Delamar Valley.

Based on the available data, hydraulic heads are highest along the valley margins closest to the areas of groundwater recharge, and lower in the middle of the valley. Along the central axis of the valleys, hydraulic heads are higher in northern Dry Lake Valley (Muleshoe Valley), and lower to the south. The systematic decrease in hydraulic heads from northern Dry Lake Valley to southern Delamar Valley are indicative of a north-south groundwater flow direction. A hydraulic gradient from the central portion of Dry Lake Valley to the central portion of Delamar Valley was calculated to be 13 ft/mi or 0.0025 ft/ft.

8.3.2 Groundwater Sources

Sources of water for the aquifer system underlying Dry Lake and Delamar valleys are the groundwater recharge areas within the mountain ranges surrounding the valleys.

For Dry Lake Valley, the primary sources include recharge in the Schell Creek Range to the northwest, the Fairview Range to the northeast, the series of north-south trending ranges to the east (e.g., Bristol Range, Highland Range, Chief Range, Burnt Springs Range), and the North Pahroc Range to the southwest (Plate 2). In Delamar Valley, the recharge areas are within the South Pahroc Range to the west and the Delamar Mountains to the east. The surface geology of these ranges is predominantly carbonate rocks, with coarse alluvial material forming the alluvial fans. These permeable units readily accept groundwater recharge. The carbonate rocks are continuous within the ranges except where interrupted by the western margin of the Indian Peak caldera complex in the south Fairview Range, and the various calderas forming the base of the Delamar Mountains. The surface geology transitions from carbonate rock units in the north, to Tertiary volcanic rocks (e.g., Hiko Tuff) to the south forming the South Pahroc Range and the Delamar Mountains. These volcanic rocks overlie the carbonate rocks and are generally less permeable; however, recharge still occurs here based on the isotopic data and analysis presented in Thomas et al. (2001) and Thomas and Mihevc (2007; 2011, p. 24).

The isotopic data indicate that the source of recharge is precipitation on the surrounding ranges, except for possible interbasin inflow from northeastern Pahroc Valley to northern Dry Lake Valley, just south and east of the area referred to as Muleshoe Valley (Thomas and Mihevc, 2011, p. 24). The volume of this inflow is thought to be small, probably less than 2,000 afy (Section 7.0).

8.3.3 Groundwater Movement

Groundwater flow in Dry Lake and Delamar valleys is from north to south, driven by the hydraulic potential created by groundwater recharge at higher elevations within the mountain ranges. Based on the hydraulic head data, groundwater flows from these recharge areas toward the central axis of the valleys, and then south to the southern part of Delamar Valley. The hydraulic head data from the few wells and springs in Delamar Valley, and the adjacent areas of southern Pahranagat and northern Coyote Spring valleys, indicate a hydraulic gradient to the southwest and south along the PSZ, and to northern Coyote Spring Valley (Plate 2). Based on this gradient and permissible flow paths in the hydrogeologic framework, groundwater flows directly into Coyote Spring Valley to the south, with some remaining amount likely flowing to the southwest and south along and across the PSZ to the very southern part of Pahranagat Valley. Elsewhere, groundwater outflow from the valley is precluded by higher potentials in the recharge areas, the South Pahroc Range and its associated range-front faults to the west, and the calderas comprising the Delamar Mountains to the east and southeast.

8.3.4 Temporal Variation of Water-Levels

Water-level fluctuations in both Dry Lake and Delamar valleys appear to be minor with several wells showing slight upward trends over the past 25 years similar to the trend observed in the well in Cave Valley. The water-level variations can likely be attributed to climatic variability, as little to no groundwater development has occurred in these two basins. Water-level elevations for the USGS-MX well (N. Dry Lake Well) completed in the carbonate aquifer have increased approximately five feet from 1986 to the present. Most of the other wells for which hydrographs were constructed were identified as penetrating the basin-fill or volcanic aquifer system. These hydrographs are provided in Section C.2.2 of Appendix C.

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9.0 GROUNDWATER BUDGETS

The components of the groundwater budgets derived for the Project Basins as a result of this groundwater-resources assessment are summarized in Table 9-1 and Figure 9-1. The groundwater budgets are considered mean-annual estimates and form the basis of the perennial yield estimates for these basins.

Table 9-1
Estimated Groundwater Budgets for Project Basins

HA	HA Name	Recharge (afy)	Inflow (afy)	From	Groundwater ET (afy)	Outflow (afy)	To
184	Spring Valley	99,200	0	---	94,800	4,400	Hamlin Valley
180	Cave Valley	13,700	0	---	1,300	3,800	White River Valley
						8,600	Pahroc Valley
181	Dry Lake Valley	16,200	2,000	Pahroc Valley	0	18,200	Delamar Valley
182	Delamar Valley	6,600	18,200	Dry Lake Valley	0	24,800	Coyote Spring Valley

For Spring Valley, recharge from precipitation is estimated to be 99,200 afy. Minor inflow from Tippett Valley might occur in the northeastern part of the valley, but any such flow is believed to pass through the area to western Snake Valley; thereby, producing a net inflow of zero. Most of the groundwater discharge in Spring Valley occurs in the form of ET, which is estimated to be about 94,800 afy. Groundwater outflow from southeastern Spring Valley to Hamlin Valley is estimated to be about 4,400 afy.

For Cave Valley, recharge from precipitation is estimated to be 13,700 afy. Groundwater discharge occurs in the form of ET in the northern part of the valley, and subsurface outflow to White River and Dry Lake valleys. Groundwater ET is estimated at 1,300 afy, groundwater outflow to White River Valley through Shingle Pass is estimated at 3,800 afy, and outflow to Pahroc Valley at 8,600 afy.

For Dry Lake Valley, recharge from precipitation is estimated to be 16,200 afy. Inflow from northern Pahroc Valley is estimated to be 2,000 afy, and constitutes additional recharge to the aquifer system in Dry Lake Valley. No groundwater ET occurs in Dry Lake Valley; therefore, discharge only occurs in the form of outflow to Delamar Valley, which is estimated to be 18,200 afy.

For Delamar Valley, recharge from precipitation is estimated to be 6,600 afy. Subsurface inflow from Dry Lake Valley enters Delamar Valley from its northern boundary, and is estimated to be 18,200 afy. No groundwater ET occurs in Delamar Valley; therefore, the inflow from Dry Lake Valley and the recharge from precipitation, a total of about 24,800 afy, discharges from the basin as groundwater outflow through its southern boundary, to Coyote Spring Valley and perhaps the very southern end of Pahranagat Valley.

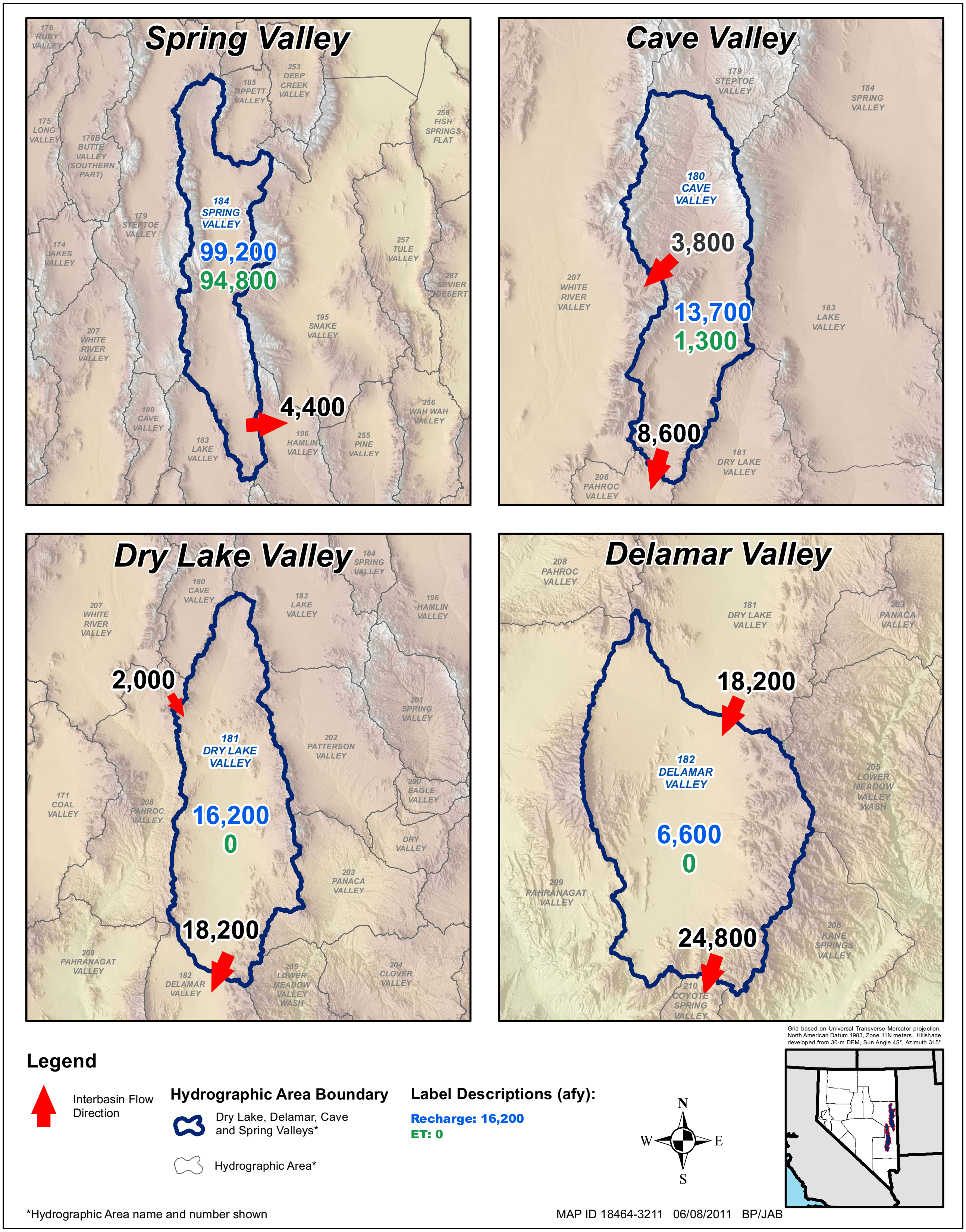

Figure 9-1
Groundwater Budgets of Spring, Cave, Dry Lake and Delamar Valleys

The groundwater budgets derived by this study for Cave, Dry Lake, and Delamar valleys, along with the locations of interbasin flow, are consistent with the available isotope data described and interpreted by Thomas and Mihevc (2011, p. 24).

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10.0 UNAPPROPRIATED GROUNDWATER

For a given groundwater basin or a hydrographic area in Nevada, unappropriated groundwater is calculated as the perennial yield of the basin reduced by the amount of existing committed groundwater rights. The perennial yields derived as part of this groundwater-resources assessment (Section 9.0) and the committed groundwater rights (Stanka, 2011) are used in this section to derive estimates of unappropriated groundwater volumes for Spring, Cave, Dry Lake, and Delamar valleys.

10.1 Perennial Yield

The NDWR (Scott et al., 1971, p. 13) defines the perennial yield of a hydrographic area as:

> 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.

For basins with significant groundwater discharge to the surface, in the form of springs and/or ET, the perennial yield is limited to the total annual discharge to the surface. For basins without significant groundwater discharge to the surface, the definition of the perennial yield has been interpreted in different ways. The maximum perennial yield has, however, always been defined as no more than the total annual recharge volume to the basin. The estimates of groundwater ET and recharge derived as part of this groundwater-resources assessment are considered to be the most accurate of all published estimates because they are based on more extensive databases, fieldwork, and more advanced mapping and data-analysis techniques. These estimates are, therefore, also considered to form the strongest basis for estimating the perennial yields of the Project Basins.

10.1.1 Spring Valley

The estimate of perennial yield derived for Spring Valley as part of this study is presented and compared to that previously reported by the NDWR (Scott et al., 1971).

As described in this report, Spring Valley has a large amount of groundwater discharge to the surface and a relatively small volume of subsurface outflow. As a result, the perennial yield for this basin is at least equal to the estimated annual groundwater ET of about 94,800 afy (Section 5.0) but cannot be larger than the estimated volume of annual recharge of about 99,200 afy (Section 6.0).

The estimate of perennial yield initially established by the NSE for Spring Valley is 100,000 afy (Scott et al., 1971, p. 23); whereas, the annual recharge estimate is 75,000 afy based on the

USGS Water Resources-Reconnaissance Series Report completed by Rush and Kazmi (1965). The basis for the perennial yield estimate is described by Rush and Kazmi (1965) as the sum of the groundwater discharge by ET and the salvageable portion of mountain-front runoff. Rush and Kazmi (1965, p. 22 and 23) estimated groundwater ET at 70,000 afy, which is underestimated compared to the 94,800 afy estimated for this study. Given that the acreage of the discharge area estimated by Rush and Kazmi (1965) is within less than 1 percent of the acreage estimated by this study (Section 5.3.2), the difference must be due to the ET rates. Rush and Kazmi (1965) derived their estimate of 70,000 afy based on the "probable average rate of use of water" for each type of land-cover present within the discharge area. These rates represent estimates of groundwater-ET rates based on the scarce information available at the time, and are significantly less than the groundwater-ET rates derived from field measurements of ET in Spring Valley, particularly for the wetland/meadow land-cover class. Rush and Kazmi (1965, p. 23) used a rate of 1.5 ft/yr for the "wet meadow & salt grass" class, which is almost one half of the average groundwater-ET rate of 2.81 ft/yr measured at the UNLV, DRI, SNWA, and USGS wetland/meadow sites in Spring Valley during the period 2006-2010 (Appendix D).

The estimate of groundwater ET derived for Spring Valley as part of this groundwater-resources assessment (94,800 afy) is considered to be the most accurate of all estimates made to date because it is based on more comprehensive ET data that were collected in the basin over multiple years, using the most advanced methods of measurement and analytical tools to derive estimates of groundwater ET. As such, the estimate is also considered the best estimate of the perennial yield for Spring Valley. The available data, studies, and analyses indicate that the preliminary estimate of groundwater ET derived by Rush and Kazmi (1965) most probably represents the lower bound rather than the long-term average. However, their perennial yield estimate is consistent with these new estimates.

10.1.2 Cave, Dry Lake and Delamar Valleys

The estimates of perennial yield derived for Cave, Dry Lake, and Delamar valleys, as part of this study, are presented and compared to those previously reported by NDWR (Scott et al., 1971).

For the purpose of this groundwater assessment, the perennial yields of Cave, Dry Lake, and Delamar valleys are equated to the annual recharge volumes estimated for each.

- Cave Valley does have a minor amount of groundwater ET (Section 5.0) but most of the discharge is by subsurface outflow (Section 7.0). The exact perennial yield for this basin is not known but may be as large as the estimated volume of annual recharge of 13,700 afy (Section 6.0).

- Dry Lake Valley has no groundwater ET as all the discharge is by subsurface outflow (Section 7.0). The perennial yield for this basin may be as large as the estimated volume of annual recharge of 16,200 afy (Section 6.0). Additional groundwater from Pahroc Valley that likely flows into Dry Lake Valley is not included in this estimate.

- Delamar Valley has no groundwater ET, and all groundwater discharge is by groundwater outflow (Section 7.0). The perennial yield for this basin may be as large as the estimated volume of annual recharge of 6,600 afy (Section 6.0).

NDWR assigned perennial yield values of 2,000 afy, 2,500 afy and 3,000 afy to Cave, Dry Lake and Delamar valleys (Scott et al., 1971, p. 23), respectively, citing the Reconnaissance Reports (Eakin, 1962 and 1963). It is not clear how the estimate of perennial yield for Cave Valley was derived as Eakin (1962) did not specify a value. However, Eakin (1962, p. 1, 14) described the perennial yield of Cave Valley as (1) substantially larger than the estimate of groundwater ET, (2) not exceeding a few thousand acre-feet per year, and (3) not exceeding the average annual recharge on a continuing basis. Eakin (1962) estimated annual groundwater ET at a few hundred acre-feet per year and annual recharge at 14,000 afy. For Dry Lake and Delamar valleys, Scott et al. (1971) simply used half of the annual recharge volumes estimated by Eakin (1963), 5,000 and 6,000 afy, respectively. These recharge estimates are based on invalid assumptions regarding the precipitation zones used by Eakin (1963) which resulted in significantly underestimated precipitation and recharge in Dry Lake and Delamar valleys (Sections 3.0 and 6.0). The underestimation of annual recharge in these two basins by Eakin (1963) constitutes a primary source of error in the estimates of perennial yield reported by Scott et al. (1971) for Dry Lake and Delamar valleys.

The annual recharge volumes estimated in this study for Cave, Dry Lake and Delamar valleys constitute the best available estimates of perennial yields for these basins. These estimates are considered to be the most accurate of all estimates made to date because they are based on a more accurate precipitation map (800-m PRISM grid) and more comprehensive ET data that were collected in the WRFS, particularly White River Valley, over multiple years using the most advanced methods of measurement and state-of-the-art analytical tools to derive estimates of groundwater ET. As such, these estimates are also considered the best estimates of the perennial yields for these Project Basins.

10.2 Summary of Existing Committed Groundwater Rights

A summary of the existing committed groundwater rights within Spring, Cave, Dry Lake, and Delamar valleys are provided in this section, and is based on the water-right analysis presented in Stanka (2011, p. ES-3).

SNWA applications located in Spring, Cave, Dry Lake, and Delamar valleys have a priority date of October 17, 1989; therefore, only committed groundwater rights existing prior to that date are used here to derive estimates of unappropriated groundwater. These are listed for each Project Basin as follows:

- Spring Valley: 10,429.51 afy
- Cave Valley: 17.77 afy
- Dry Lake Valley: 61.12 afy
- Delamar Valley: 8.95 afy

10.3 Unappropriated Groundwater Resources

Estimates of the unappropriated groundwater resources in the Project Basins, calculated as the difference between the perennial yield estimate and the pre-1989 committed groundwater rights, are listed in Table 10-1.

Table 10-1
Unappropriated Groundwater Resources

HA Name	Perennial Yield[a] (afy)	Committed Groundwater Rights[b] (afy)	Unappropriated Groundwater Resources (afy)
Spring Valley	94,800	10,429.51	84,370.49
Cave Valley	13,700	17.77	13,682.23
Dry Lake Valley	16,200	61.12	16,137.74
Delamar Valley	6,600	8.95	6,591.05

[a]Annual groundwater ET for Spring Valley, annual recharge for others
[b]Committed groundwater rights with priority dates earlier than October 17, 1989 (Stanka, 2011, p. ES-3).

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Appendix A

Summary of SNWA Data Collection and Analysis Activities

A.1.0 INTRODUCTION

Since the groundwater applications were filed in 1989, LVVWD and SNWA have supported the applications by conducting activities to characterize the geologic and hydrogeologic framework, and the hydrologic conditions of the Project Basins and adjacent areas. Extensive data collection and analysis have been performed to define the groundwater resources and characterize baseline hydrologic conditions. These data collection and analysis activities are summarized in this appendix.

A.2.0 GEOLOGY AND SURFACE GEOPHYSICS

Geologic and surface geophysical data collection and analyses associated with the Project Basins have been performed by SNWA since before 2003 to (1) provide an overview of the geology for an area encompassing the Project Basins, including a description of how that geology relates to the hydrogeology of the area; (2) present the geologic and hydrogeologic framework of the Project Basins and surrounding area; and (3) evaluate the framework to assess the potential for groundwater flow at selected basin boundaries.

The scope of the geologic investigations included significant data compilation and acquisition, and development of geologic and hydrogeologic surface maps and cross sections. Significant fieldwork was performed to improve the geologic understanding of selected areas. The scope of work was defined, in part, to differentiate between aquifers and confining zones, that is, HGUs with high and low hydraulic conductivity, respectively. The geologic investigation also focused on identifying areas where confining zones of sufficient thickness are present and inhibit groundwater flow. The results of the these investigations were reported in several reports published over the years (Dixon et al., 2007; SNWA, 2008a; Rowley et al., 2009), which are superseded by more recent work published in the expert report of Rowley et al. (2011).

The investigations included gravity surveys of the Project Basins and vicinity completed by the USGS through joint funding agreements with SNWA. The analysis of geophysical measurements throughout the area of interest were used to define the overall shape and thickness of basins, identify buried faults that may be either barriers, conduits, or both, to groundwater flow, provide estimates of the depth to pre-Cenozoic basement rocks, help characterize interbasin flow across boundaries as likely, unlikely, or permissible, and to assist in describing aquifers. The survey results are published in several USGS reports (Scheirer, 2005; Mankinen, 2007; Mankinen et al., 2006, 2007, 2008; Mankinen and McKee, 2009, 2011; Rowley et al., 2009).

In conjunction with the gravity surveys, audiomagnetotelluric (AMT) surveys were performed to characterize targeted faults and stratigraphy within the Project Basins, as well as, estimate the depth to pre-Cenozoic basement. AMT technology detects variations in shallow, subsurface electrical resistivity, which is largely dependent on the fluid content, porosity, density, fractures, and conductive mineral content of the subsurface geology. The results are presented as a cross section along a linear profile, providing information on the third dimension in the geologic framework. Several reports prepared by the USGS and document the findings of these surveys (McPhee et al., 2007, 2008, and 2009; Layne Geosciences, 2009; and Pari and Baird, 2011).

A.3.0 SNWA Monitor and Test Wells and Spring Piezometers

SNWA has implemented drilling programs within the Project Basins and other neighboring basins for the purposes of refining interpretations of the hydrogeologic framework and groundwater flow through the acquisition and analysis of new data, and baseline and long-term monitoring of groundwater levels. Through the implementation of these programs, monitor and test wells have been completed in the basin-fill, carbonate and volcanic aquifers, and shallow piezometers installed at selected spring sites to monitor groundwater levels (Figure A-1).

A.3.1 Monitor and Test Wells

SNWA has installed a total of 39 monitor and test wells to support its water-right applications. These wells were completed within the following basins:

- Cave Valley (HA 180): 3 monitor wells and 1 test well
- Delamar Valley (HA 182): 2 monitor wells
- Dry Lake Valley (HA 181): 2 monitor wells
- Spring Valley (HA 184): 14 monitor wells and 6 test wells
- Coyote Spring Valley (HA 210): 6 monitor wells
- Muddy River Springs Area (HA 219): 1 monitor well
- Pahranagat Valley (HA 209): 1 monitor well
- Tikaboo Valley North (HA 169A): 3 monitor wells

The 10 monitor wells installed in Delamar, Dry Lake, Cave, Pahranagat, and Tikaboo North valleys are part of a monitor-well network installed in 2005. Eight monitor wells and six test wells in Spring Valley were installed between 2006 and 2008, and an additional six monitor wells during 2010 and 2011. The third monitor well and the test well located in Cave Valley were installed in 2007. The monitor wells in Coyote Spring Valley and MRSA were installed by SNWA prior to 2005.

Data collected during monitor and test well construction and hydraulic testing were used to help evaluate the geologic and hydrologic characteristics of the aquifer system. These tests are as follows:

- Drilling parameters, lithologic samples, and geophysical data were logged and documented during the drilling operations. These data are presented in several geologic analysis reports documenting the well construction activities associated with these wells (Eastman, 2007a through g; Eastman and Muller, 2009a through d; Eastman and Dano, 2009a and b; Dano and Muller, 2009; Mace, 2011a, b, and c, Mace and Muller, 2010a through d; Pari and Mace, in

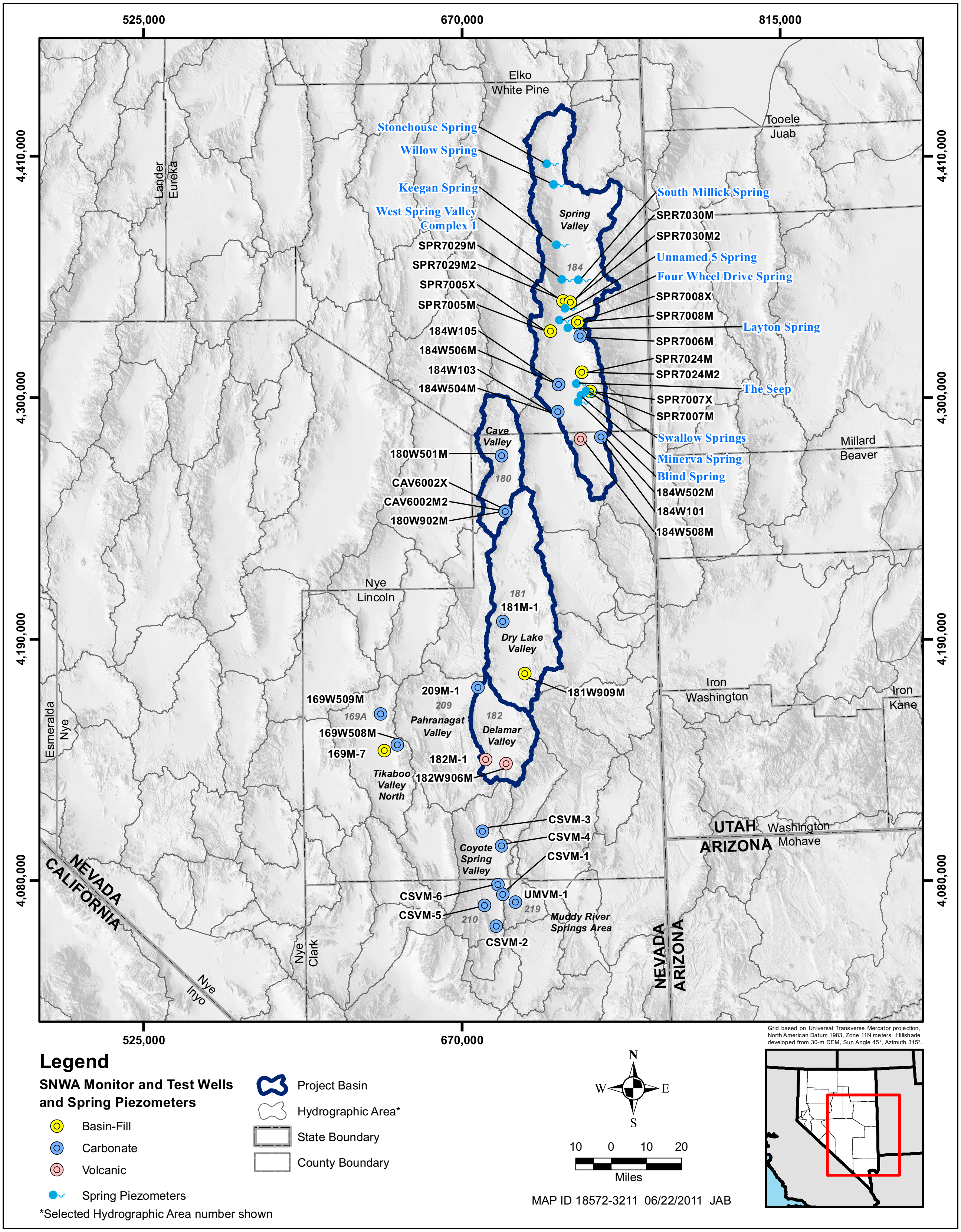

Figure A-1
Location of SNWA Wells and Piezometers within the Project Basins and Vicinity

press; Baird, 2011; Muller et al., 2009, and Converse Consultants, 2009a and b), and were used in the development of the geologic framework model presented in Rowley et al. (2011).

- Recent water-level data collected from the SNWA wells were compiled up to October 2010 and are included in the well inventory presented in Appendix C.

- Short-term, single-well-pumping tests, generally seven to eight hours in duration, were performed at limited discharge rates at selected monitor wells after installation to assess the viability of a test well at each site for extended aquifer testing.

- Test wells were subjected to extensive development after completion. A step-drawdown test, followed by a 72- to 120-hour constant-rate test, and a recovery test were performed on each test well. The aquifer-test information for test wells completed in the carbonate aquifer was used to update the existing data. The updated data set is included in the data set presented in Appendix C.

- Aquifer test data analyses have been completed for tests performed at the test wells, and have been used along with existing data to estimate interbasin flow in this groundwater-resource assessment (Appendix E). The details of all well testing information are provided in a series of SNWA reports (Prieur et al., 2009; 2010a, b, and c; 2011a, b, and c).

- Water-chemistry samples were collected for a limited suite of chemical parameters at the end of the short-term tests. Water-chemistry samples were collected during the constant-rate test for an extensive suite of chemical parameters; the resulting data are documented in the SNWA reports (Prieur et al., 2009; 2010a, b, and c; 2011a, b, and c) and internal databases, and also in Thomas and Mihevc (2011).

A.3.2 Spring Valley Spring Piezometers

Thirteen piezometers adjacent to representative spring complexes in Spring Valley were installed for the purposes of monitoring groundwater levels near the spring orifices, and to fulfill the requirements of the Spring Valley Hydrologic Monitoring and Mitigation Plan Status and Data Report (SNWA, 2011a). The locations of these piezometers are depicted on Figure A-1.

A.4.0 Evapotranspiration Studies

In 2004, SNWA initiated a study with UNLV to measure ET at sites located within the groundwater discharges areas of Spring and White River Valleys. The study was expanded in 2007 to include additional sites in Spring Valley and new sites in Snake Valley, and expanded again in 2009 by funding DRI to maintain and operate additional sites in Spring Valley. Spring and Snake valleys were selected for the study because of their large discharge areas and because of the potential for water-resource development in these basins by SNWA. Because SNWA also holds applications in hydrographic basins of the WRFS, White River Valley was selected for the study because it contains the largest groundwater discharge area in the flow system.

SNWA's primary objective for initiating these studies was to refine previous estimates of annual ET rates using newer methodologies to support the development of groundwater budgets in the basins of interest. Both studies used eddy covariance systems to measure ET rates for specific plant communities, and remote sensing methods to scale those rates to estimate annual ET for the entire groundwater discharge areas. Eddy covariance stations were eventually established in all three valleys for the UNLV study, and included one in White River Valley, three in Spring Valley and two in Snake Valley. The DRI study was performed only for Spring Valley and utilized four new EC stations. The locations of the stations are presented in Figure A-2. ET data collected during 2006 through 2010 were utilized in this water-resource assessment and are reported in Shanahan et al. (2011). The data types and related analyses utilizing these data are summarized as follows:

- Types of data collected from the ET sites between 2006 and 2010 include precipitation, groundwater levels, soil, and EC data. The data collection, quality-assurance, and reduction culminating in annual ET rates for each station and each year are presented in a data report prepared by Shanahan et al. (2011).

- Regression analysis was performed to derive an empirical relationship between growing-season average NDVI and annual ET using satellite imagery and EC-station data collected at sites located within the groundwater discharge areas of Spring, Snake and White River Valleys. This work was performed in cooperation with DRI and reported in (Fenstermaker et al., 2011).

- Finally, the annual estimates of ET distribution and volumes for the groundwater discharge areas were combined with estimates of ET for agricultural lands, playas and open water to estimate the total ET for Spring and White River valleys. The total ET estimates were then adjusted to reflect groundwater ET only by removing the effect of precipitation. This part of the analysis is documented in Appendix D of this report.

A.5.0 HYDROLOGIC MONITORING

Hydrologic monitoring performed by SNWA is described in the SNWA Hydrologic Monitoring, Management and Mitigation Program presented in Prieur (2011), and is summarized in this section. The future hydrologic monitoring locations at groundwater, spring, and stream sites associated with the hydrologic monitoring plans (HMPs) comprising the Program are also presented in Prieur (2011).

Hydrologic and water-chemistry data collected pursuant to the HMPs are provided to the NSE and DOI on a quarterly basis and in annual data reports which have been published since 2008 (SNWA 2008b and c; 2009a through d; 2010a and b; 2011a and b). The data collected for each element of the HMPs as of January 2011 is presented in the 2010 data reports.

SNWA also performs substantial supplemental hydrologic monitoring beyond the scope of the HMPs, which has increased understanding of hydrologic conditions within the Project Basins and vicinity. Some of the activities include collection of regional hydrologic data in east-central Nevada and western Utah by SNWA and by the USGS through cooperative funding agreements. The scope of data collection in these agreements and other SNWA monitoring activities includes continuous and

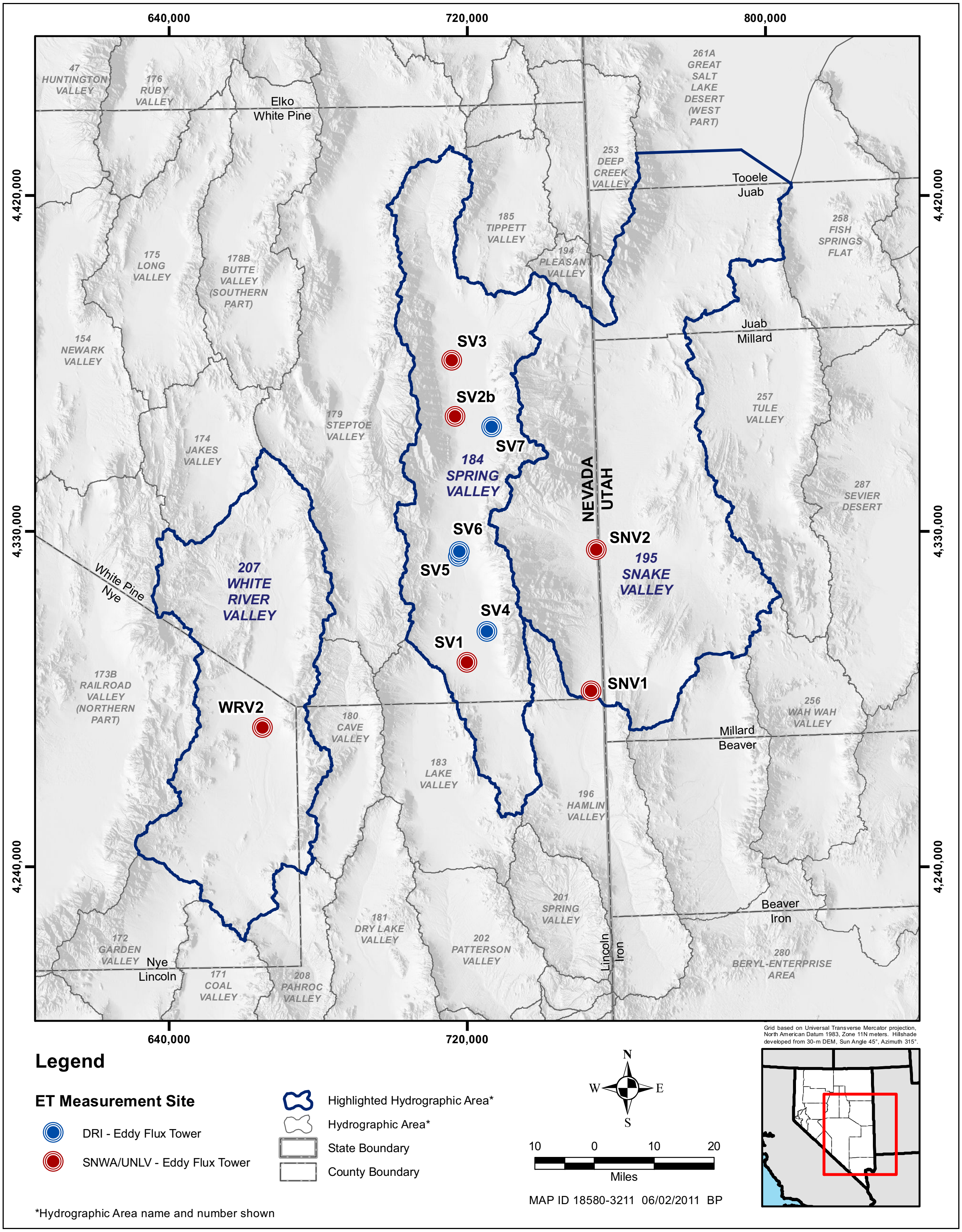

Figure A-2
Location of SNWA and DRI ET-Measurement Sites

periodic measurement of surface-water and spring discharge at numerous surface-water sites, and continuous and periodic measurement of groundwater levels.

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Appendix B

Spatial Precipitation Distribution

B.1.0 INTRODUCTION

Precipitation plays an essential role in the hydrology of the area of interest and the Project Basins because it is the main source of surface water and groundwater. Precipitation is also an important parameter in the estimation of groundwater ET for the Project Basins. Measured ET rates represent total ET rates which must be reduced by the amount of precipitation stored in the unsaturated zone to yield rates of groundwater ET. Precipitation data used to estimate groundwater ET are presented in Appendix D of this document. This appendix only discusses precipitation information used to support the estimation of recharge efficiencies described in Appendix F.

B.2.0 OBJECTIVE

The objective of this analysis is to select a spatial distribution of precipitation that approximates long-term mean conditions for use in estimating a spatial recharge distribution for the Project Basins and vicinity. Long-term mean conditions are represented by mean precipitation values for the historical period of record.

B.3.0 APPROACH

The approach followed to achieve the objective described above consists of the following steps:

1. Identify and evaluate methods available to generate spatial distributions of precipitation and select the best available method to generate precipitation distribution over the area of interest.

2. Describe the precipitation distribution selected to represent long-term mean conditions over the area of interest.

3. Select precipitation stations located within the area of interest for use in the evaluation of the selected precipitation distribution. Derive period-of-record means and ranges of uncertainty for selected stations.

4. Compare the selected precipitation distribution to the selected stations period-of-record means to ensure that the selected method of spatial precipitation distribution is representative of long-term average conditions. Use the period-of-record means of precipitation for Nevada U.S. Climate Divisions to support this evaluation.

The available methods used to generate spatial distributions of precipitation and a description of the method selected for this analysis are presented first.

B.4.0 PRECIPITATION SPATIAL DISTRIBUTION METHOD

Spatial precipitation patterns are highly variable and depend on many factors. As a result, the spatial distribution of precipitation cannot be directly derived from station data by simple interpolation for example, especially considering the sparsity of the available station data. However, several methods are available and have been used to estimate the spatial distribution of precipitation. These methods are briefly presented in this section, followed by a more detailed description of the selected method.

B.4.1 Available Methods

Available methods used to derive precipitation distributions in Nevada include the Hardman maps (Hardman, 1936, 1962, 1965), PRISM (Daly et al., 1994, 1997, 1998, 2008), and the precipitation-altitude regression models.

- Hardman (1936) developed a hand-drawn precipitation contour map for Nevada using U.S. Weather Bureau records, USGS topographic maps, and Nevada Experiment Station forage-type maps. The Hardman map includes six precipitation zones, defined as follows: less than 5 in., 5 to 8 in., 8 to 12 in., 12 to 15 in., 15 to 20 in., and over 20 in. This map was also published in Hardman and Mason (1949) and was later updated by Hardman (1962 and 1965). This updated map was later revised by the NSE (Scott et al., 1971). The original Hardman (1936) precipitation map is used in the Maxey-Eakin recharge method (Maxey and Eakin, 1949).

- PRISM is a mapping model of climate variables developed by the NRCS in partnership with the Climate Center and the PRISM Group at Oregon State University (Daly et al., 1994, 1997, 1998). Daly et al. (1997, p. 1) describe PRISM as "...a coordinated set of rules, decisions, and calculations, designed to approximate the decision-making process an expert climatologist would invoke when creating a climate map." The basic information used in PRISM consists of point measurements of a given climate variable (e.g., precipitation) and a digital-elevation model (DEM). The PRISM model is designed to fit local linear regressions of climate variables versus slopes representing topography that vary with elevation. The local regressions account for spatially-varying elevation relationships; the effectiveness of terrain as barriers, terrain-induced climate transitions (rain shadows), cold air drainage and inversions, and coastal effects (Daly, 2006). PRISM products include grids of precipitation, temperature, and other climate variables for a given period of time and monthly, yearly, and event-based climatic parameters. PRISM has been used to estimate precipitation for each state of the United States, including Nevada (Daly et al., 1998).

- Precipitation-altitude regression models have been developed for many areas of Nevada to derive precipitation distributions and to estimate precipitation volumes (Quiring, 1965; Daly et al., 1994; Maurer and Halford, 2004). The regression models are defined by equations that express the relationship between precipitation and altitude based on station data compiled from various sources. The equation are then applied to DEMs to derive precipitation distributions. Typically, the regression models are developed for local-scale (e.g., hydrographic area) analyses where the data density is relatively high. For large areas with sparse precipitation data, the derived distribution of precipitation may not be representative of reality.

B.4.2 Selected Method

The main criterion for the selection of the precipitation distribution for use in the recharge estimate is a spatially-accurate distribution of precipitation. The magnitude of the precipitation volume does not have a direct impact on the volume of recharge from precipitation. The PRISM method (Daly et al., 1994, 1997, 1998, 2008), which incorporates important physical processes and uses state-of-the-art spatial methods, was selected to approximate the precipitation distribution of the area of interest. The precipitation maps constructed by Hardman (1936, 1962, 1965) were rejected simply because they were developed using the archaic methods and sparse station data available at the time. Development of a separate precipitation-altitude regression model was rejected because it would duplicate the PRISM work and would yield a product of lesser quality.

The PRISM data sets, including those of precipitation, are developed for the conterminous United States and represent state-of-the-art distributions at the basin and regional scales. The PRISM data sets are recognized worldwide as the highest-quality spatial climate data sets currently available. The U.S. Department of Agriculture, for example, adopted PRISM as its official climatological data set (Daly et al., 2008). The PRISM method uses modern tools and incorporates more recent station data and information not reflected in previous mapping efforts. More recent data include additional stations and precipitation records. Additional information not reflected in previous mapping efforts includes the use of the DEM to represent the topography to simulate rain-shadow effects.

Several PRISM precipitation grids are available at many sites on the Internet (e.g., http://www.prism oregonstate.edu/products/). The grids include precipitation distributions for various periods of time and different resolutions. All PRISM precipitation grids are based on the 1-degree DEM grid available at http://edc.usgs.gov/guides/dem.html. The detailed station-precipitation data set used to generate the PRISM maps is not available to the public.

B.5.0 PRECIPITATION DISTRIBUTION

The precipitation distribution used to generate the recharge distribution, the available information used to evaluate this distribution, and the evaluation process and results are described in this section.

B.5.1 Description

The precipitation distribution for an area encompassing Spring Valley and the entire WRFS was extracted from the most recent PRISM normal precipitation grid (800-m 1971 to 2000 precipitation normals, Version 3, May, 10, 2010), which is available from the PRISM website (PRISM, 2010a).

Changes to the normal grid from the previous version (Version 2, May 3, 2007) include improvements to the station period averaging scheme and minor changes to the model parameterizations (PRISM, 2010b). The distribution of the precipitation values extracted from the 800-m PRISM precipitation grid for the area of interest is shown in Figure B-1.

B.5.2 Precipitation-Station Data

Precipitation-station data are needed to evaluate whether the 800-m PRISM precipitation grid is representative of long-term mean conditions. Thus, the available precipitation-station data were compiled and analyzed to fulfill this purpose. The needed data types and identified sources are presented, followed by descriptions of the data compilation and reduction, data-quality evaluation, and finally the identification of period-of-record statistics.

B.5.2.1 Data Types and Sources

In general, the data sets of interest include site attribution, reported precipitation values, and summary statistics. Specific station attribution includes the following:

- Station Name
- Location data (x- and y-coordinates)
- Altitude
- Date (may be any period of time from one hour to years)
- Depth of Precipitation (inches)

The available precipitation-station data for the Project Basins and adjacent valleys were obtained from the following sources:

- The NCDC which is a division of National Oceanic and Atmospheric Administration (NOAA) and is the national repository of weather data.

- The WRCC which is one of six regional climate centers in the United States that are administrated by NOAA.

- The NDWR which maintains a network of high-altitude precipitation stations in Nevada.

- The USGS (Nevada District) which maintains a network of moderate to high-altitude precipitation stations in Nevada.

- The NRCS which maintains the SNOTEL sites in which continuous precipitation data are collected.

- The RAWS network which maintains a network of stations monitoring various environmental variables, including precipitation.

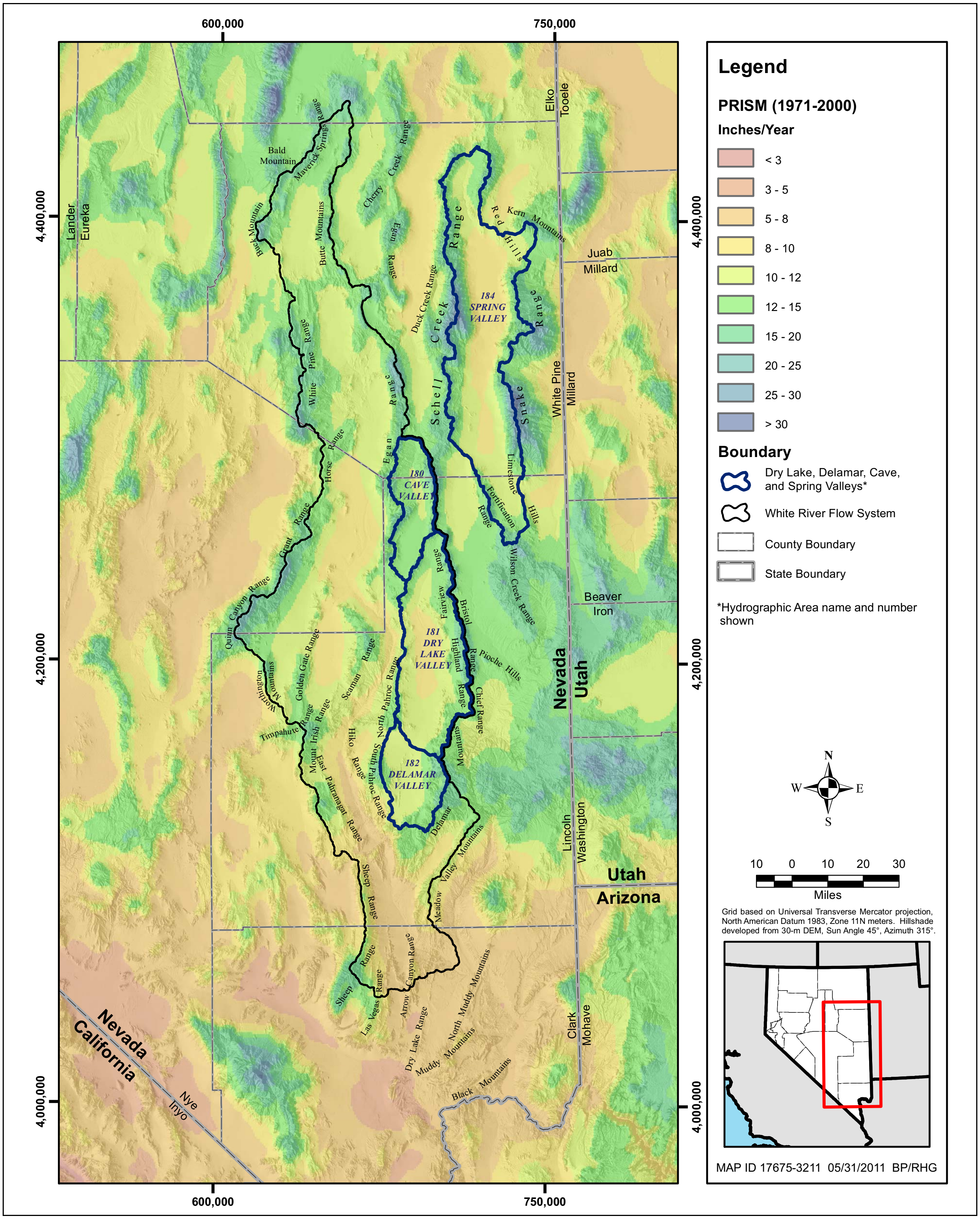


Figure B-1
800-m PRISM Precipitation Distribution over Spring Valley, White River Flow System, and Vicinity

B.5.2.2 Data Compilation and Reduction

Precipitation data collected at stations located throughout the area of interest were compiled and then reduced to a subset for further analysis.

The available precipitation-station data were obtained from the identified data sources through the end of 2010 calendar year.

- Monthly total precipitation reports were automatically generated from the WRCC website (WRCC, 2010). The monthly report includes long-term monthly and annual summary statistics. Long-term annual statistics were reported for sites with 12 months of reported data with no less than 5 days of missing data in a single month. Data for NCDC stations not included in the WRCC data set were obtained from NCDC through EarthInfo, Inc. (EarthInfo, 2009) in the form of CDs. The NCDC Summary of the Day CDs contain daily weather observations from over 20,000 stations throughout the United States. The NCDC data used in this analysis are limited to data collected prior to December 31, 2008.

- The NDWR data were requested and obtained from the State of Nevada (Sullivan, pers. comm., 2011). Most of the NDWR precipitation data have been collected at the same or a nearby location since the mid-1950s or 1960s. The locations of the sites are within the mountain blocks at moderate to high altitudes. Precipitation is collected in bulk-storage gages. The NDWR precipitation data are collected and reported on an annual basis.

- The NRCS SNOTEL data-collection network measures precipitation, air temperature, and snow water equivalence (SWE) for numerous river basins in the United States. Within the area of interest, these stations are located within the mountain blocks and at high altitudes. Daily precipitation data from the SNOTEL sites were downloaded from the NRCS website and used to calculate the period-of-record annual average. No long-term statistics are reported for the SNOTEL sites, only individual annual water year statistics. However, because the data are continuous and 100 percent complete, calendar year or water-year totals can be calculated with relative ease. The annual water-year statistics were organized in a manner that facilitated the calculation of long-term calendar year statistics.

- The USGS precipitation data included in this analysis were collected as part of a program initiated under joint-funding agreements between the USGS, LVVWD, and NDWR. The network was designed to augment the existing NDWR network by providing precipitation data from new locations and at higher altitudes. The sites are located in the mountain blocks at moderate to high altitudes, and accessibility restrictions due to the weather may cause maintenance delays. The gages are based on designs that are very similar to those of the NRCS SNOTEL bulk-storage gages. These sites are visited on a semi-annual basis. The data are available from the USGS website.

- Monthly summary time-series of precipitation data were downloaded from the RAWS online database. Annual precipitation values and associated statistics are reported in this database for months with less than 30 percent of missing data for any one given month. Period-of-record annual summary statistics were automatically derived from the database.

The data were then combined into a single data set and organized by data source to facilitate subsequent evaluation and analysis. The complete data set contains data for a total of one hundred and twenty-nine (129) regional precipitation stations. One hundred and four (104) stations have records sufficient to report relevant period-of-record annual statistics, and more than half of those stations (59) have a minimum of 20 years of available “non-zero” years of data. The stations with at least 20 years of “non-zero” were selected for further analysis and are listed in Table B-1 and shown in Figure B-2 by data source. The selected precipitation stations exclude 7 low-quality RAWS sites for reasons described in Section B.5.2.3, and include all stations qualified as “climate normal” by the NCDC. A “non-zero” year of reported annual precipitation is a year in which the reported annual precipitation was greater than zero. These sites range in elevation from 1,250 to 10,650 ft amsl and their reported precipitation ranges from 5.31 in. near the southern end of the area of interest, to 27.54 in. at the Berry Creek SNOTEL site.

B.5.2.3 Data-Quality Evaluation

The quality of the precipitation-station source data sets was evaluated in two ways: (1) the reported locations/land surface elevations were verified; and (2) the precipitation values were evaluated based on data qualifiers assigned by the originating entity, data documentation, methods of data collection, and reporting frequency. While this evaluation was not explicitly represented in the data analysis by applying weights or associated accuracies to the data, it was relied upon in discussing the results of the analysis.

To verify the location and altitude data for each precipitation station, the coordinate and altitude data were first transformed to common datums (UTM Zone 11, NAD83; NAVD88). Upon completion of this process, the station data were checked against the USGS 30-m DEM to identify differences between their altitudes. For most stations, except a few, the reported altitude matched the DEM altitude value closely (within 600 ft). The exceptions are as follows:

- Sites with erroneous land surface elevations: McGill Junction and Dale. Both of these sites have less than 20 years of non-zero data.

- Sites with missing land surface elevations: Alamo, and Matthew Ranch. Of the two sites, only Alamo has 20 years of non-zero data. The DEM value at the Alamo site was used to represent the land surface elevation.

The quality of the precipitation values was evaluated based on data qualifiers assigned by the source agency, data documentation, methods of data collection, and reporting frequency. While this evaluation was not explicitly represented in the data analysis by applying weights or associated accuracies to the data, it was relied upon in discussing the results of the analysis.

- The database maintained by NCDC is the most comprehensive climate source in the United States. NCDC also defines and qualifies “climate normals,” which have been subjected to strict quality-control procedures. The NCDC climate normal represents the arithmetic mean of a climatological element computed over three consecutive decades (WMO, 1989, p. 2 and 3) and following a consistent methodology to produce a time series that best represents the measured data (NOAA, 2002). For the purposes of this analysis, data from these stations are

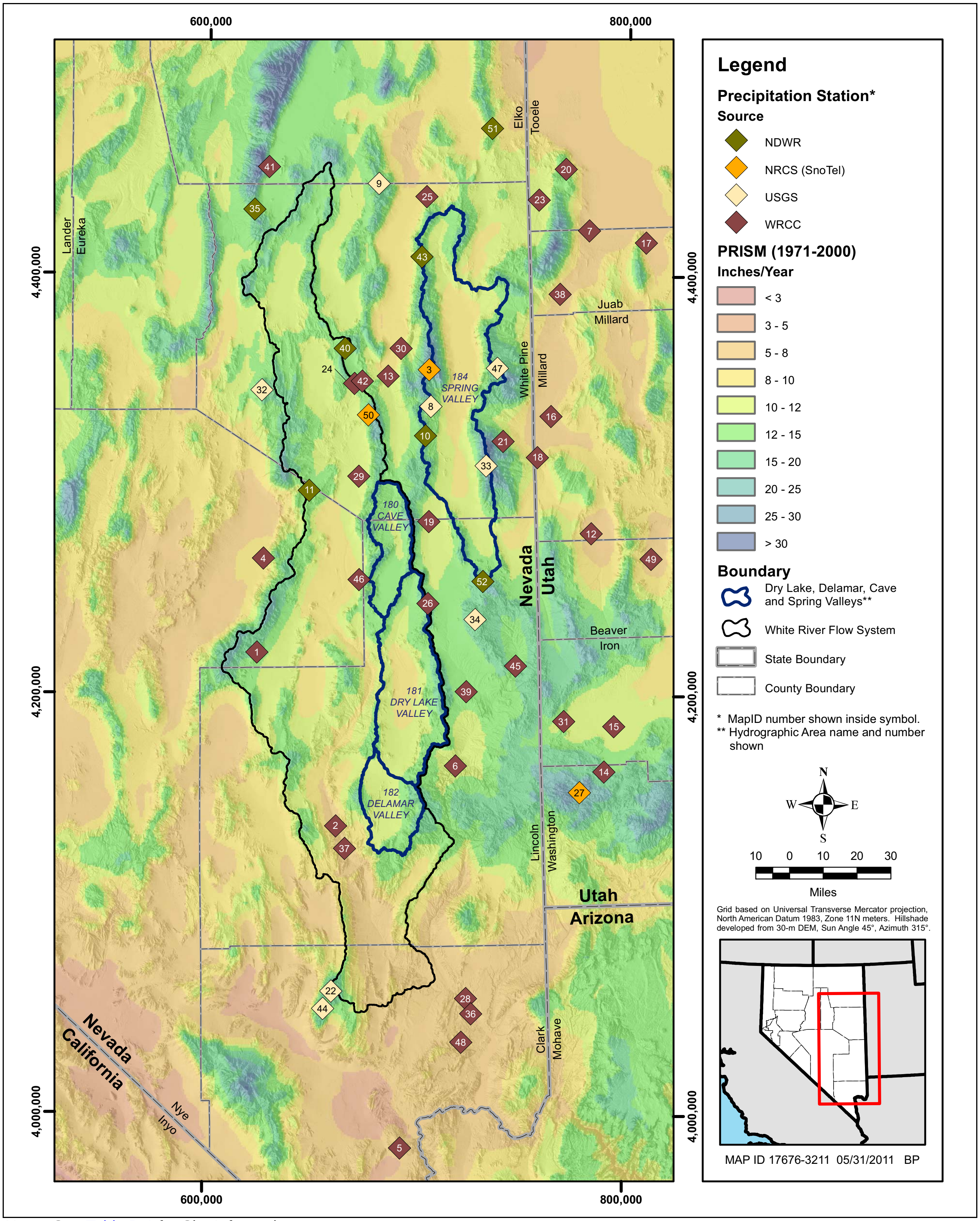
Table B-1
Precipitation Station Data Set Used in Evaluation of 800-m PRISM Distribution
(Page 1 of 2)

Map ID	Station Name	Location[a]		Source	Elevation (ft amsl)	Period-of-Record									NCDC Normals (1971-2000) Annual Average (in.)	800-m PRISM 1971-2000
		UTM Northing (m)	UTM Easting (m)			Start	End	Duration	Years of Non-zero Precipitation	Annual Average (in.)	Annual Minimum (in.)	Annual Maximum (in.)	Standard Deviation (in.)	Standard Error of the Mean (Percent of Average)		
1	Adaven	4,219,708	624,186	WRCC	6,250	1914	1982	69	50	12.94	4.42	23.64	4.13	4.51	---	14.25
2	Alamo	4,137,126	662,343	WRCC	3,480[b]	1921	1962	42	20	6.34	1.23	11.16	2.93	10.33	---	6.98
3	Berry Creek	4,354,989	705,169	NRCS (SNOTEL)	9,100	1976	2010	35	28	27.54	17.20	39.30	5.83	4.00	27.4	28.48
4	Blue Eagle Ranch Hank	4,264,579	626,889	WRCC	4,780	1978	2010	33	27	8.54	4.41	15.11	2.96	6.67	8.78	8.59
5	Boulder City	3,983,875	694,163	WRCC	2,500	1931	2004	74	63	5.63	0.67	13.36	2.69	6.02	6.32	5.76
6	Caliente	4,166,217	719,251	WRCC	4,400	1903	2010	108	67	8.63	1.84	18.73	3.22	4.56	9.92	9.99
7	Callao	4,421,802	781,034	WRCC	4,342	1902	2010	109	67	5.68	0.94	10.59	2.04	4.39	6.28	6.25
8	Cave Mountain	4,337,545	706,107	USGS	10,650	1983	2009	27	26	20.21	12.00	32.16	5.11	4.96	---	22.03
9	Cherry Creek Range	4,443,653	680,593	USGS	9,700	1983	2009	27	26	15.55	7.75	26.25	4.63	5.84	---	16.33
10	Connors Pass	4,323,532	703,651	NDWR	7,740	1953	2010	58	51	13.96	3.40	23.94	4.01	4.02	---	15.40
11	Current Creek NDWR	4,297,077	648,450	NDWR	6,830	1953	2010	58	53	12.88	6.00	24.49	3.86	4.12	---	13.86
12	Desert Exp Range	4,277,401	783,035	WRCC	5,249	1950	1984	35	33	6.22	2.40	10.68	2.12	5.93	---	7.13
13	Ely WBO	4,351,755	685,692	WRCC	6,262	1893	2010	118	79	9.57	4.22	16.16	2.85	3.35	9.97	9.83
14	Enterprise	4,163,891	790,106	WRCC	5,320	1905	2010	106	51	13.99	5.08	28.61	4.65	4.65	14.76	14.70
15	Enterprise Beryl Jct	4,185,535	794,591	WRCC	5,150	1940	2008	69	43	10.35	5.65	16.53	2.42	3.57	10.58	10.70
16	Eskdale	4,333,158	763,441	WRCC	4,980	1966	2010	45	29	6.34	3.18	12.57	2.32	6.80	6.63	6.97
17	Fish Springs Refuge	4,416,211	808,238	WRCC	4,357	1960	2010	51	42	7.83	3.89	12.64	2.26	4.45	8.16	7.75
18	Garrison	4,313,564	757,154	WRCC	5,260	1903	1990	88	30	7.42	4.35	14.69	2.37	5.83	7.70	8.30
19	Geyser Ranch	4,282,623	705,658	WRCC	6,020	1904	2002	99	20	9.06	1.65	19.04	4.00	9.87	---	10.50
20	Gold Hill UT	4,451,066	769,671	WRCC	5,250	1966	1990	25	15	11.55	5.29	22.08	4.56	10.19	---	11.22
21	Great Basin NP	4,321,069	740,678	WRCC	6,850	1948	2010	63	54	13.32	7.37	21.20	3.19	3.26	13.61	13.66
22	Hayford Peak USGS	4,058,445	660,853	USGS	9,840	1985	2009	25	24	15.80	6.50	38.25	7.61	9.83	---	16.09
23	Ibapah	4,436,297	756,954	WRCC	5,279	1903	2010	108	47	9.91	3.20	16.41	2.87	4.22	10.54	10.52
24	Kimberly	4,348,213	669,663	WRCC	7,234	1928	1958	31	25	13.28	6.86	19.95	3.57	5.38	---	12.84
25	Lages	4,437,512	703,405	WRCC	5,960	1984	2010	27	23	8.14	4.10	13.20	2.29	5.87	7.90	9.05
26	Lake Valley Steward	4,243,564	705,447	WRCC	6,350	1971	1998	28	20	16.05	9.39	28.29	5.15	7.17	---	15.63
27	Little Grassy	4,153,894	778,503	NRCS (SNOTEL)	6,100	1985	2010	26	25	24.73	9.60	45.50	9.13	7.38	24.30	23.81

Table B-1
Precipitation Station Data Set Used in Evaluation of 800-m PRISM Distribution
(Page 2 of 2)

Map ID	Station Name	Location[a]		Source	Elevation (ft amsl)	Period-of-Record									NCDC Normals (1971-2000) Annual Average (in.)	800-m PRISM 1971-2000
		UTM Northing (m)	UTM Easting (m)			Start	End	Duration	Years of Non-zero Precipitation	Annual Average (in.)	Annual Minimum (in.)	Annual Maximum (in.)	Standard Deviation (in.)	Standard Error of the Mean (Percent of Average)		
28	Logandale	4,055,299	725,064	WRCC	1,410	1968	1992	25	21	5.31	3.23	9.81	1.93	7.93	---	5.55
29	Lund	4,303,974	672,091	WRCC	5,546	1957	2010	54	44	10.09	4.99	18.83	2.91	4.35	11.01	10.93
30	McGill	4,365,043	691,693	WRCC	6,270	1892	2010	119	89	8.86	3.76	16.21	2.54	3.04	8.74	8.87
31	Modena	4,187,863	770,699	WRCC	5,460	1901	2004	104	69	10.00	4.17	19.07	3.14	3.78	10.94	10.68
32	Mount Hamilton	4,344,781	625,558	USGS	10,600	1983	2009	27	24	21.31	9.00	43.75	8.45	8.09	---	21.41
33	Mount Washington	4,309,377	732,764	USGS	10,440	1983	2009	27	26	25.56	12.00	52.00	8.98	6.89	---	26.79
34	Mount Wilson	4,236,084	728,118	USGS	9,200	1983	2009	27	22	19.53	3.00	47.00	10.42	11.38	---	20.21
35	Overland Pass 2	4,430,903	621,477	NDWR	6,740	1953	2010	58	47	14.30	9.60	23.32	3.63	3.70	---	13.92
36	Overton	4,048,053	727,517	WRCC	1,250	1939	2010	72	38	4.69	0.71	12.37	2.64	9.13	---	5.00
37	Pahranagat WR	4,126,390	666,716	WRCC	3,400	1964	2010	47	29	6.42	2.23	11.54	2.26	6.54	6.61	6.50
38	Partoun	4,391,420	767,275	WRCC	4,780	1905	2010	106	44	6.92	2.03	12.34	2.38	5.18	7.18	7.41
39	Pioche	4,201,608	724,101	WRCC	5,990	1888	2010	123	62	13.85	3.81	27.29	4.63	4.25	13.76	14.15
40	Robinson Summit	4,364,871	665,017	NDWR	7,630	1953	2010	58	43	14.61	10.15	22.65	3.07	3.20	---	15.93
41	Ruby Lake WRCC	4,451,291	628,254	WRCC	6,019	1940	2010	71	61	13.17	5.94	23.86	3.59	3.49	13.66	14.14
42	Ruth	4,349,372	673,282	WRCC	6,858	1958	2010	53	33	12.28	6.68	19.46	3.24	4.59	12.45	12.35
43	Schellbourne Pass	4,408,812	701,241	NDWR	7,580	1953	2010	58	51	14.39	0.00	26.80	5.37	5.23	---	12.75
44	Sheep Peak	4,050,080	656,908	USGS	9,600	1985	2009	25	22	13.62	3.00	29.50	7.42	11.61	---	14.98
45	Spring Valley SP	4,214,070	747,476	WRCC	5,950	1974	2010	37	21	12.15	5.05	23.48	4.49	8.06	12.23	12.95
46	Sunnyside	4,254,668	672,599	WRCC	5,297	1891	2010	120	28	9.41	5.73	17.11	2.98	5.98	10.37	10.61
47	Unnamed Peak Northwest of Mount Moriah	4,355,938	737,691	USGS	9,300	1983	2009	27	24	17.95	8.50	28.75	5.46	6.21	---	17.21
48	Valley of Fire SP	4,034,487	722,940	WRCC	2,000	1972	2010	39	36	6.71	1.66	16.90	3.32	8.25	6.50	6.28
49	Wah Wah Ranch	4,265,468	811,730	WRCC	4,880	1955	2008	54	39	6.71	3.12	11.26	2.03	4.84	6.91	7.21
50	Ward Mountain	4,333,184	676,331	NRCS (SNOTEL)	9,200	1978	2010	33	29	24.17	12.80	39.70	6.90	5.15	22.40	22.57
51	White Horse Pass	4,470,239	734,374	NDWR	6,038	1953	2010	58	45	9.05	2.70	16.25	3.05	5.02	---	10.52
52	Wilson Creek Summit	4,254,245	731,613	NDWR	7,370	1953	2010	58	54	16.62	7.50	28.30	4.80	3.93	---	17.93

See Figure B-2 for locations.
[a]UTM, NAD83, Zone 11N.
[b]Replaced unreported elevation value with DEM value at reported station location.



Note: See Table B-1 for Site Information.

Figure B-2
Locations and Data Sources for Precipitation Stations Located in Area of Interest

considered to be the highest quality due to their level of quality control and long periods of record. The NWS Cooperator stations that are not qualified as climate normals are also available from the NCDC website. While these stations are not considered climate normals, they were subjected to further evaluations to determine their qualifications with respect to this analysis. The WRCC precipitation data set is a subset of the NCDC data set and includes data for the NCDC climate-normal stations and other NWS Cooperator stations. The WRCC summary statistics are considered to be of high quality.

- The NDWR data are typically very reliable if the gages are well placed and properly maintained. Because of the long periods of record and strategic placement of these stations, the NDWR data set provided important data for the data analysis. Although the stations are bulk-storage gages like the NRCS SNOTEL gages, they are not equipped to continuously measure precipitation. However, for the purposes of this analysis these data were considered to be important and were qualified as good data.

- The NRCS SNOTEL bulk-storage gages are equipped with standard sensors to measure SWE, precipitation, temperature and snow depth, which combined, give a relatively accurate record of precipitation. Site visits are conducted every year to ensure proper operation and calibration of the sensors and to perform routine maintenance on the gage. For the purposes of this analysis, the NRCS SNOTEL data were considered high-quality data because of their completeness and documentation.

- The USGS gages are not equipped to continuously measure precipitation, but, like the NDWR gages, were considered important due to their strategic placement with respect to altitude. For the purposes of this analysis, the USGS data set was qualified as good.

- The RAWS precipitation data set is of limited-quality: quality-control information related to the RAWS precipitation data is provided on the ROMAN website, which states "Quality control of precipitation data is limited to gross checks" (NOAA, 2005, p. 1). The National Wildfire Coordinating Group reports that there has been no consistent station standards applied to maintenance, fire weather network analysis, communication, and archiving for the RAWS stations until May 2005 (NWCG, 2005, p. iii). Because of these many deficiencies, the RAWS data were qualified as poor for the purposes of this analysis, and were not used.

B.5.2.4 Identification of Period-of-Record Means and Statistics

The precipitation data were then processed to identify or calculate the period-of-record average annual precipitation and associated statistics for each station with 20 years of records or more. The procedures by which individual data sets were processed varied due to the intervals in which the data were reported (i.e., daily, monthly, semi-annually, or annually). The following discussion provides a brief description of the available data sets and the procedures by which they were processed.

- The long-term annual statistics reported on the WRCC online database were used for the data analysis. Additional summary statistics were secured through CDs offered by the NCDC through EarthInfo, Inc. (2009) for precipitation sites not included as part of the WRCC online database.

- The USGS bulk storage precipitation data are reported on a water-year reporting cycle. This is inconsistent with the other agencies reporting cycles used in this analysis, so it was assumed that the water year data reported herein is in line with calendar year data reported by other agencies.

- No long-term statistics are reported for the SNOTEL sites. The monthly precipitation data statistics are provided by water year. The monthly water year statistics were organized to calculate calendar year and long-term statistics for the period of record.

- The NDWR precipitation data are collected and reported on an annual basis and required little processing to calculate the period-of-record average. Processing the data included calculating the period-of-record average and deriving the summary statistics describing the individual station records.

The summary statistics include the period of record, period-of-record average annual precipitation, minimum and maximum annual precipitation, the standard deviation of the annual average precipitation, and the standard error of the mean. For data reported on a monthly basis, the statistics were derived by summation of the period of record monthly values (average, minimums, maximums, standard deviations) for all twelve calendar months. The standard error on the mean precipitation provides a measure of the uncertainty of the mean values over the periods of record. For each station, the standard error of the mean is calculated by dividing the standard deviation by the square root of the sample size, then dividing by the average precipitation value. These values range between 3 and 12 percent, with an average standard error of 7 percent The average error of the mean is 14 percent (2 times the average standard error of the mean). For the sake of simplicity, the error on the period-of-record means for the precipitation stations were set at 10 percent for the remainder of the analysis.

The total number of years during the period of record in which the annual precipitation value was reported as zero, is an important statistic. This is because for some stations, particularly those comprising the RAWS data set, the annual precipitation was reported as zero for numerous consecutive years. This is a highly unlikely occurrence since the minimum average annual precipitation in Nevada is 3 to 4 in. (NDWR, 1992), and calls into question the reliability of some of the RAWS Stations in terms of their usefulness in accomplishing the objectives of this analysis. The summary data for the good-quality stations identified within the area of interest are presented in Table B-1, and their mean values are shown in Figure B-3.

B.5.3 Comparison of PRISM 800-m Precipitation Grid and Station Data

Four evaluations of the 800-m PRISM grid were made to ensure that the grid is appropriate to satisfy the objectives of this assessment. The first evaluation was designed to ensure that the normal grid is consistent with the normal station data, using the normal stations listed in Table B-1. The second evaluation tests how well the 800-m PRISM grid approximates the period-of-record means of the precipitation stations. PRISM precipitation grid values were interpolated at all station locations listed in Table B-1 and were compared to their period-of-record means. The third evaluation was a comparison of the 800-m PRISM precipitation grid to selected station data in areas important to

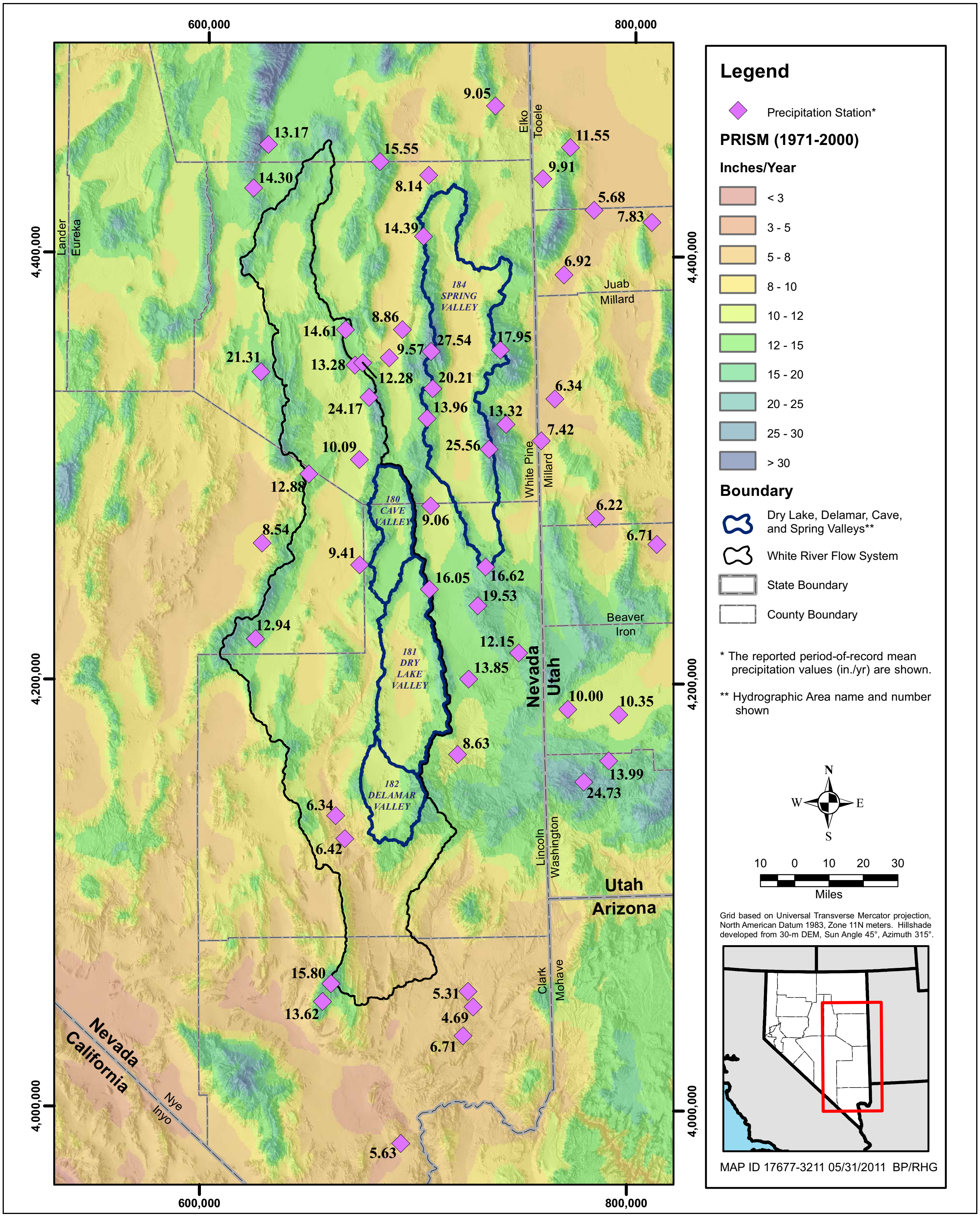
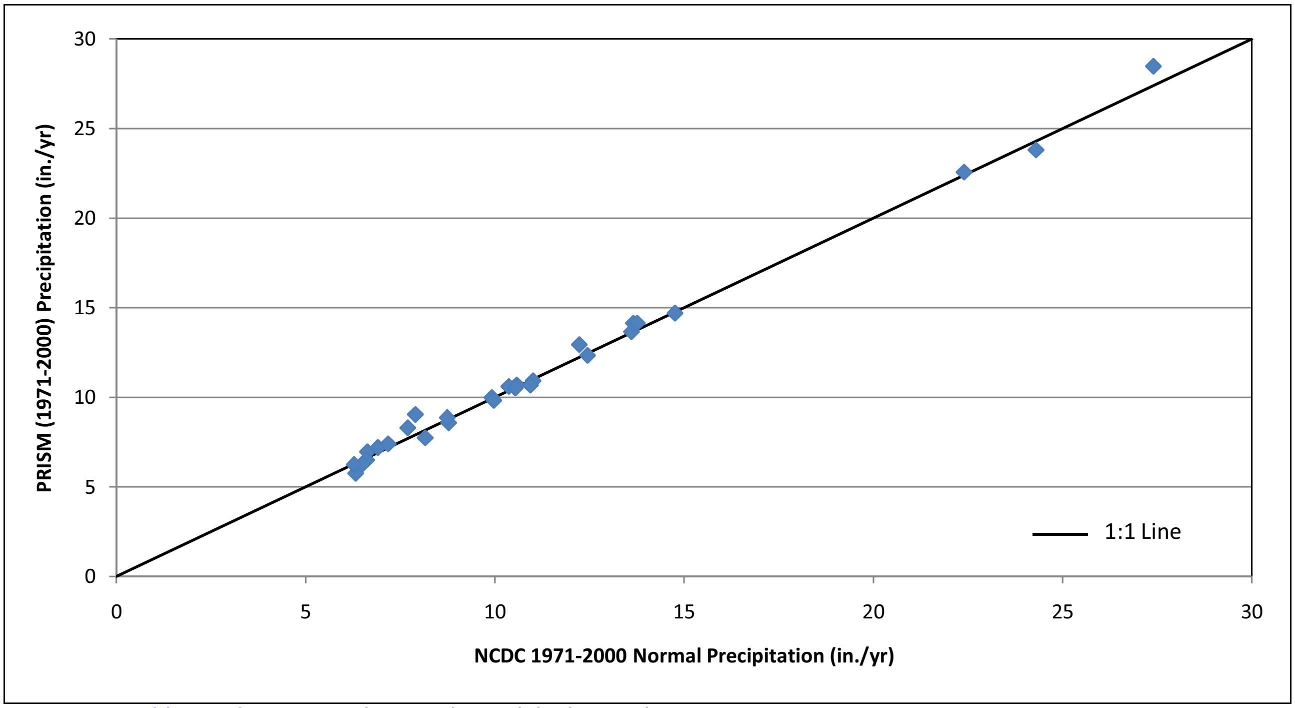


Figure B-3
Period-of-Record Mean Precipitation Values for Precipitation Stations Located in Area Encompassing Spring, Cave, Dry Lake, and Delamar Valleys

recharge for Spring Valley and the WRFS. The final evaluation consisted of gaging the temporal variability of precipitation using U.S. Climate Division data.

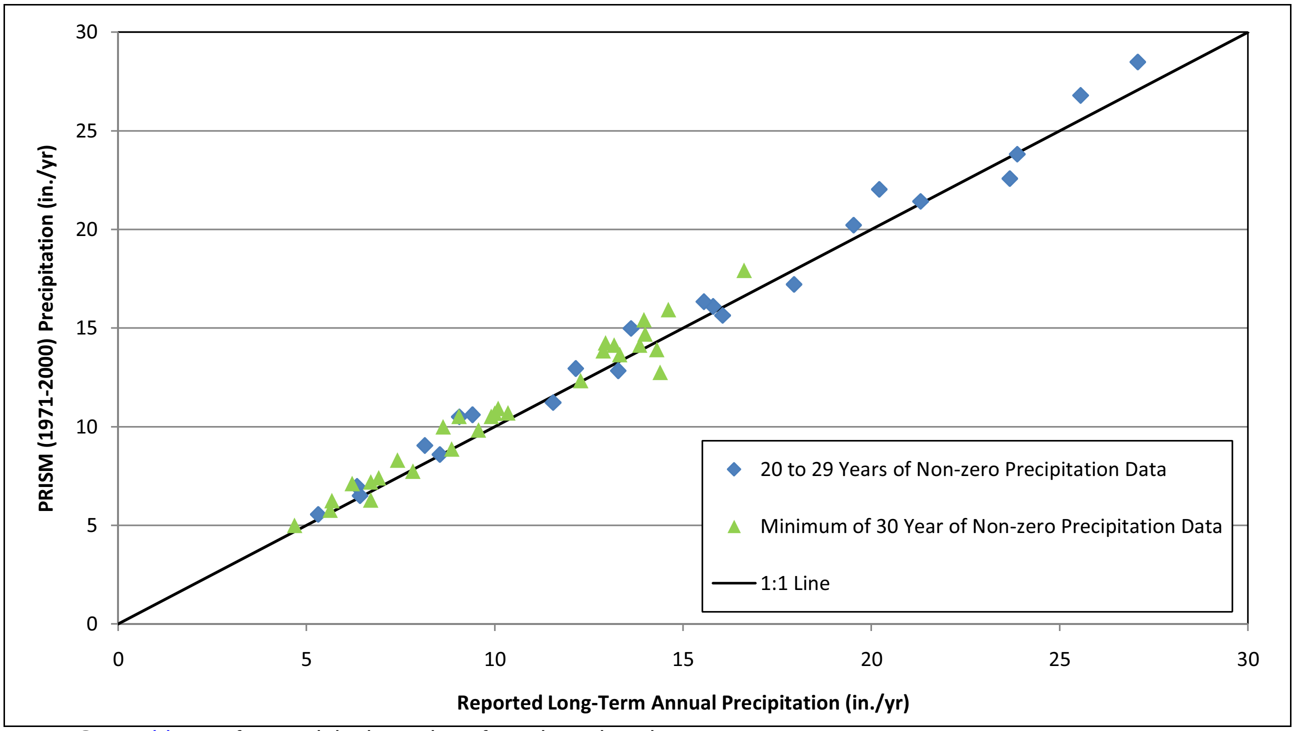
The climatological normal precipitation values for the 30-year period of 1971-2000 compiled by NCDC are available for 35 sites within the area of interest. Precipitation values were extracted from the 800-m PRISM grid (1971-2000) at the normal station locations for comparison. A graph showing the values extracted from the PRISM on the Y axis and the normal values on the X axis is presented in Figure B-4. The data points follow the 1:1 line rather closely indicating that the PRISM grid fits the normal station data very well (Figure B-4). A linear regression was also applied to the normal station data and the extracted PRISM values. The regression resulted in an adjusted R^2 value of 0.99 suggesting the two data sets have a relatively high degree of similarity.



Note: See Table B-1 for names of “normal” precipitation stations.

Figure B-4
Comparison of 800-m PRISM Precipitation Values to Normal Station Precipitation Values within Area of Interest

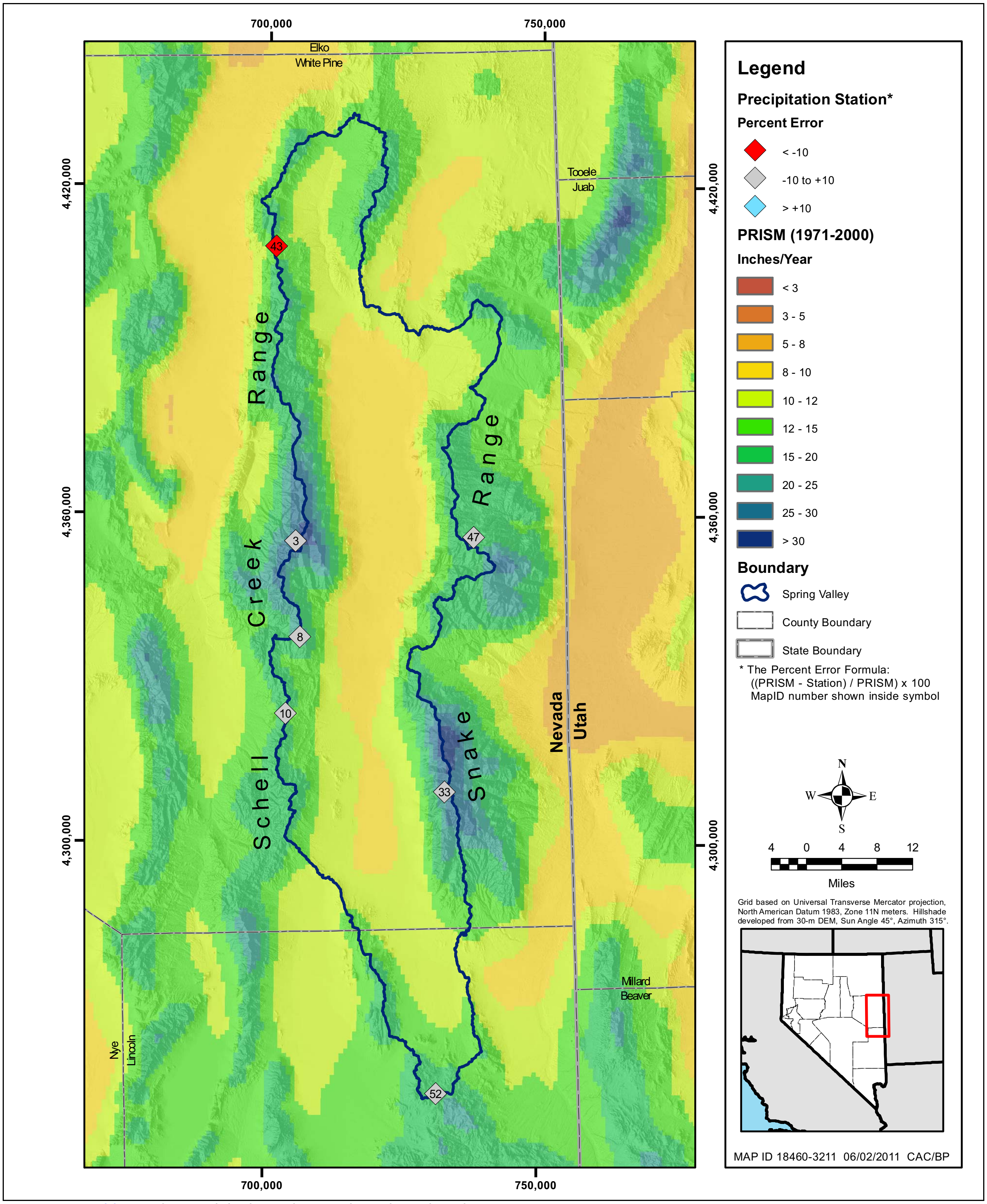
A graph showing the values extracted from the PRISM grid on the Y axis and the period-of-record values for the stations on the X axis is presented in Figure B-5. This graph indicates that although the data points follow the 1:1 line relatively closely, the values extracted from the 800-m PRISM grid are generally larger than the period-of-record values. This indicates that the mean precipitation values in the 800-m normal PRISM grid, which represents a time period of 30 years (1971-2000), are generally larger than the period-of-record values. Considering that many of the period-of-record means are based on more than 30 years of data, they are assumed to represent long-term means. However, some of the period-of-record means are based on less than 30 years of data. A linear regression was also applied to the selected station period-of-record mean values and the extracted PRISM values (Figure B-5). The regression resulted in an adjusted R^2 value of 0.99, also indicating that the two data sets have a relatively high degree of similarity.



Note: See Table B-1 for precipitation values for selected stations.

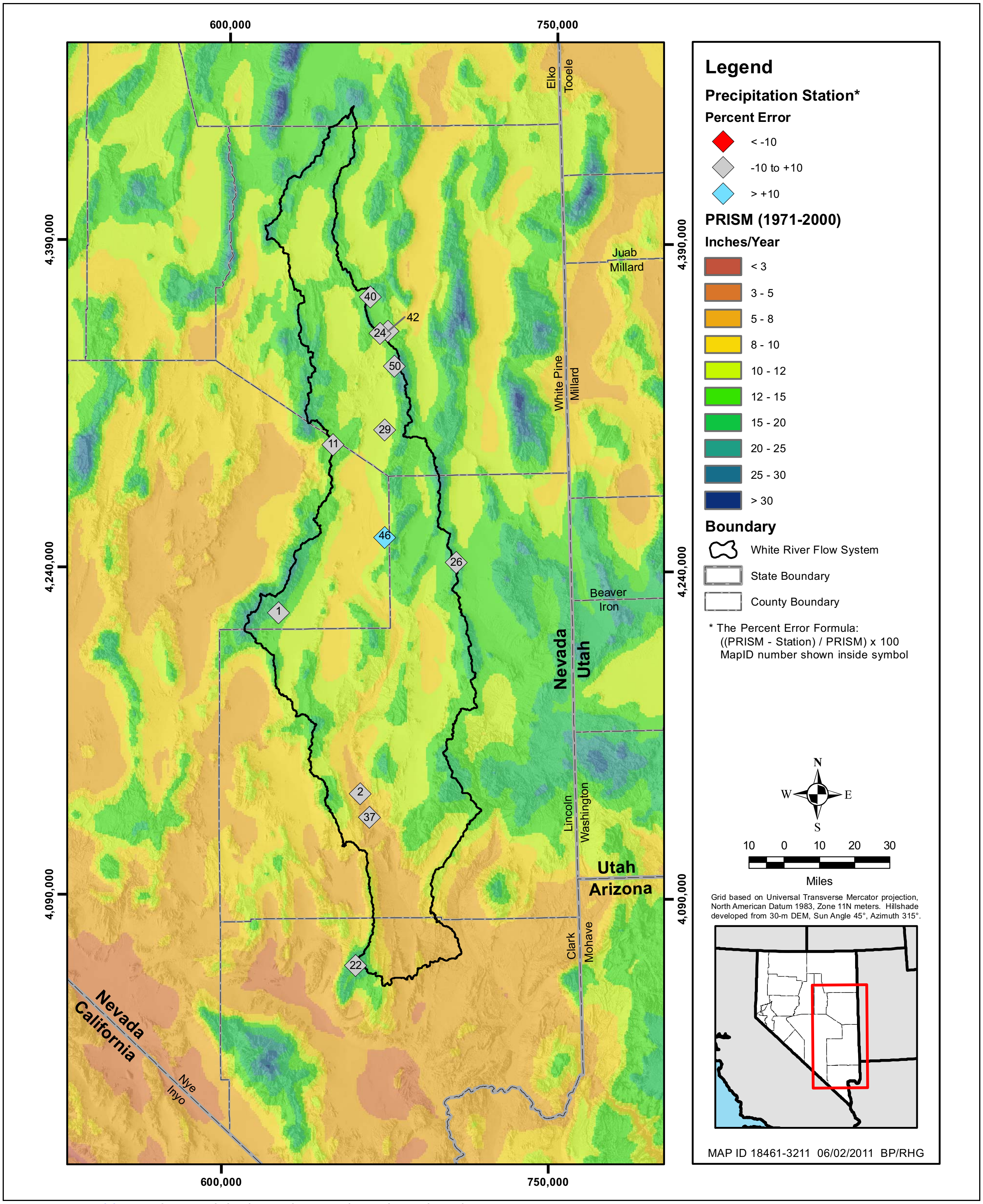
Figure B-5
Comparison of 800-m PRISM Precipitation Values to Period-of-Record Mean Station Values within Area of Interest

Figures B-6 and B-7 depict the results of the comparison of the PRISM values at the selected precipitation stations and their period-of-record mean values for Spring Valley and the WRFS, respectively. The precipitation stations were selected to represent the main areas of potential recharge (mountain blocks and alluvial aprons). These stations were selected to be located in Spring Valley and the WRFS or across their external boundaries but on the same mountain ranges forming their boundaries. The reasoning behind this comparison is that the portions of the PRISM grid that influence the estimates of recharge from precipitation are those located within Spring Valley and the WRFS. The stations located outside of their boundaries were added only to augment the data for a more thorough comparison. The differences were classified into 3 categories: less than -10 percent, -10 percent to +10 percent, and greater than +10 percent. Differences within the middle category represent an excellent match between the PRISM grid and the station data, as the maximum standard error on the station period-of-record mean for the selected station is about 10 percent (Table B-1). Most of the differences between the selected station values and the PRISM values fall within the middle difference category (-10 percent to +10 percent), indicating that the 800-m PRISM matches the period-of-record means of the selected stations. Only one station in Spring Valley (Map ID 43) and one station in the WRFS (Map ID 46) have differences that are slightly outside of the 10-percent error band. However, the period-of-record means of these two stations have an error larger than



Note: See Table B-1 for precipitation values at the selected stations.

Figure B-6
Percent Error between 800-m PRISM and Period-of-Record Average for Precipitation Stations Located in Spring Valley Potential Recharge Areas



Note: See Table B-1 for precipitation values at the selected stations.

Figure B-7
Percent Error between 800-m PRISM and Period-of-Record Average for Precipitation Stations Located in White River Flow System's Potential Recharge Areas

10 percent at the 95-percent confidence level. This comparison indicates that the 800-m PRISM distribution is generally representative of the long-term mean precipitation in the potential recharge areas.

The temporal variability of precipitation was also evaluated using historical mean annual precipitation values calculated by the Climate Diagnostics Center/NOAA (NOAA, 2011). These historical mean annual precipitation values are available for all U.S. Climate Divisions. Climate Divisions intersecting the area of interest include Nevada Divisions 2, 3, and 4 (Figure B-8). The historical mean annual precipitation values were obtained for these three divisions and are shown in Figure B-9. The mean precipitation values for the three divisions were calculated for the period of 1971 to 2000 (represented in the 800-m PRISM) and for the whole historical period of 1895 to 2010. The difference between the two means is 0.9 in./yr and indicates that the mean precipitation during the 1971 to 2000 period is about 11.1 percent larger than the overall mean precipitation value (1895 to 2010). For Climate Divisions 2 and 3, which encompass the four Project Basins, a similar calculation reveals that the mean precipitation value for the 1971-to-2000 period is only about 9.9 percent larger than the overall mean precipitation value (1895 to 2010). This is consistent with the comparison of the 800-m grid values to the period-of-record values of the stations. The U.S. Climate Division data were also used to evaluate the temporal variability of the mean precipitation for the 3 climate divisions over the period of record (1895 to 2010). A moving average of the mean values was calculated for each year in the record. The moving average values fluctuate in a cyclical fashion, within a range of 7.324 to 8.196 in./yr, or 0.88 in. The historical precipitation record, therefore, indicates that the overall variability of the average precipitation within the area of interest is limited.

These evaluations demonstrate that the 800-m PRISM precipitation grid represents long-term mean conditions (over the historical period of record) reasonably well, within a margin of error of 10 percent. This is assuming that the period-of-record means of the stations (including the climate division means) represent their long-term mean values. The precipitation stations' period-of-record means are themselves known within a margin of about 10 percent. The maps presented in Figure B-6 and Figure B-7 also demonstrate that no significant bias exists in the spatial distribution of precipitation (800-m PRISM grid) in areas where potential recharge occurs in Spring Valley and basins in the WRFS.

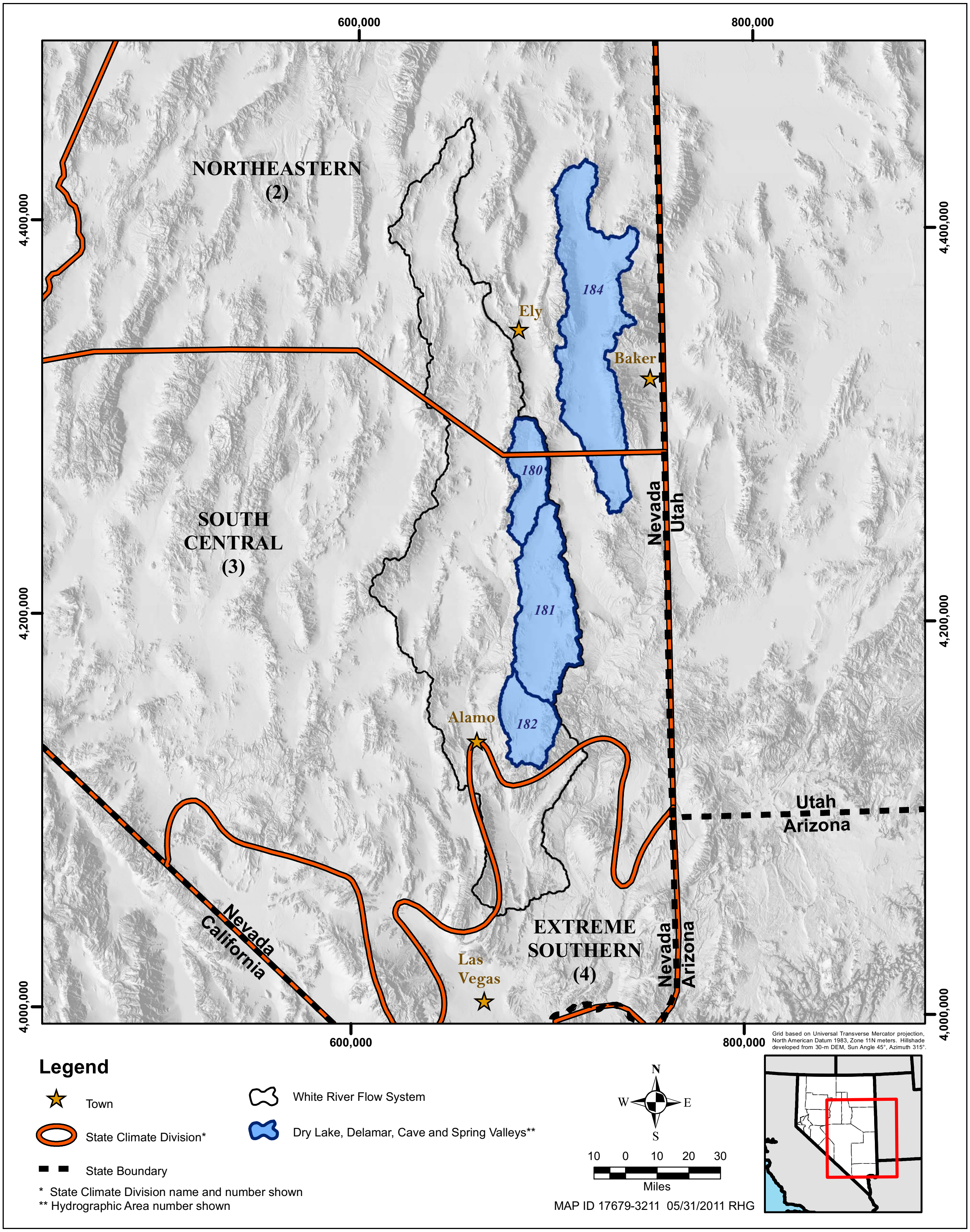
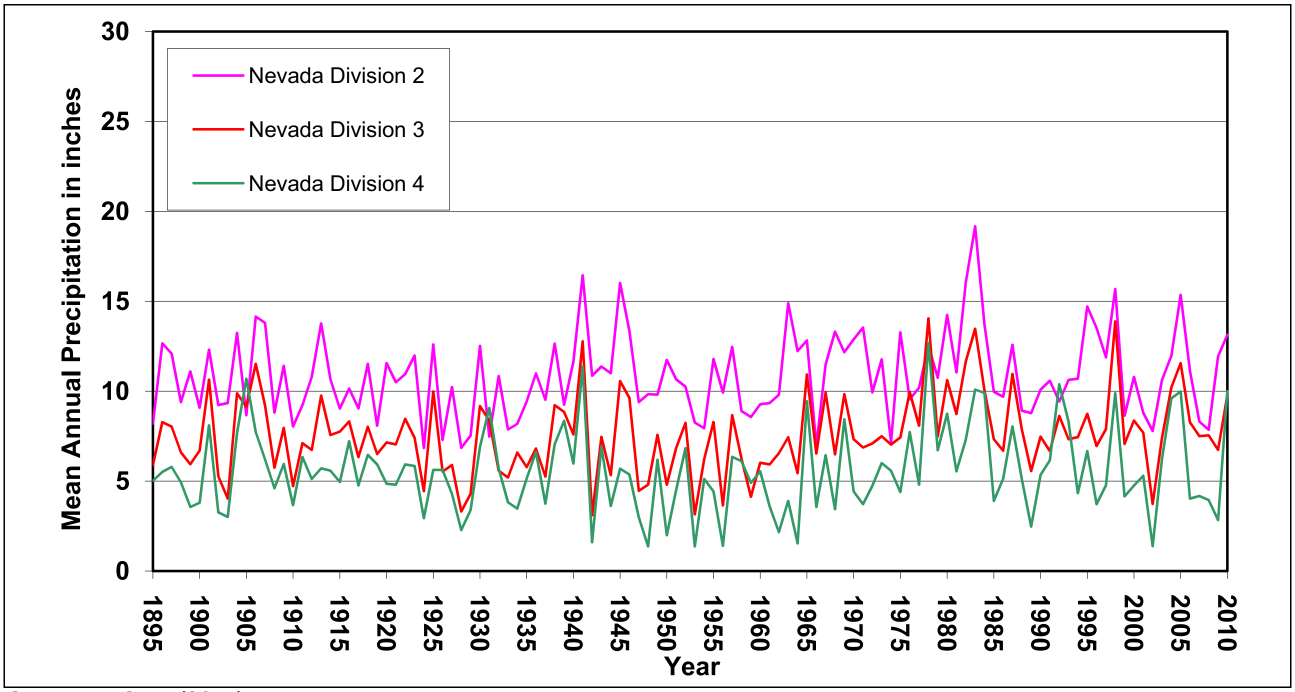


Figure B-8
Location of U.S. Climate Divisions in the Area of Interest



Source: NOAA (2011)

Figure B-9
Historical Precipitation Variability in the Area of Interest

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WRCC, see Western Regional Climate Center.

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Appendix C

Hydrologic Data

C.1.0 INTRODUCTION

This appendix describes the hydrologic data compiled for the Project Basins and vicinity, including well and spring data, and also aquifer-test data. Wells and springs provide indications of groundwater occurrence and movement, including flow directions and quantification of hydraulic gradients. Aquifer properties are important characteristics of the subsurface environment because they indicate the ability of different rock types to conduct and store water. Aquifer properties are also necessary for flux calculations using simple analytical equations of groundwater flow. The data described in this appendix consist of (1) an inventory of wells for which static water-level measurements are available; and selected water-level hydrographs; (2) an inventory of springs and associated data; and (3) selected aquifer-property data. The data sets are provided in electronic form and can be found on the DVD included with the hard copy of this report.

C.2.0 WELL INVENTORY

This section presents an inventory of the wells located in the Project Basins and adjacent basins, and the hydrographs that were constructed for the wells in the Project Basins. The inventory only includes wells for which static water-level measurements are available and is not inclusive of all existing wells and test holes. Dry holes, for example, are not included. Hydrographs were constructed only for wells located in the Projects Basins that have ten or more DTW measurements. The hydrographs were constructed to investigate temporal variations of water levels. The well inventory and the selected water-level hydrographs are provided in electronic form in the subfolder named "Well_Inventory."

C.2.1 Well Data File

The Adobe Acrobat Document file (i.e., portable document format [PDF]) containing the well data is named "Well_Data.pdf". The well data file includes four parts named as follows:

- 1-Explanation
- 2-Well Data
- 3-Data Dictionary
- 4-References

A description of each of the four file parts is provided in the following text.

C.2.1.1 "1-Explanation"

This part of the file contains a brief description of the PDF file and its contents.

C.2.1.2 "2-Well Data"

This part of the file contains a table of site information, coordinate locations, HGU designation, period of record, DTW, and water-level elevation for the selected measurement of record.

The well data were compiled from a variety of sources including published and unpublished reports, and from databases or spreadsheets maintained by different agencies including USGS, UGS, NDWR and SNWA. The SNWA monitor and test wells and their most recent data up to October 2010 are included in this data set. The data set contains the following fields along with their respective definitions:

1. Well Map ID - A unique identifier used to associate well locations depicted on the figures and plates of the report to this well data table.
2. HA - The number designation of the hydrographic area in which the well is located.
3. Station Number - A unique identifier for every well site in the table.
4. Station Name - Common name for a given well in the table.
5. UTM Northing - The Universal Transverse Mercator projection, North American Datum of 1983, Zone 11 meters northing coordinate of the well site.
6. UTM Easting - The Universal Transverse Mercator projection, North American Datum of 1983, Zone 11 meters easting coordinate of the well site.
7. Ref Pt Elev - The reference point elevation. Typically, the land surface elevation, in ft amsl.
8. Site Type - A general designation for the HGU in which the well is completed.
9. Hole Depth - Drilled depth of the borehole, in ft bgs.
10. Well Depth - Depth of the well, in ft bgs.
11. Effective Open Interval - The open interval of the well, in ft bgs.
12. Meas Count - The number of water-level measurements (not including measurements excluded from consideration) available for a given site.
13. First Meas - Date of the first measurement in the period of record.
14. Last Meas - Date of the last measurement in the period of record.
15. Date of Selected Meas - Date of the selected measurement.
16. Selected DTW - Selected depth-to-water measurement.

17. Selected Elevation - Water-level elevation for the selected DTW measurement.

18. Selected Observation - Status of the site at the time of the selected water-level measurement.

19. Selected Data Source - Source of the selected depth-to-water measurement.

20. Plotting Value - Selected water-level elevation measurement rounded to the nearest foot. Used for plotting on the figures and plates.

C.2.1.3 "3-Data Dictionary"

This part of the file contains the list of the columns found in the well data table, along with their respective definitions.

C.2.1.4 "4-References"

This part of the file contains a list of the references that were cited in the well data table.

C.2.2 Project Basin Hydrographs File

The PDF file containing the water-level hydrographs is named: "Project_Basin_Hydrographs.pdf." A description of its contents is provided in the following text.

The PDF file contains the Project Basin hydrographs. The hydrographs are organized numerically by hydrographic area number and then alphabetically by the station name.

C.3.0 SPRING INVENTORY

This section presents an inventory of the springs located in the Project Basins and surrounding areas. In addition to site information, the inventory includes summary flow statistics, temperature statistics, and isotopic data for selected springs. The spring inventory is provided in electronic form in the subfolder named "Spring_Inventory". The PDF file containing the spring data is named: "Spring_Data.pdf". The spring data file includes four parts named as follows:

- 1-Explanation
- 2-Spring Data
- 3-Data Dictionary
- 4-References

A description of each of the four parts of the file is provided in the following text.

C.3.1 "1-Explanation"

The part of the file contains a brief description of the file and its contents.

C.3.2 "2-Spring Data"

This part of the file contains spring data including coordinate locations, land-surface elevations, a geographic physical setting classification, summary flow statistics, temperature statistics, stable isotope data, and spring classifications as discussed in Section 4.2.1 (i.e., local, intermediate, regional). The inventory of the spring locations was performed by compiling data from various published reports, including USGS topographic maps, and publicly available databases administered by the USGS and DRI. SNWA has augmented these databases through hydrologic data collection programs (see Section 4.0).

The summary flow statistics are based on the available measurements. These data were evaluated to relate the magnitude, variability and sources of spring discharge, and assess their hydraulic connectivity to regional, intermediate, and/or local flow regimes. Discharge data for springs include miscellaneous discharge measurements and continuous gage records. The miscellaneous discharge measurements for the springs were compiled from numerous sources, including USGS, U.S. Fish and Wildlife Service, DRI, SNWA, and various published reports. The sources of individual records are listed with the discharge rating, measurement method, measured value, and the date the measurement was performed. Figure C-1 shows the spatial distribution of springs for which summary statistic data were derived. The summary temperature statistics are based on temperature measurement records compiled from numerous sources including SNWA hydrologic data collection programs, DRI reports, USGS reports and databases, and various other published reports. The stable isotope data were obtained from Thomas and Mihevc (2011). The spring data set contains the following fields along with their respective definitions:

1. Spring Map ID - A unique identifier used to associate spring locations depicted on figures and plates of the report to the spring data table.

2. HA - The number designation for the hydrographic area in which the spring is located.

3. Station No - Unique identifier for spring location.

4. Station Name - Common name for the spring.

5. Aliases - Additional names that the spring might also be known as.

6. UTM Northing - The Universal Transverse Mercator projection, North American Datum of 1983, Zone 11 meters northing coordinate of the spring.

7. UTM Easting - The Universal Transverse Mercator projection, North American Datum of 1983, Zone 11 meters easting coordinate of the spring.

8. Land Elev. - The land surface elevation of the spring, in ft amsl.

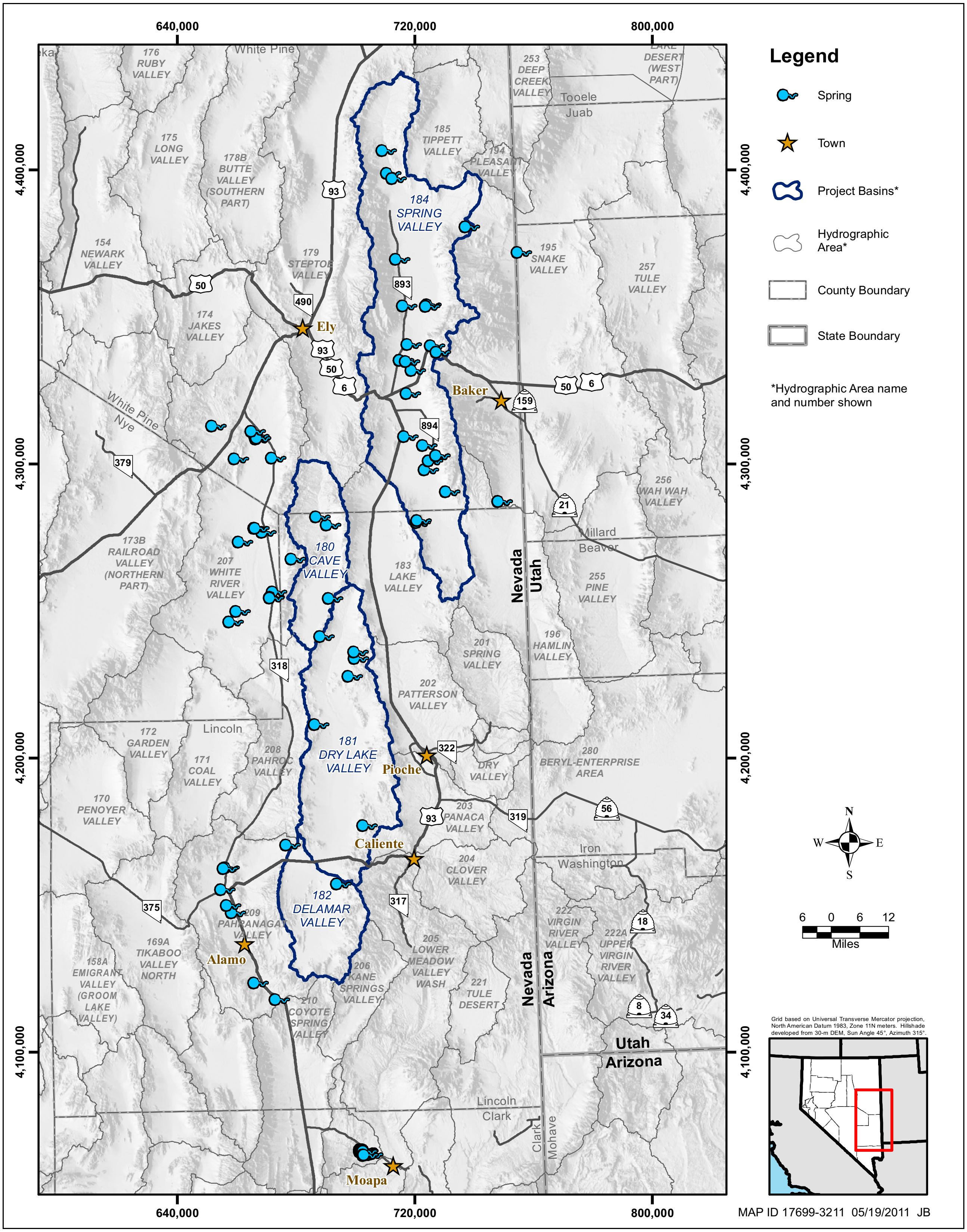

Figure C-1
Location of Selected Springs in the Area of Interest

9. Basin Location - A general classification of the geographic location of a spring into one of three categories including valley floor, valley margin, or mountain block.

10. Discharge Measurement, Earliest - The date of the earliest recorded discharge measurement.

11. Discharge Measurement, Last - The date of the latest recorded discharge measurement.

12. Count of Measurements Used - The count of the number of measurements used to derive the average discharge measurement for a spring.

13. Average Discharge (cfs) - The average discharge measurement for the spring, in cfs.

14. Minimum Discharge (cfs) - The minimum discharge measurement, in cfs, of the discharge records available for the spring.

15. Maximum Discharge (cfs) - The maximum discharge measurement, in cfs, of the discharge records available for the spring.

16. Standard Deviation - The standard deviation of the discharge records available for the spring.

17. Count of Measurements Used - Number of temperature measurements used to derive the average temperature.

18. Minimum (^{o}C) - Minimum temperature measurement, in ^{o}C.

19. Maximum (^{o}C) - Maximum temperature measurement, in ^{o}C.

20. Average Temperature (^{o}C) - Average temperature measurement, in ^{o}C.

21. 18O - Oxygen-18 isotopic composition of the water sample, in permil.

22. D - Deuterium, or hydrogen-2, isotopic composition of the water sample, in permil.

23. Stable Isotope Sample Date - Sample date for the stable isotope data.

24. Spring Classification - Classification of the spring into one of three categories including local, intermediate, or regional (as discussed in Section 4.2.1).

C.3.3 "3-Data Dictionary"

This part of the file contains the list of columns in the spring data table, along with their respective definitions.

C.3.4 “4-References”

This part of the file contains a list of the references that were cited in the spring data table.

C.4.0 AQUIFER-PROPERTY DATA

This section presents the aquifer-property data set. The data set consists of three subsets provided for documentation purposes (Project Basins) and/or interbasin flow calculation purposes (Appendix E). The aquifer property data set is provided in electronic form in the subfolder named “Aquifer_Property_Data.” The PDF file containing the data is titled: “Aquifer_Property_Data.pdf” and includes eight parts named as follows:

- “1-Explanation”
- “2-Project Basin Aquifer Tests”
- “3-Regional Carbonate Tests”
- “4-Regional Carbonate Statistics”
- “5-So. WRFS Basin Fill Tests”
- “6-So. WRFS Basin Fill Stats”
- “7-Data Dictionary”
- “8-References”

A description of each of the eight parts of the file is provided in the following text.

C.4.1 “1-Explanation”

This part of the file contains a brief description of the file and its contents.

C.4.2 “2-Project Basin Aquifer Tests”

This part of the file contains a table of the constant-rate aquifer tests conducted in the Project Basins. This data set is included here to document data available for the Project Basins. Information on constant-rate aquifer tests was obtained from previous investigations: the MX-missile program well tests (Ertec Western, Inc., 1981a, b) and the White Pine Power Project (Leeds, Hill and Jewett, Inc., 1981, 1983). Since then, SNWA has augmented these earlier investigations with several constant-rate aquifer tests in Spring Valley (Prieur et al., 2009; 2010a, b, and c; 2011a, b, and c). Other investigators including Bunch and Harrill (1984), Belcher et al. (2001) in support of the Death Valley Regional Flow System (DVRFS), and IT Corporation (1996) in support of the NTS Regional Model, compiled hydraulic property data for areas including the Project Basins. However, their data for the Project Basins were obtained from the same original sources (Ertec Western, Inc., 1981a, b; Leeds, Hill and Jewett, Inc., 1981, 1983). The aquifer-property data set for the Project Basins contains the following fields:

- Test Well ID - A unique identifier used to associate aquifer test well locations depicted on the figures of the report to this aquifer test data set.

- Observation Well Station Name - Observation well name.
- Reference Station Name - Name of the site as listed in the reference for the data.
- UTM Northing (m) - The Universal Transverse Mercator projection, North American Datum of 1983, Zone 11 meters northing coordinate of the well.
- UTM Easting (m) - The Universal Transverse Mercator projection, North American Datum of 1983, Zone 11 meters easting coordinate of the well.
- Test Type - Type of test performed to estimate the hydraulic properties.
- Date Test Started - Date the testing began.
- Date Test Ended - Date the testing ended.
- Avg Pumping or Injection Rate (gpm) - Average pumping or injection rate for the record, in gpm.
- Radius or Interwell Distance (ft) - Radius of a well in a single well test or the distance between wells for a multiple well test, in ft.
- Pumped or Injection Well - Reference name for the well being pumped or injected during a multi-well aquifer test.
- Transmissive Interval Top (ft) - Top of the transmissive interval, in ft bgs.
- Transmissive Interval Bottom (ft) - Bottom of the transmissive interval, in ft bgs.
- Transmissive Thickness (ft) - The thickness of the transmissive interval calculated by subtracting the Transmissive Interval Top from the Transmissive Interval Bottom, in ft.
- Stratigraphic Unit - Stratigraphic unit or units found within the transmissive interval, as reported in the data source.
- Lithologic Description - Description of the lithology or lithologies found within the transmissive interval, as reported in the data source.
- Analytical Method - Method used to analyze the test data.
- Analyzed Record (minutes) - Time duration of test data that was analyzed, in minutes.
- Analyzed Data - Description of what data was analyzed for the test results.
- Horizontal Hyd Conductivity (ft/d) - The horizontal hydraulic conductivity, in ft/d.

- Transmissivity (ft^2/d) - Transmissivity, in ft^2/d.
- Storativity - Storativity of the aquifer, dimensionless.
- Specific Yield - Specific yield of a formation, dimensionless.
- Reference - Contains the primary reference information where the record data was obtained.

C.4.3 "3-Regional Carbonate Tests"

This part of the file contains a table of the constant-rate aquifer tests that were used to support interbasin flow calculations for selected boundary segments.

The constant-rate aquifer test data were obtained from a number of sources including the Death Valley Regional Flow System (DVRFS) Model data (Belcher et al., 2001), NTS Regional Model data (IT Corporation, 1996), MX-missile program well tests (Ertec Western, Inc., 1981c), and other site-specific data sources (Johnson, 2002, 2005a and b; Johnson et al., 2001; SNJV, 2004; 2005; and USGS, 2011). SNWA has also augmented these earlier investigations with several carbonate-rock, constant-rate aquifer tests in Spring Valley (Prieur et al., 2009; 2010a and b; 2011b). The regional carbonate aquifer-properties data set contains the following fields along with their respective definitions:

- Observation Well Station Name - Observation well name.
- Reference Station Name - Name of the site as listed in the reference for the data.
- Test Type - Type of test performed to estimate the hydraulic properties.
- Date Test Started - Date the testing began.
- Date Test Ended - Date the testing ended.
- Avg Pumping or Injection Rate (gpm) - Average pumping or injection rate for the record, in gpm.
- Radius or Interwell Distance (ft) - Radius of a well in a single well test or the distance between wells for a multiple well test, in ft.
- Pumped or Injection Well - Reference name for the well being pumped or injected during a multi-well aquifer test.
- Transmissive Interval Top (ft) - Top of the transmissive interval, in ft bgs.
- Transmissive Interval Bottom (ft) - Bottom of the transmissive interval, in ft bgs.

- Transmissive Thickness (ft) - The thickness of the transmissive interval calculated by subtracting the Transmissive Interval Top from the Transmissive Interval Bottom, in ft.
- Stratigraphic Unit - Stratigraphic unit or units found within the transmissive interval, as reported in the data source.
- Lithologic Description - Description of the lithology or lithologies found within the transmissive interval, as reported in the data source.
- Analytical Method - Method used to analyze the test data.
- Analyzed Record (minutes) - Time duration of test data that was analyzed, in minutes.
- Analyzed Data - Description of what data was analyzed for the test results.
- Horizontal Hyd Conductivity (ft/d) - The horizontal hydraulic conductivity, in ft/d.
- Transmissivity (ft^2/d) - Transmissivity, in ft^2/d.
- Reference - Contains the primary reference information where the record data was obtained.

C.4.4 "4-Regional Carbonate Statistics"

This part of the file contains the summary statistics of the Log_{10} hydraulic conductivity derived from the constant-rate aquifer tests performed on wells completed in the carbonate aquifer. The corresponding geometric means are also presented and were used to calculate interbasin flow for selected boundary segments.

C.4.5 "5-So. WRFS Basin-Fill Tests"

This part of the file contains the transmissivity estimates that were derived for sediments including the Tertiary Horse Spring and Muddy Creek formations. A composite transmissivity for these materials was estimated using reported values from aquifer tests performed on wells completed in these units in this area. The constant-rate aquifer test data were obtained from a number of site-specific data sources (Burbey et al., 2006; Johnson, 1995; Pompeo, 2008; URS, 2001). The basin-fill aquifer-properties data set contains the following fields along with their respective definitions:

- Observation Well Station Name - Observation well name.
- Reference Station Name - Name of the site as listed in the reference for the data.
- Test Type - Type of test performed to estimate the hydraulic properties.
- Date Test Started - Date the testing began.

- Date Test Ended - Date the testing ended.
- Avg Pumping or Injection Rate (gpm) - Average pumping or injection rate for the record, in gpm.
- Radius or Interwell Distance (ft) - Radius of a well in a single well test or the distance between wells for a multiple well test, in ft.
- Pumped or Injection Well - Reference name for the well being pumped or injected during a multi-well aquifer test.
- Transmissive Interval Top - Top of the transmissive interval, in ft bgs.
- Transmissive Interval Bottom - Bottom of the transmissive interval, in ft bgs.
- Transmissive Thickness - The thickness of the transmissive interval calculated by subtracting the Transmissive Interval Top from the Transmissive Interval Bottom. The thickness is reported, in ft.
- Stratigraphic Unit - Stratigraphic unit or units found within the transmissive interval, as reported in the data source.
- Lithologic Description - Description of the lithology or lithologies found within the transmissive interval, as reported in the data source.
- Analytical Method - Method used to analyze the test data.
- Analyzed Record (minutes) - Time duration of test data that was analyzed, in minutes.
- Analyzed Data - Description of what data was analyzed for the test results.
- Horizontal Hyd Conductivity - Horizontal hydraulic conductivity, in ft/d.
- Transmissivity - Transmissivity, in ft^2/d.
- Reference - Contains the primary reference information where the record data was obtained.

C.4.6 “6-So. WRFS Basin-Fill Stats”

This part of the file contains the summary statistics of the Log_{10} transmissivity derived from the constant-rate aquifer tests for the basin-fill materials in the southern part of the WRFS. The corresponding geometric means are also presented.

C.4.7 "7-Data Dictionary"

This part of the file contains the list of columns found in the aquifer property tables for the carbonate aquifer and the southern WRFS basin fill, along with their respective definitions.

C.4.8 "8-References"

This part of the file contains a list of the references that were cited in the aquifer property tables for the carbonate aquifer and the southern WRFS basin fill.

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Appendix D

Groundwater-ET Estimates for Spring and White River Valleys

D.1.0 INTRODUCTION

Estimates of groundwater ET for the groundwater discharge areas of Spring and White River valleys are presented in this appendix. These estimates are used in Sections 6.0, 8.0, 9.0, and Appendix F to derive potential recharge distributions, describe groundwater occurrence and movement, and define groundwater budgets for the Project Basins.

The objective of this analysis is to derive pre-development estimates of groundwater ET for the groundwater discharge areas of Spring and White River valleys. Predevelopment conditions are defined as the current condition with agricultural croplands removed or replaced by an interpreted distribution of natural vegetation. The technical approach, data requirements, data analysis, results and discussion are presented in the following sections.

D.2.0 TECHNICAL APPROACH

Details regarding the specific approach applied to the groundwater discharge areas of Spring and White River valleys are described in this appendix. Annual estimates of groundwater-ET distributions and volumes were derived for each area for the period 2006 through 2010 by performing the following activities:

- Delineating potential groundwater-ET extent boundaries and classifying the land cover within them.
- Compiling, processing, and analyzing precipitation data to derive precipitation distributions within the potential groundwater-ET extent boundaries.
- Estimating annual total-ET distributions and volumes for the groundwater discharge areas by applying an empirically-derived relationship between footprint-weighted growing-season average NDVI and annual total ET to growing-season average NDVI grids.
- Estimating annual distributions of groundwater ET for the groundwater discharge areas as differences between the annual total-ET and precipitation distributions.
- Calculating the annual and period of record average annual groundwater-ET volumes from the annual groundwater-ET distributions.

Additional activities were performed for Spring Valley to estimate groundwater ET for the groundwater discharge area in the northern part of the valley (defined in Section D.3.0) because the remotely-sensed data required to implement this approach were not acquired for this area. Therefore, groundwater ET volumes for the northern groundwater discharge area were estimated using a different approach by performing the following activities:

- Using the groundwater-ET extent and land-cover classification map to derive the areas of each land-cover class present within the northern Spring Valley groundwater discharge area.
- Estimating the average annual groundwater ET for each land-cover class using annual ET-rate and precipitation data for ET-measurement sites in Spring Valley.

D.2.1 Data Requirements and Sources

The data required to complete the analysis described in this appendix included groundwater-ET extent maps, precipitation data, ET-rate data, and growing-season average NDVI grids. These data and their sources are generally described as follows:

- Groundwater-ET Extent Maps – Maps of the groundwater-ET extent boundaries and land-cover classes for Spring and White River valleys were required to delineate areas of agricultural croplands, playas, and open water. The development of the maps is discussed in Section D.3.0.
- Annual Precipitation Data – Annual 4-km precipitation grids from PRISM were selected to estimate the precipitation distribution within the groundwater discharge areas. Precipitation-station data were required to assess the accuracy of these grids and to adjust them, as appropriate, to provide a better fit to the observed data. Data sources for the station data include UNLV, DRI, SNWA (Shanahan et al., 2011, p. 4-3), and USGS (Moreo et al., 2007, Appendix A).
- ET-Rate Data – Annual precipitation and ET-rate data for ET-measurement sites located in Spring Valley were required to derive average annual groundwater-ET rates for land-cover classes in northern Spring Valley. The sources of these data include UNLV, DRI, SNWA (Shanahan et al., 2011), and USGS (Moreo et al., 2007).
- Growing-Season Average NDVI Grids – These grids were required for the derivation of annual total ET using the empirical relationship between footprint-weighted growing-season average NDVI and annual total ET described in Fenstermaker et al. (2011). The grids were derived as part of the data analysis performed by Fenstermaker et al. (2011), and are described in that report. For Spring Valley, these grids are only available for the main groundwater discharge area described in Section D.3.0.

D.3.0 DELINEATION OF GROUNDWATER-ET AREAS

The groundwater-ET areas for Spring and White River valleys were delineated in two steps: (1) the extent of the groundwater-ET areas were delineated using satellite imagery and previous mapping; (2) land-cover within the groundwater-ET extent boundaries was classified using the NDVI. The following discussion provides a more detailed accounting of the processes and assumptions used to construct these maps.

The extents of groundwater ET areas within Spring and White River valleys were initially delineated based on a compilation of earlier work described in the Reconnaissance Series Reports (Maxey and Eakin, 1949; Rush and Kazmi, 1965), Woodward-Clyde Consultants et al. (1994), LVVWD (2001), and Nichols (2000, Table C17). In some instances, the Southwest Regional Gap Analysis Project (SWReGAP) data (USGS, 2004) and the National Land Cover Data (NLCD, 1992) were used to refine the extent boundaries if there was great uncertainty over the initial boundary location. Refinements were also focused on the edges of the valley floors where the extent boundaries would be expected. These areas were defined as land expanses in the valley where the land-surface slope is less than or equal to 2 percent, and were delineated by performing a slope analysis in ArcGIS® using USGS 30-m National Elevation Dataset seamless DEMs. The extent boundaries were refined in these areas to exclude land-cover features that fell on slopes greater than 2 percent.

Landsat 7 Thematic Mapper satellite imagery for 2002 was used to verify, and in some instances refine, the groundwater-ET extent boundaries. Imagery from 2002 was selected because during this year precipitation was significantly below normal according to the Palmer Drought Severity Index (NCDC, 2011), and it was assumed that the extent of the groundwater-ET areas would be more apparent in the imagery under conditions in which the vegetation is relying more exclusively on groundwater rather than precipitation. Land-cover within the extent boundaries was then classified using the NDVI. To represent current conditions, the areas of groundwater ET were classified into the six land-cover classes listed in Table 5-1. Figure 5-1 presents the map of Spring Valley which identifies the main and northern groundwater discharge areas, and Figure D-1 presents the map of White River Valley.

A number of transects were also generated to validate the remote-sensing techniques used to delineate the extent boundaries and define the land-cover classes within them. Along each transect the percent cover and density of the vegetation community was observed and recorded. Percent cover was estimated as the fraction of the transect covered by each species, and density estimates were calculated as described in Barbour et al. (1987).

Many of the boundaries delineating the groundwater-ET extents and land-cover classes were checked in the field during the summer of 2004, and modified as appropriate using high-resolution global positioning system equipment. An assessment was completed to evaluate the accuracy of the land classification using accepted protocols as outlined in Congalton and Green (1999). A total of 249

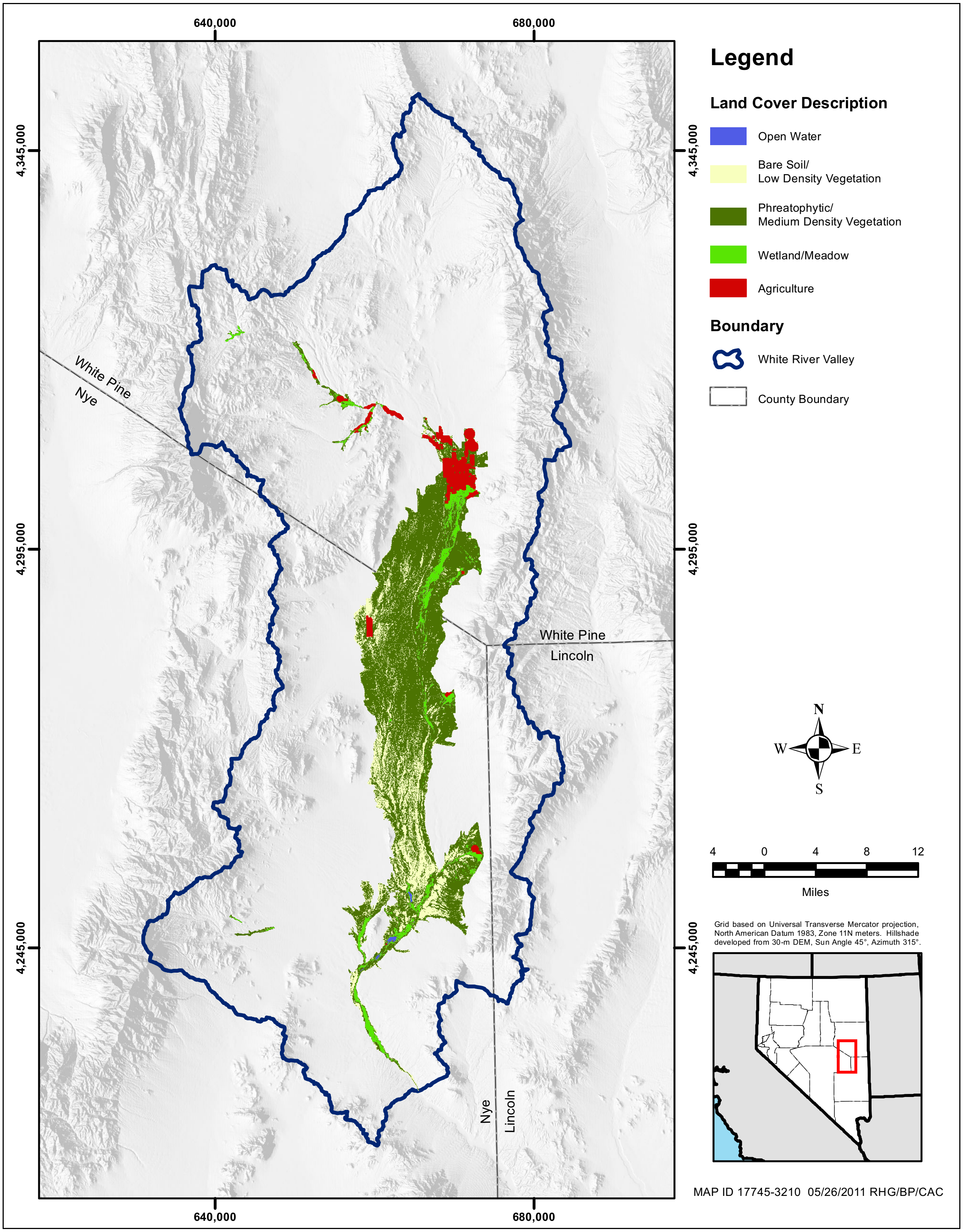


Figure D-1
White River Valley Groundwater-ET Extent Map

randomly selected points representing each classification were field checked. This assessment returned an overall accuracy of 88 percent, the detailed results of which are presented by land-cover class in Table D-1. This value is above the generally accepted value of 85 percent as established by Anderson et al. (1976, p. 5). More recent imagery was acquired for the period 2006-2010 as part of the Fenstermaker et al. (2011) investigation, and was used to assess changes in the extent and land-cover boundaries since 2004, and no significant changes were observed.

Table D-1
Reported Accuracy on ET Classification

ET Class	Reported Accuracy
Open Water	0.92
Bare Soil/Low Vegetation	0.78
Phreatophyte/Medium Vegetation	0.89
Wetland/Meadow	0.90
Agriculture	0.88

D.4.0 Annual Precipitation within the Groundwater Discharge Areas

Estimating annual groundwater ET for the groundwater discharge areas of Spring and White River valleys using Equation 5-1 requires estimates of the annual precipitation distributions for the areas. Annual PRISM precipitation grids were acquired for the years 2006 through 2010 for this purpose. Additionally, precipitation data collected at stations located within the areas were acquired and compiled to evaluate the accuracy of the PRISM precipitation grids, and adjust them, as necessary, to ensure a best fit to the station data. The following sections describe the precipitation-station data and their processing, PRISM precipitation grids, and the approach taken to adjust the grids to yield the final distributions used in the estimation of groundwater ET.

D.4.1 Precipitation-Station Data

Precipitation data for stations located within the groundwater discharge areas of Spring and White River valleys were compiled from numerous sources including UNLV, DRI, SNWA, and USGS for the period 2006 through 2010. The station locations are depicted on Figure D-2, and all were associated with data-collection activities supporting ET investigations involving the two valleys. The periods of record for some of the stations are intermittent over the 5-year period because the ET investigations started and concluded during this time. The precipitation gages installed at these locations were either tipping-bucket or 8-in. diameter standard bulk-storage rain gages or, in the case of the UNLV and SNWA sites, both types were installed to provide redundancy in case technical issues with the data collection were encountered. The station attributes and corresponding periods of record are listed in Table D-2. The details regarding the data collection, processing, and annual precipitation values for each entity are described in the following sections.

D.4.1.1 Precipitation Data

At the UNLV, DRI, and SNWA precipitation stations, data were collected as part of data collection activities performed in support of a multi-year collaborative investigation to evaluate and quantify ET within the groundwater discharge areas of Spring, Snake and White River valleys. Details regarding data collection are reported in Devitt et al. (2008) for UNLV, Arnone et al. (2008) for DRI, and Shanahan et al. (2011) for SNWA. Shanahan et al. (2011) re-processed the precipitation data reported by each entity using a single, uniform approach to derive annual measurements for each station consistent with WRCC standards for qualifying and estimating records. A quality review of each precipitation data set was performed to identify missing or anomalous records. Missing or anomalous records were estimated using half-hourly tipping-bucket data from other gages installed at the same site. For instances in which no other gage was installed at the site, the next nearest gage within the groundwater discharge area was used as an index station to estimate the missing or anomalous records. For these cases a correlation between the index-station record and the station gage was

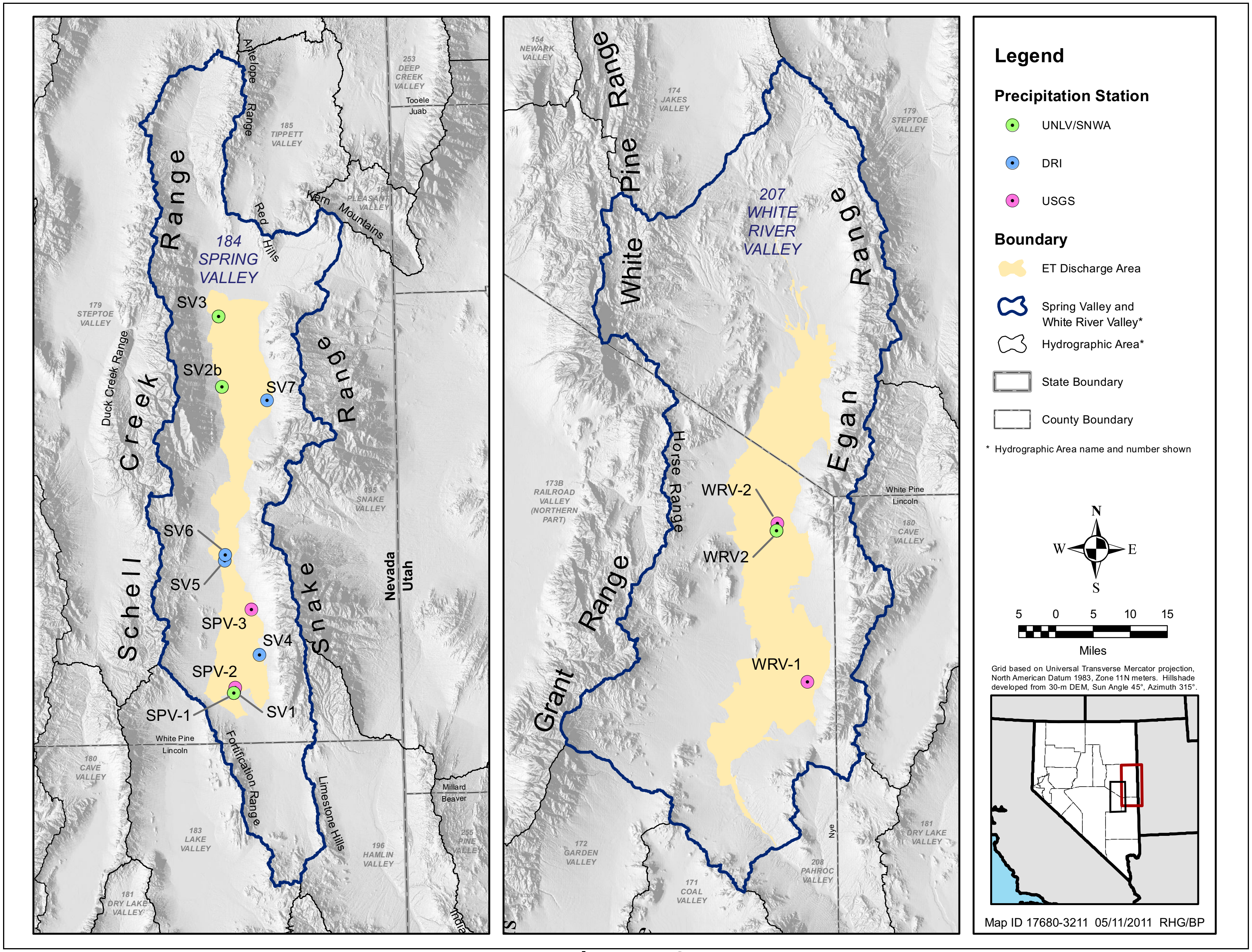


Figure D-2
Locations of Precipitation Stations within Groundwater Discharge Areas of Spring and White River Valleys

Table D-2
Precipitation-Station Attributes

Station Name	Location[a] UTM Northing (m)	UTM Easting (m)	Elevation (ft amsl)	Agency	Tipping Bucket	Standard Rain Gage	Period of Record
WRV2	4,277,445	665,017	5,308	UNLV/SNWA	Yes	Yes	2006-2010
WRV-1	4,253,502	670,164	5,250	USGS	No	Yes	2006
WRV-2	4,278,594	665,131	5,320	USGS	No	Yes	2006
SV1	4,294,919	719,920	5,780	UNLV/SNWA	Yes	Yes	2006-2010
SV2b	4,360,829	716,743	5,595	UNLV/SNWA	Yes	Yes	2007-2010
SV3	4,375,912	715,857	5,615	UNLV/SNWA	Yes	Yes	2007-2010
SV4	4,303,125	725,311	5,816	DRI	Yes	No	2007-2009
SV5	4,323,395	717,653	5,774	DRI	Yes	No	2007-2009
SV6	4,324,555	717,824	5,760	DRI	Yes	No	2007-2009
SV7	4,357,985	726,575	5,555	DRI	Yes	No	2007-2009
SPV-1	4,295,137	719,969	5,785	USGS	No	Yes	2006
SPV-2	4,296,065	720,129	5,780	USGS	No	Yes	2006
SPV-3	4,312,911	723,515	5,785	USGS	No	Yes	2006

[a]All coordinates are UTM, NAD83, Zone 11.

developed, and the missing records were estimated using a best-fit linear approximation describing the correlation between the two records. This processing yielded annual values for each station which are listed in Table D-3 for Spring and White River valleys.

USGS installed six precipitation gages in Spring and White River valleys as part of data collection activities performed in support of BARCASS ET studies. The gages were installed with EC stations at sites SPV-1, SPV-2 and SPV-3 located in Spring Valley; and WRV-1 and WRV-2 located in White River Valley. At each site, 8-in. diameter standard bulk-storage rain gages were installed, and data were collected as part of the study from September 2005 through August 2006 (Moreo et al., 2007). Collection of precipitation data continued after BARCASS, from September 2006 through August 2007. These data are unpublished, but provisional data for this period were obtained from the USGS to complete the annual records for 2006 (pers. comm. M. Moreo on January 11, 2008). Annual precipitation data for the USGS sites in Spring and White River valleys are also listed in Table D-3.

D.4.2 PRISM Precipitation Grids

The precipitation distributions within the groundwater discharge areas of Spring and White River valleys were estimated using annual 4-km PRISM precipitation grids for the years 2006 through 2010. These grids were acquired from the Oregon State University online PRISM database available at http://www.prism.oregonstate.edu/ (Daly et al., 2011). The precipitation values were converted from mm/yr to in./yr by multiplying the values by a conversion factor of 0.03937 in./mm. The converted grids are presented in Figures D-3 and D-4 for Spring and White River valley, respectively. Precipitation is lower during 2006 through 2008, with 2008 having the lowest precipitation and 2010 having the highest. This observation is corroborated by the station data and U.S. Climate Division precipitation indices which are presented in Figures B-8 and B-9.

Table D-3
Annual Precipitation Station Data for Spring and White River Valleys (in./yr)

Station Name	2006	2007	2008	2009	2010
WRV2	10.45	6.23[a]	6.44	9.02	14.13
WRV-1[b]	7.42	---	---	---	---
WRV-2[b]	11.49	---	---	---	---
SV1	6.11	5.00	6.00	8.17	12.60
SV2b	---	5.27[a]	2.79	7.51	8.42
SV3	---	4.21[a]	3.17	7.78	10.17
SV4	---	5.79[a]	5.12	6.96[a]	---
SV5	---	5.44[a]	3.50	8.70[a]	---
SV6	---	5.24[a]	3.37	8.18[a]	---
SV7	---	3.95[a]	2.59	6.19[a]	---
SPV-1[b]	7.07	---	---	---	---
SPV-2[b]	7.89	---	---	---	---
SPV-3[b]	6.60	---	---	---	---

[a]Missing months estimated using record of next nearest gage.
[b]January 2006 through August 2006 data as reported by Moreo et al. (2007, Table 7, p. 20) with September, 2006 through December, 2006 data considered provisional (per. comm. M. Moreo, January 11, 2008)

D.4.2.1 Evaluation of PRISM Grids

Values from the 4-km PRISM precipitation grids were extracted at the precipitation-station locations using ESRI ArcGIS 9.3 Spatial Analyst tools and compared to the station data to assess how well the grid values fit the observed data. This comparison is listed in Table D-4 and presented graphically in Figure D-5. The charts presented in Figure D-5 demonstrate that for each of the years the PRISM grids overestimate precipitation at the Spring Valley stations. For White River Valley, the PRISM grids underestimate precipitation at the stations for all years except 2007. Based on the comparison results and the fact that the station locations are well distributed throughout the groundwater discharge areas (Figure D-2), it is concluded that the entire PRISM precipitation distributions within these areas reflect the same biases. Had these station data been used in the generation of the PRISM precipitation grids, the model fit would be expected to be much better. Instead, the grids were adjusted to remove the biases and improve their fit to the observed data using a simple method described as follows.

- For each respective valley, the differences between the station data and the extracted PRISM precipitation values were averaged for each of the years (Table D-4).

- The average difference for each year and respective valley were added to each precipitation value of the corresponding PRISM precipitation grid to yield an adjusted-PRISM precipitation distribution.

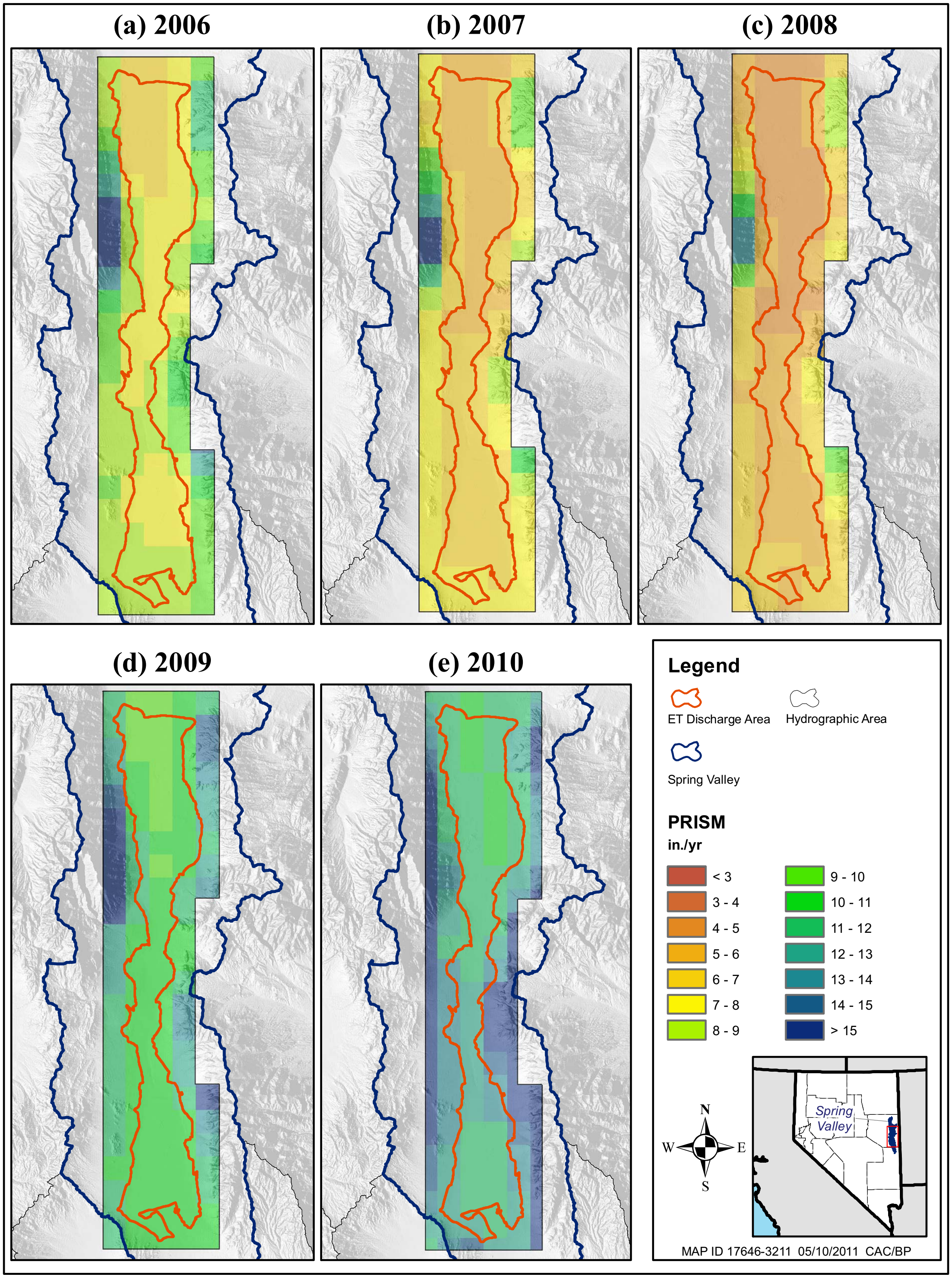


Figure D-3
4-km PRISM Precipitation Distribution for Spring Valley, 2006 through 2010

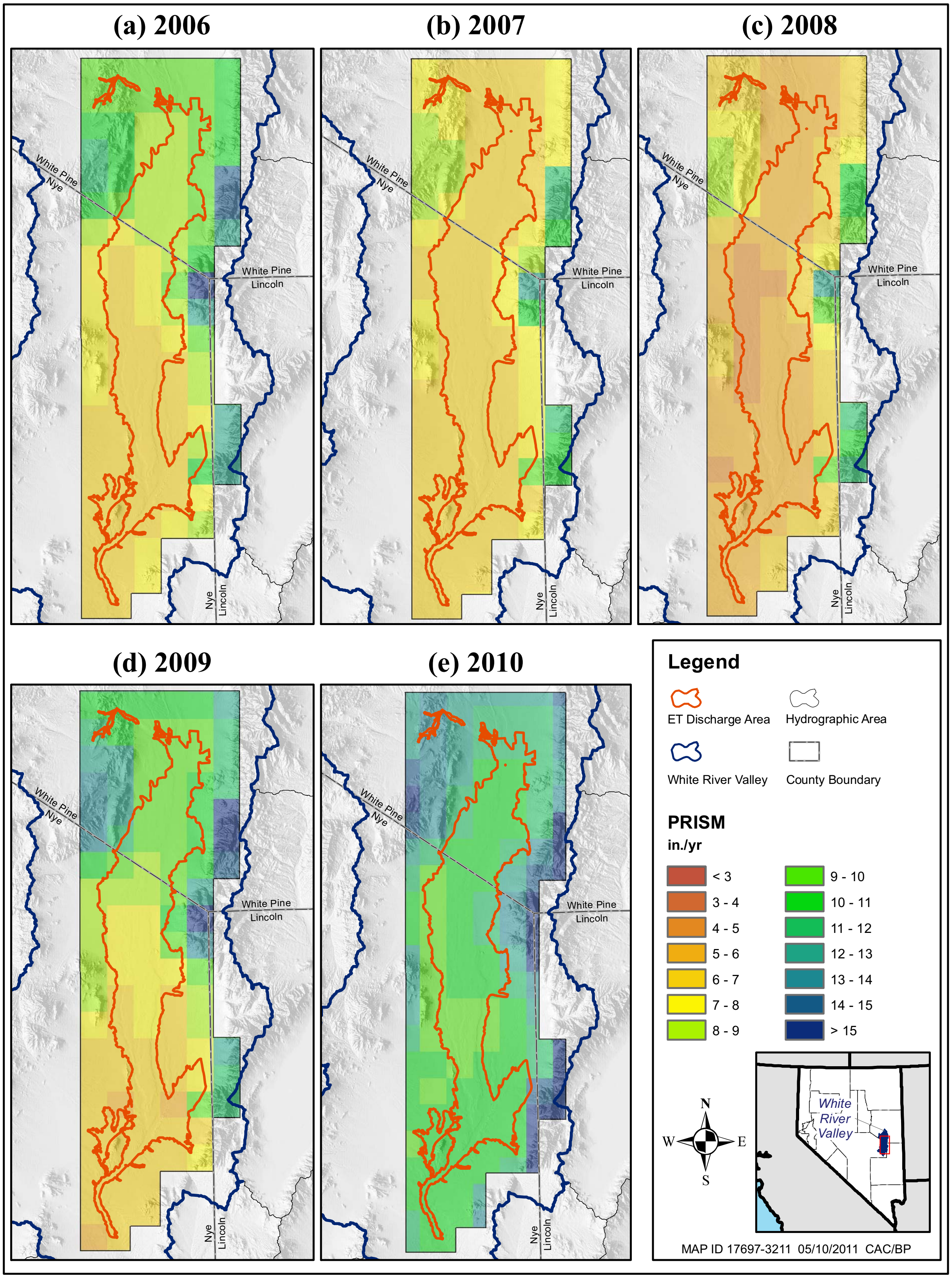


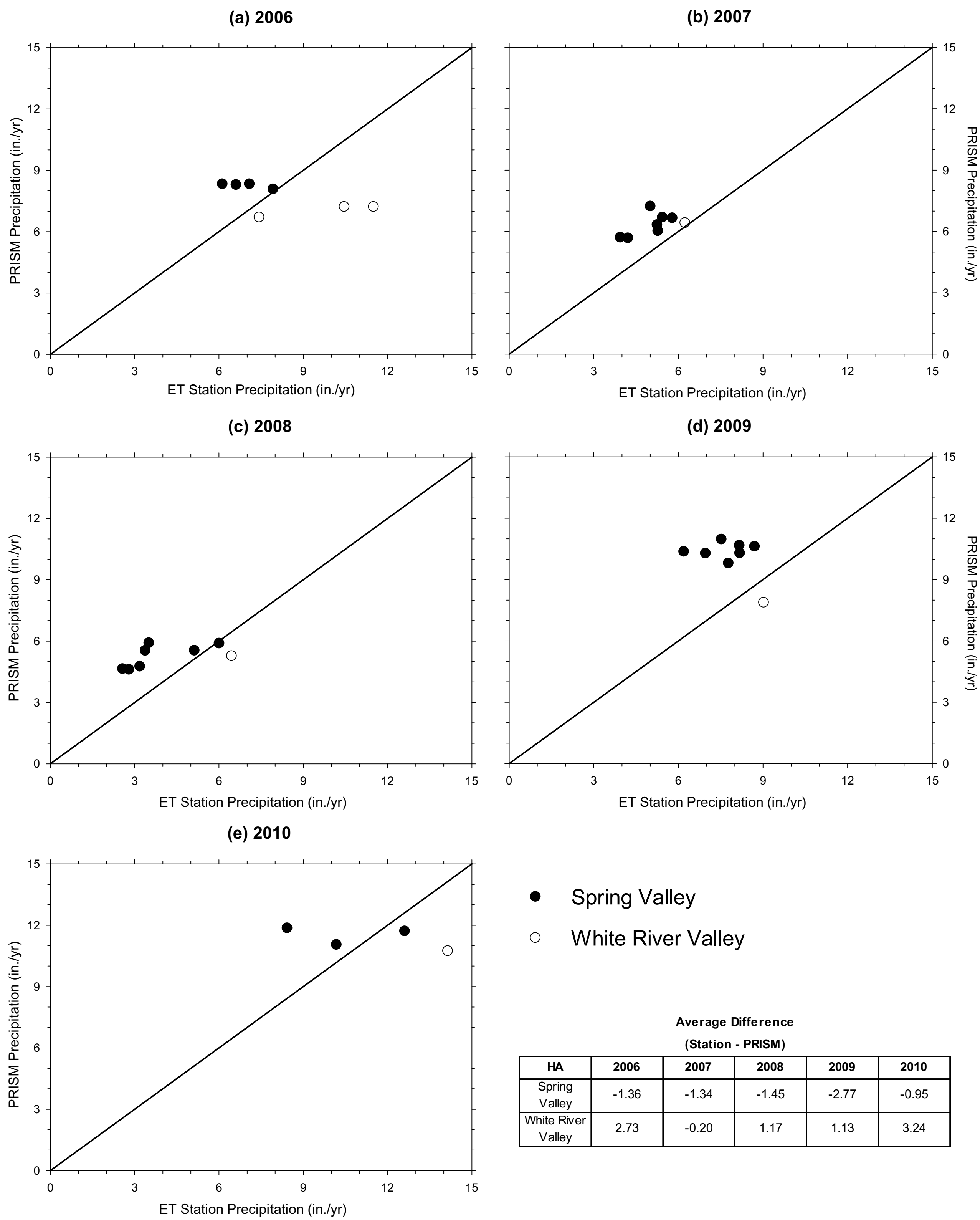
Figure D-4
4-km Precipitation Distribution for White River Valley, 2006 through 2010

Table D-4
Comparison of 4-km Annual PRISM Precipitation to Station Data in Groundwater ET Areas of Spring and White River Valleys

Station Name	2006			2007			2008			2009			2010		
	Station	PRISM	Difference	Station	PRISM	Difference	Station	PRISM	Difference	Station	PRISM	Difference	Station	PRISM	Difference
WRV2	10.45	7.22	3.23	6.23[a]	6.43	-0.20	6.44	5.27	1.17	9.02	7.89	1.13	14.13	10.89	3.24
WRV-1[b]	7.42	6.72	0.70	---	---	---	---	---	---	---	---	---	---	---	---
WRV-2[b]	11.49	7.22	4.27	---	---	---	---	---	---	---	---	---	---	---	---
Average	---	---	**2.73**	---	---	**-0.20**	---	---	**1.17**	---	---	**1.13**	---	---	**3.24**
SV1	6.11	8.35	-2.24	5.00	7.25	-2.25	6.00	5.90	0.10	8.17	10.68	-2.51	12.60	11.60	1.00
SV2b	---	---	---	5.27[a]	6.04	-0.77	2.79	4.62	-1.83	7.51	10.98	-3.47	8.42	11.60	-3.18
SV3	---	---	---	4.21[a]	5.54	-1.33	3.17	4.55	-1.38	7.78	9.60	-1.82	10.17	10.84	-0.67
SV4	---	---	---	5.79[a]	6.67	-0.88	5.12	5.55	-0.43	6.96[a]	10.29	-3.33	---	---	---
SV5	---	---	---	5.44[a]	6.70	-1.26	3.50	5.91	-2.41	8.70[a]	10.63	-1.93	---	---	---
SV6	---	---	---	5.24[a]	6.33	-1.09	3.37	5.54	-2.17	8.18[a]	10.31	-2.13	---	---	---
SV7	---	---	---	3.95[a]	5.72	-1.77	2.59	4.65	-2.06	6.19[a]	10.38	-4.19	---	---	---
SPV-1[b]	7.07	8.35	-1.28	---	---	---	---	---	---	---	---	---	---	---	---
SPV-2[b]	7.89	8.09	-0.20	---	---	---	---	---	---	---	---	---	---	---	---
SPV-3[b]	6.60	8.30	-1.70	---	---	---	---	---	---	---	---	---	---	---	---
Average	---	---	**-1.36**	---	---	**-1.34**	---	---	**-1.45**	---	---	**-2.77**	---	---	**-0.95**

[a]Missing months estimated using record of next nearest gage.

[b]January 2006 through August 2006 data as reported by Moreo et al. (2007, Table 7, p. 20) with September 2006 through December 2006 data considered provisional (per. comm. M. Moreo, January 11, 2008)



Average Difference
(Station - PRISM)

HA	2006	2007	2008	2009	2010
Spring Valley	-1.36	-1.34	-1.45	-2.77	-0.95
White River Valley	2.73	-0.20	1.17	1.13	3.24

Figure D-5
Comparison of PRISM Precipitation Values to Station Values in Groundwater ET Areas

- Values from the adjusted precipitation grid were extracted at the precipitation-station locations and plotted with the station data for each year. The corresponding charts are presented in Figure D-6.

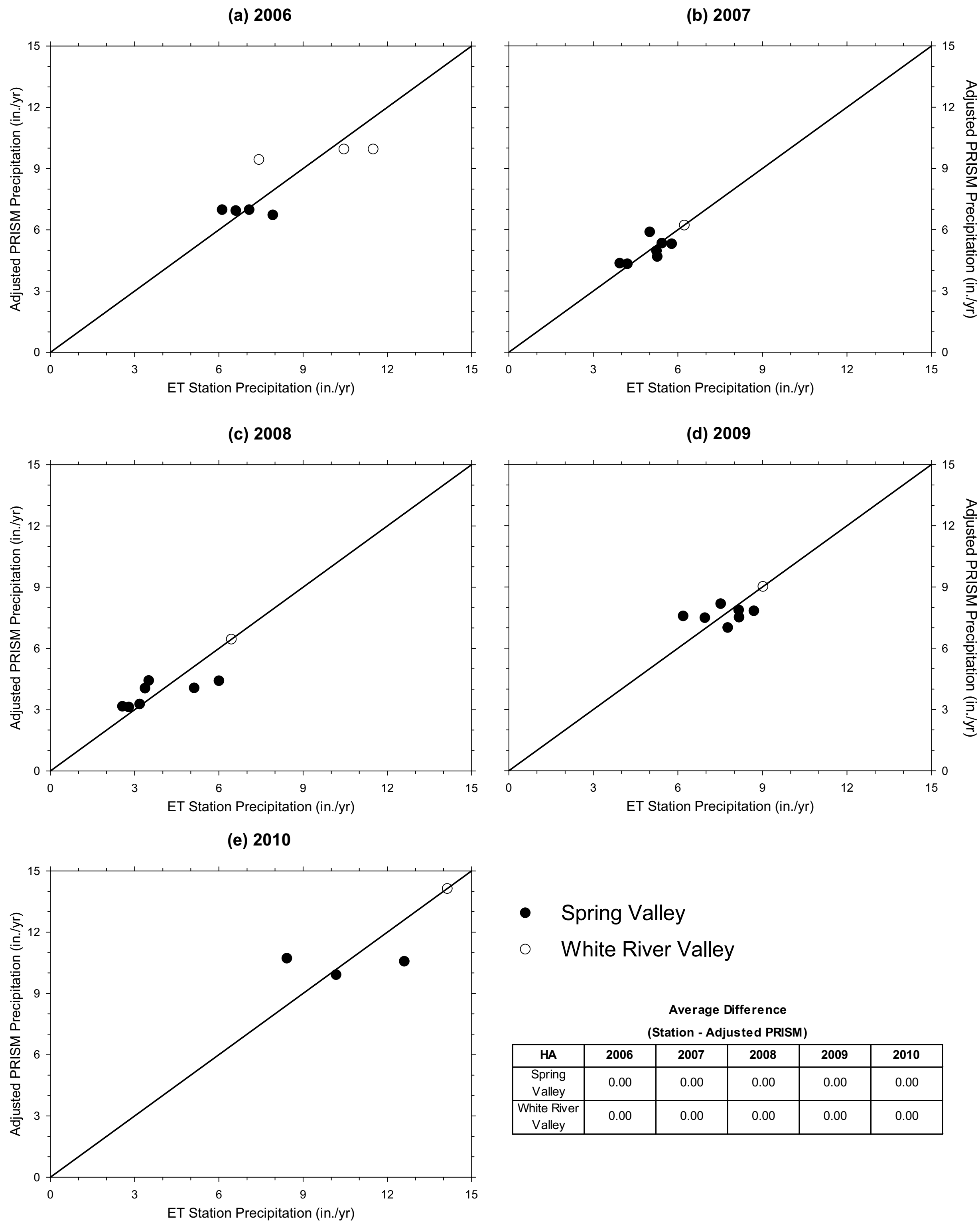
The charts presented in Figure D-6 demonstrate that the adjustment to the original PRISM removes the biases of overestimating precipitation in the Spring Valley groundwater discharge area and underestimating precipitation in White River Valley groundwater discharge area. Additionally, the accuracy of the adjusted precipitation grids were improved as demonstrated by the average difference between the station data and the adjusted grid values derived for each year and valley (Figure D-6, inset table).

Both the original-PRISM and adjusted-PRISM precipitation distributions were integrated over the groundwater ET areas of Spring and White River valleys to provide a comparison of the yearly precipitation volumes for each of the five years considered. These values are listed in Table D-5 with precipitation-index values for the U.S. Climate Division NV-2 obtained from the NCDC online database (NCDC, 2011). The annual precipitation volumes for both valleys exhibit a decreasing trend from 2006 to 2008, followed by increases in 2009 and 2010. These trends are consistent with the variation in the precipitation index. Based on these consistencies, it is concluded that the adjusted PRISM precipitation distributions reasonably reflect the meteorological conditions experienced in the groundwater discharge areas during the period 2006 through 2010.

Table D-5
PRISM Precipitation Volumes for Spring and White River Valleys for Groundwater Discharge Areas (2006-2010)

Method	2006	2007	2008	2009	2010	Source
Spring Valley (PRISM; afy)[a]	100,500	81,900	68,800	135,700	151,400	Daly et al. (2011)
Spring Valley (adjusted PRISM; afy)[a]	82,900	64,500	50,000	99,700	139,200	This Study
White River Valley (PRISM; afy)[a]	91,600	79,400	66,200	96,100	129,400	Daly et al. (2011)
White River Valley (adjusted PRISM; afy)[a]	123,300	76,300	79,400	108,800	167,100	This Study
US Climate Division NV-2 (in./yr)	11.13	8.31	7.75	11.94	12.62	NOAA/ESRL[b]

[a]Values are rounded to the nearest 100 afy.
[b]NOAA/ESRL is the National Oceanic and Atmospheric Administration Earth System Research Laboratory.



Average Difference

(Station - Adjusted PRISM)

HA	2006	2007	2008	2009	2010
Spring Valley	0.00	0.00	0.00	0.00	0.00
White River Valley	0.00	0.00	0.00	0.00	0.00

Figure D-6
Comparison of Adjusted PRISM Precipitation Values to Station Values in Groundwater ET Areas

D.5.0 GROUNDWATER-ET ESTIMATION

An empirically-derived linear relationship developed by Fenstermaker et al. (2011, p. 5-4) between footprint-weighted growing-season average NDVI and annual total ET was used to derive basin-scale estimates of annual ET distribution for the groundwater discharge areas of Spring and White River valleys. The relationship was applied to growing-season average NDVI grids, also from Fenstermaker et al. (2011), to estimate annual distributions of total ET for each area for the period 2006 through 2010. Annual distributions of groundwater ET were then estimated by subtracting the corresponding adjusted-PRISM precipitation grids from the total-ET grids.

Based on the maps delineating groundwater-ET extent boundaries and land-cover classes presented in Section D.3.0, the growing-season average NDVI grids were processed by first assigning null values to areas classified as agricultural croplands, open water (defined by NDVI values less than -0.0238), and playa. Null values were assigned to exclude these areas from the derivation of ET rates because these classes were not represented in the regression analysis; therefore, the regression model does not apply to them. Annual total-ET for agricultural croplands and open-water were derived separately as described in the following discussion, and an annual groundwater consumptive-use rate was assumed for the playa class.

The regression model from Fenstermaker et al. (2011, p. 5-4) was then applied to the NDVI grids to derive the annual total ET-rate distributions for each area and year, excluding areas of agricultural croplands, open water and playa. The regression model is expressed by the following equation:

$$ET = 2,749.087 \times NDVI + 65.426 \qquad \text{(Eq. D-1)}$$

where,

ET = Annual Total ET [mm per year]
$NDVI$ = Footprint-Weighted Growing-Season Average NDVI

These steps yielded 30×30 m grids of annual total ET for each valley and year, except for the areas delineated as agricultural croplands, open water, and playa, whose grid values remained null. The grids were then converted from mm to ft by multiplying the values by a conversion factor of 0.003281 ft/mm. The resultant grids were queried to identify grid cells whose values exceeded the average annual reference ET_{ref} for each respective valley. For Spring Valley, the average annual ET_{ref} is 4.2 ft, as measured by the UNLV, DRI, and SNWA EC stations located in the valley (Shanahan et al., 2011, p. 4-5). For White River Valley, the average annual ET_{ref} is 4.5 ft (Shanahan et al., 2011, p. 4-5). During the 5-year period, the percentage of cells that exceeded the average annual ET_{ref} in Spring Valley ranged from 0.62 to 3.40 percent, with an annual average of 2.12 percent. In White River

Valley, the percentage ranged from 0.49 to 1.15 percent, with an annual average of 0.75 percent. For these cells, the average annual ET_{ref} of the corresponding valley was assumed.

For the agricultural croplands, it was assumed that the croplands replaced natural vegetation of the land-cover class currently encompassing them. It is also assumed that prior to development the majority of water currently being used for agricultural purposes originated within the groundwater discharge area, or was the source of groundwater for the phreatophytic vegetation. The agricultural cropland areas represent approximately two and five percent of the total groundwater discharge areas in Spring and White River valleys, respectively. To remove the effects of this development, the null-value grid cells within the agricultural cropland areas were assigned values equivalent to the nearest ET-rates representing natural vegetation (i.e., phreatophytes) using a search radius of 90 m. For null-value grid cells within open-water areas, consumptive-use rates of 4.70 and 4.90 ft/yr were assigned for Spring and White River valleys, respectively, based on rates reported by Huntington and Allen (2010, p. 246 and p. 248).

Next, the annual 4 km adjusted-PRISM precipitation grids were resampled to the same resolution and origin as the annual ET grid, and converted from inches to feet by multiplying the values by a conversion factor of 1/12 ft/in. The groundwater-ET grids were derived using grid operations to subtract the adjusted-PRISM precipitation grids from the annual total-ET grids. Null-value grid cells within the playa areas of the groundwater ET grids were assigned an annual groundwater-evaporation rate of 0.09 ft based on Deverel et al. (2005). Deverel et al. (2005, p. 14) reported groundwater evaporation rates on the Yelland Dry Lake in Spring Valley ranging from 11 to 42 mm/yr (0.04 to 0.14 ft/yr) based on an analysis of chloride and deuterium data from shallow groundwater samples and soil cores collected at two sites located on the playa. The evaporation rate assigned to the playa cells is the average of these values, 0.09 ft/yr.

The annual total ET, adjusted-PRISM precipitation, and groundwater-ET distributions are depicted in Figures D-7 through D-11 for Spring Valley, and Figures D-12 through D-16 for White River Valley. The groundwater-ET grids were used to derive the groundwater-ET estimates for each year by summing the products of each grid-cell area and corresponding annual groundwater ET for all grid cells within each area. These totals are provided in Table D-6, which includes estimates for each land-cover class and the period of record average.

D.5.1 Spring Valley Northern Groundwater Discharge Area

For the groundwater discharge area in northern Spring Valley (Figure D-1), average annual groundwater-ET rates were derived for the land-cover classes from ET-rates measured at sites in Spring Valley by UNLV, DRI, SNWA, and USGS. These data are listed in Table D-7. The annual groundwater-ET rates were calculated by subtracting the annual precipitation from the annual total-ET measured at the sites. The average groundwater-ET rate was calculated for each class and multiplied by the corresponding area to calculate the average annual groundwater ET volumes. These were summed to calculate the total groundwater ET in the northern groundwater discharge area in Spring Valley. The acreages, average-annual groundwater-ET volume, and resultant groundwater ET estimates are listed in Table D-8. The average annual groundwater ET for the groundwater discharge area in northern Spring Valley is estimated to be about 3,300 afy.

Table D-6
Annual Groundwater ET Estimates for Spring (main discharge area) and White River Valleys

ET Class	2006	2007	2008	2009	2010	Period of Record Average[a]
Spring Valley (main discharge area)						
Playa	1,200	1,200	1,200	1,200	1,200	1,200
Bare Soil/Low Density Vegetation	17,800	21,900	26,200	12,600	4,200	16,500
Phreatophyte/Medium Density Vegetation	50,400	46,400	50,200	46,700	24,200	43,600
Wetland/Meadow	34,100	29,800	27,000	31,400	26,900	29,800
Open Water	900	400	100	100	200	300
Subtotal	**104,400**	**99,700**	**104,700**	**92,000**	**56,700**	**91,500**
White River Valley						
Playa	---	---	---	---	---	---
Bare Soil/Low Density Vegetation	2,300	7,100	9,700	6,600	700	5,300
Phreatophyte/Medium Density Vegetation	34,500	49,700	59,300	43,500	12,100	39,800
Wetland/Meadow	19,900	17,200	18,100	18,100	12,400	17,100
Open Water	2,700	3,100	2,600	2,700	2,400	2,700
Total	**59,400**	**77,100**	**89,700**	**70,900**	**27,600**	**64,900**

[a]Column may not total due to rounding.
Values are in afy and are rounded to the nearest 100 afy.

For Spring Valley, the period of record average-annual groundwater ET is estimated as the sum of the estimates for the main groundwater discharge area, 91,500 afy, and the northern groundwater discharge area, 3,300, afy, or 94,800 afy. For White River Valley, the period of record average-annual groundwater ET is estimated to be 64,900 afy.

Table D-7
Average Annual Groundwater-ET Rates for the Groundwater Discharge Area in Northern Spring Valley

Class	Site Name	Source	Year	Total ET Rate (ft/yr)	Precipitation (in./yr)	Precipitation (ft/yr)	Groundwater ET Rate (ft/yr)
Bare Soil/Low Density Vegetation	SV7	DRI	2007	0.43	3.95	0.33	0.10
			2008	0.61	2.59	0.22	0.39
			2009	0.80	6.19	0.52	0.28
Sparse Desert Shrubland	SPV-1	USGS[a]	2006	0.84	8.58	0.72	0.12
Bare Soil/Low Density Vegetation				**0.67**	**5.33**	**0.45**	**0.23**
Phreatophyte/Medium Density Vegetation	SV1	SNWA/UNLV	2006	0.79	6.11	0.51	0.28
			2007	0.61	5.00	0.42	0.19
			2008	0.63	6.00	0.50	0.13
			2009	0.77	8.17	0.68	0.09
			2010	0.96	12.60	1.05	0.00
	SV3	SNWA/UNLV	2007	0.79	4.21	0.35	0.44
			2008	0.78	3.17	0.26	0.52
			2009	0.99	7.78	0.65	0.34
			2010	1.16	10.17	0.85	0.31
	SV5	DRI	2007	0.80	5.44	0.45	0.35
			2008	1.09	3.50	0.29	0.80
			2009	1.61	8.70	0.73	0.89
	SV6	DRI	2007	0.68	5.24	0.44	0.24
			2008	0.87	3.37	0.28	0.59
			2009	1.28	8.18	0.68	0.60
Moderately Dense Desert Shrubland	SPV-2	USGS[a]	2006	1.01	9.17	0.76	0.25
Phreatophyte/Medium Density Vegetation				**0.93**	**6.68**	**0.56**	**0.37**
Wetland/Meadow	SV2b	SNWA/UNLV	2007	3.57	5.27	0.44	3.13
			2008	3.63	2.79	0.23	3.40
			2009	3.52	7.51	0.63	2.89
			2010	3.62	8.42	0.70	2.92
	SV4	DRI	2007	2.46	5.79	0.48	1.98
			2008	3.43	5.12	0.43	3.00
			2009	4.19	6.96	0.58	3.61
Grassland/Meadowland	SPV-3	USGS[a]	2006	2.25	7.97	0.66	1.59
Wetland/Meadow				**3.33**	**6.23**	**0.52**	**2.81**

[a]Moreo et al. (2007, p. 20)

Table D-8
Annual Groundwater-ET Estimate for the Groundwater Discharge Area in Northern Spring Valley

Class	Area (acres)	Groundwater ET (ft/yr)	Groundwater ET (afy)
Bare Soil/Low Density Vegetation	540	0.23	100
Phreatophyte/Medium Density Vegetation	1,720	0.37	600
Wetland/Meadow	920	2.81	2,600
		Total	**3,300**

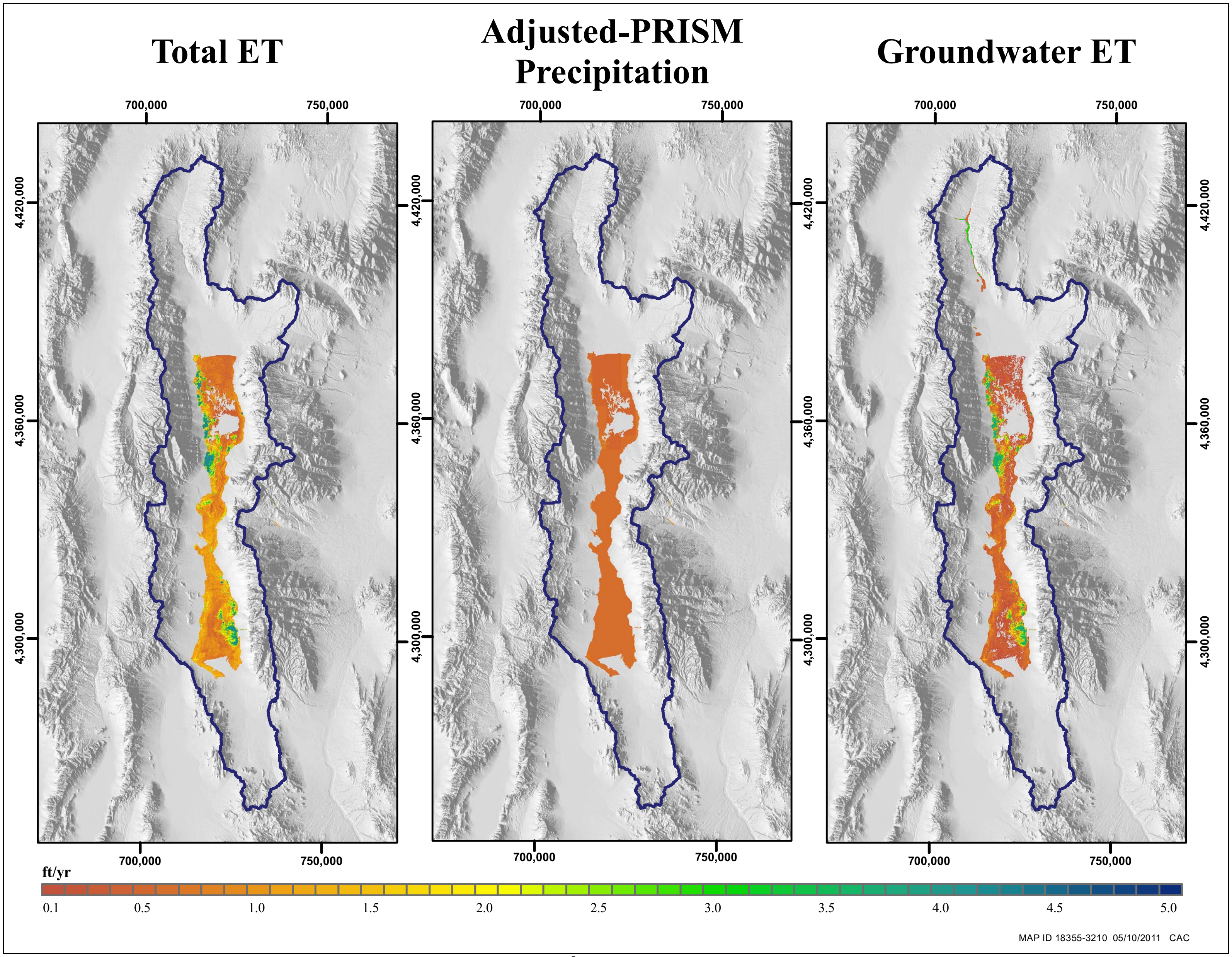


Figure D-7
Spring Valley 2006–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

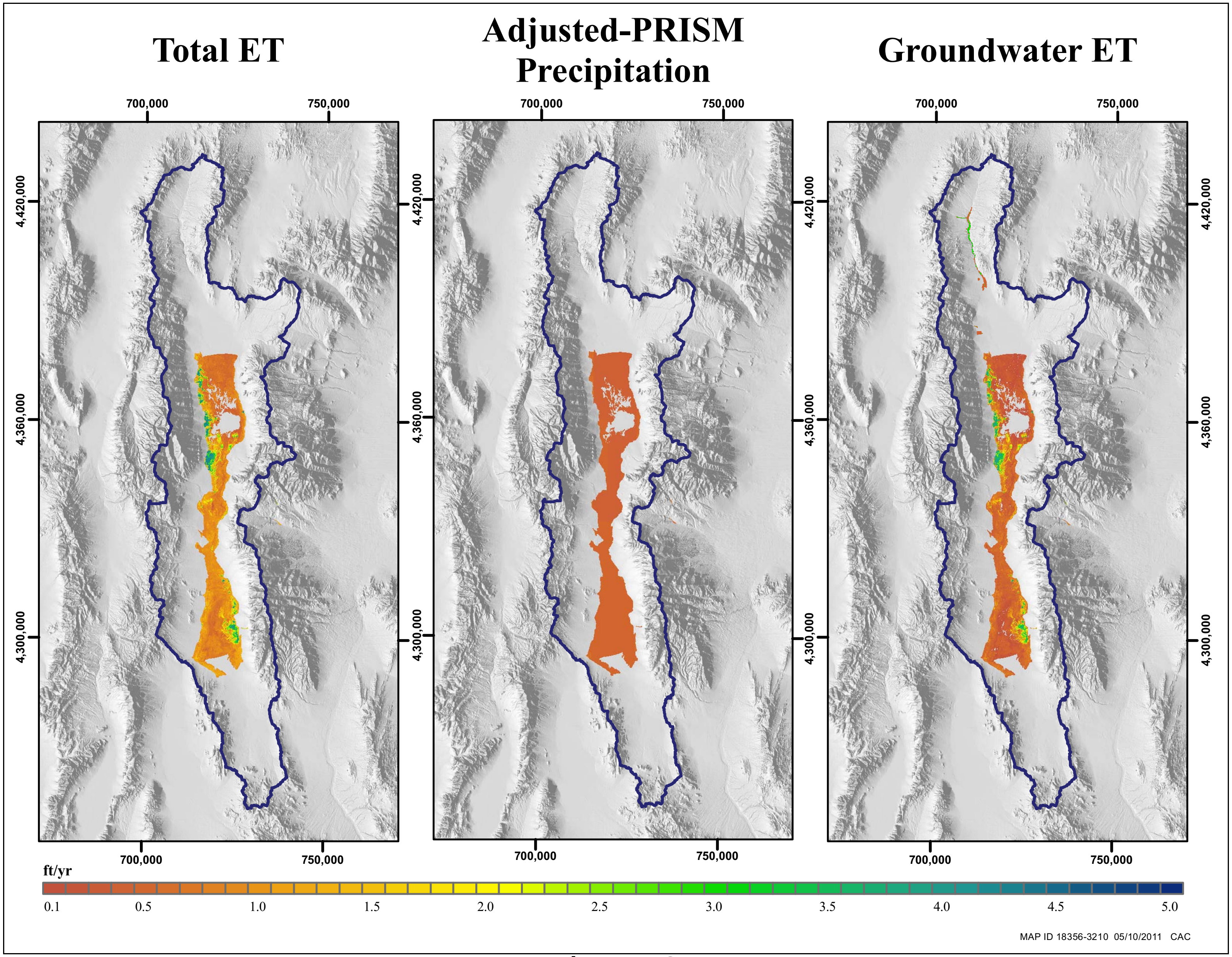


Figure D-8
Spring Valley 2007–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

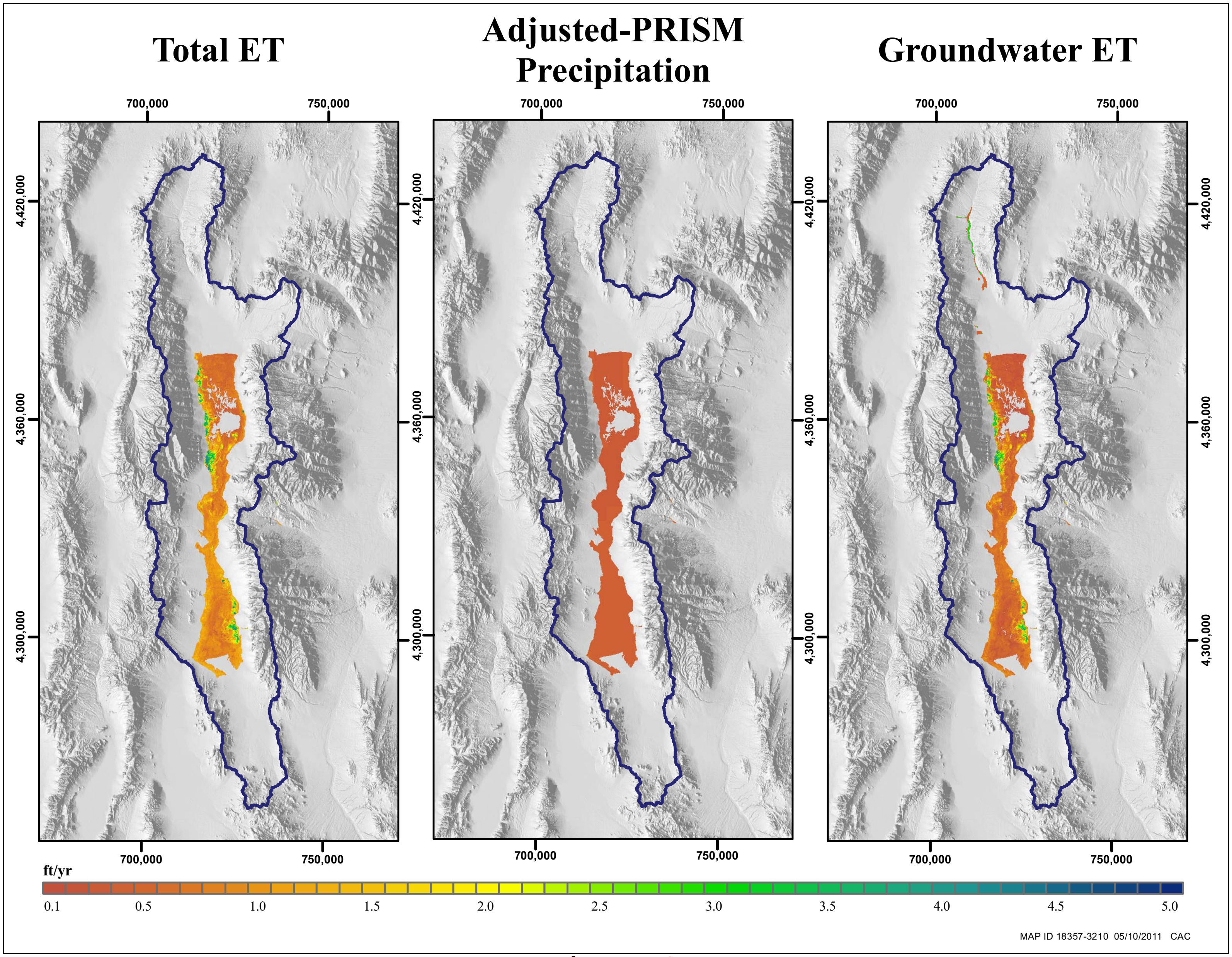


Figure D-9
Spring Valley 2008–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

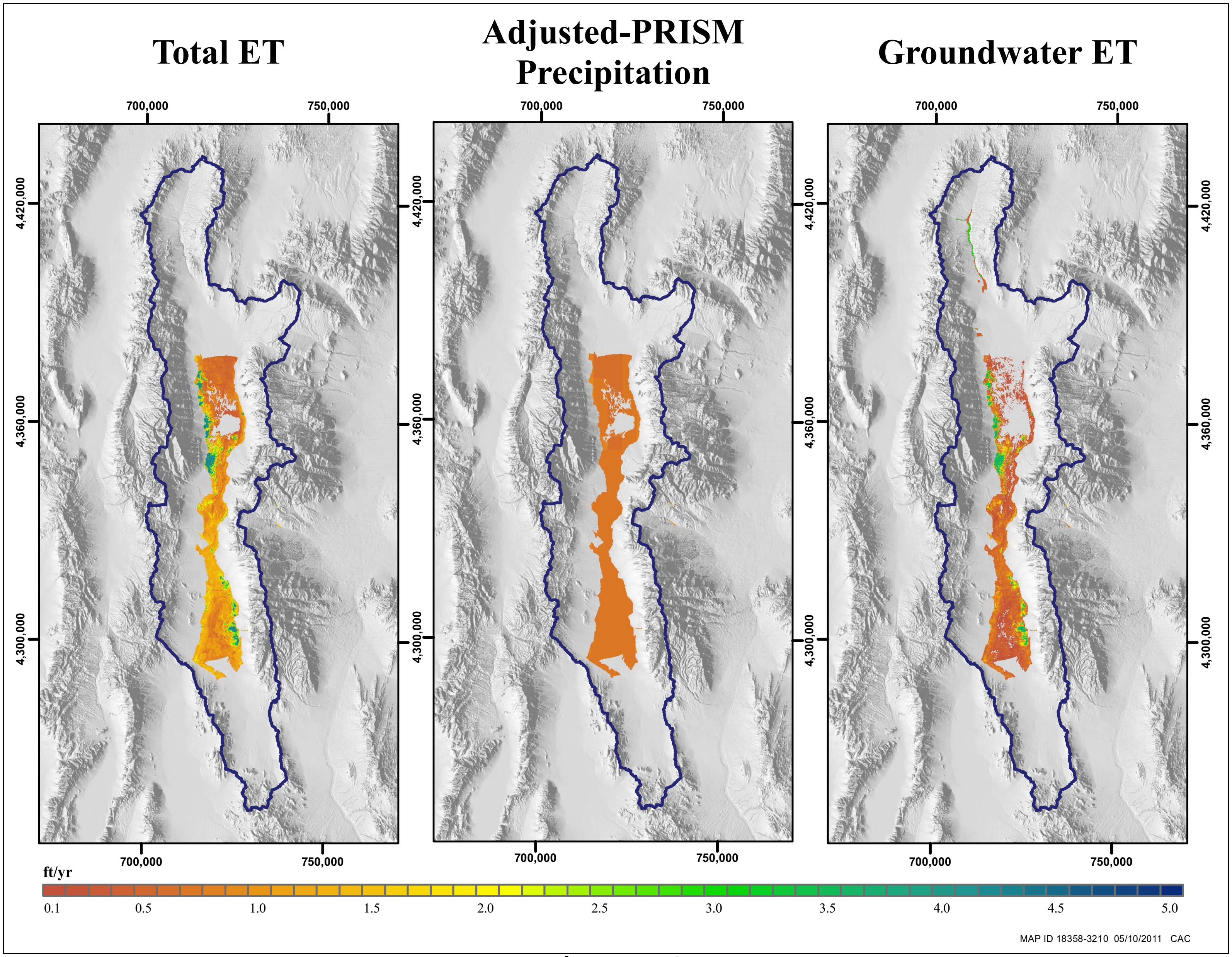


Figure D-10

Spring Valley 2009–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

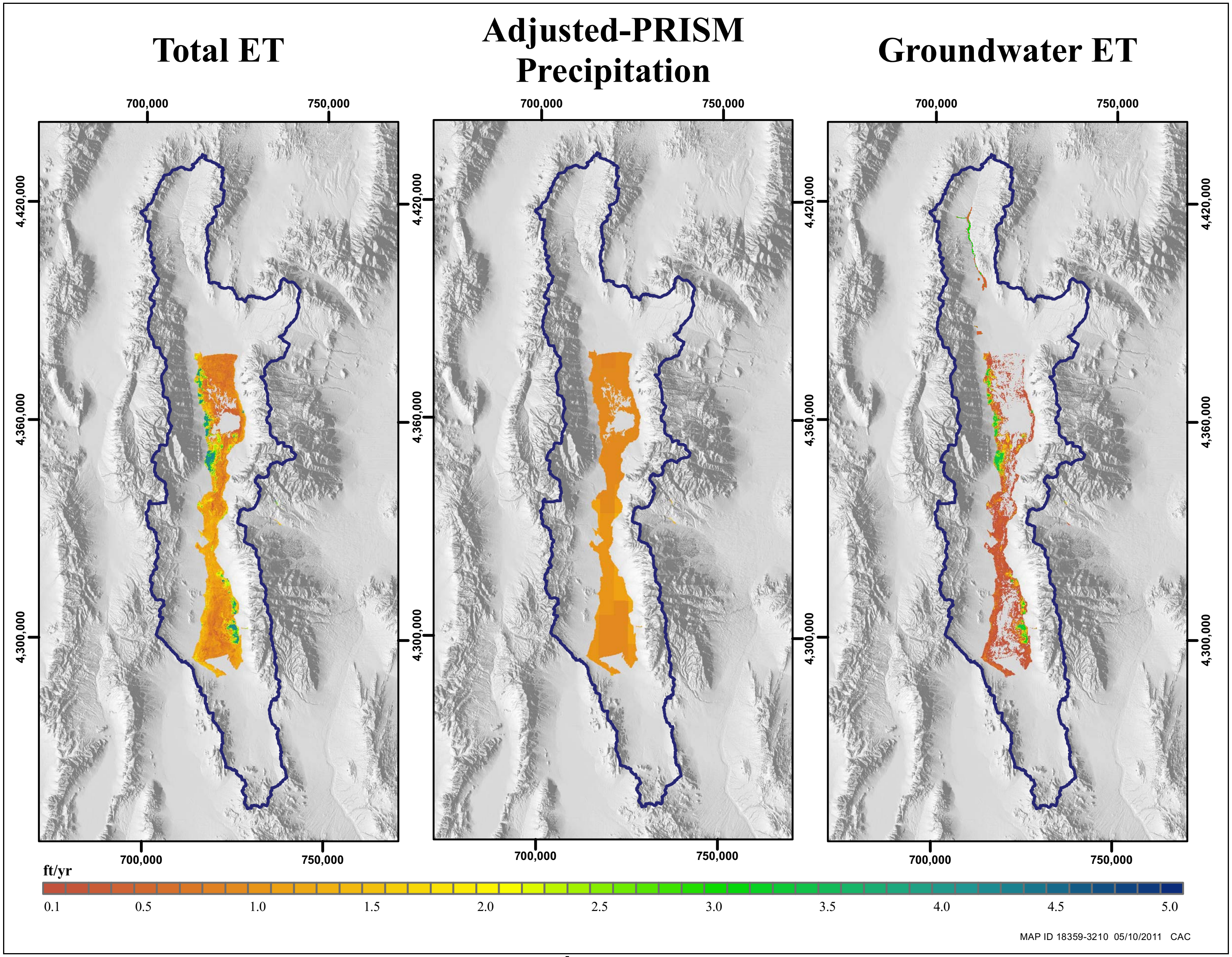


Figure D-11
Spring Valley 2010–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

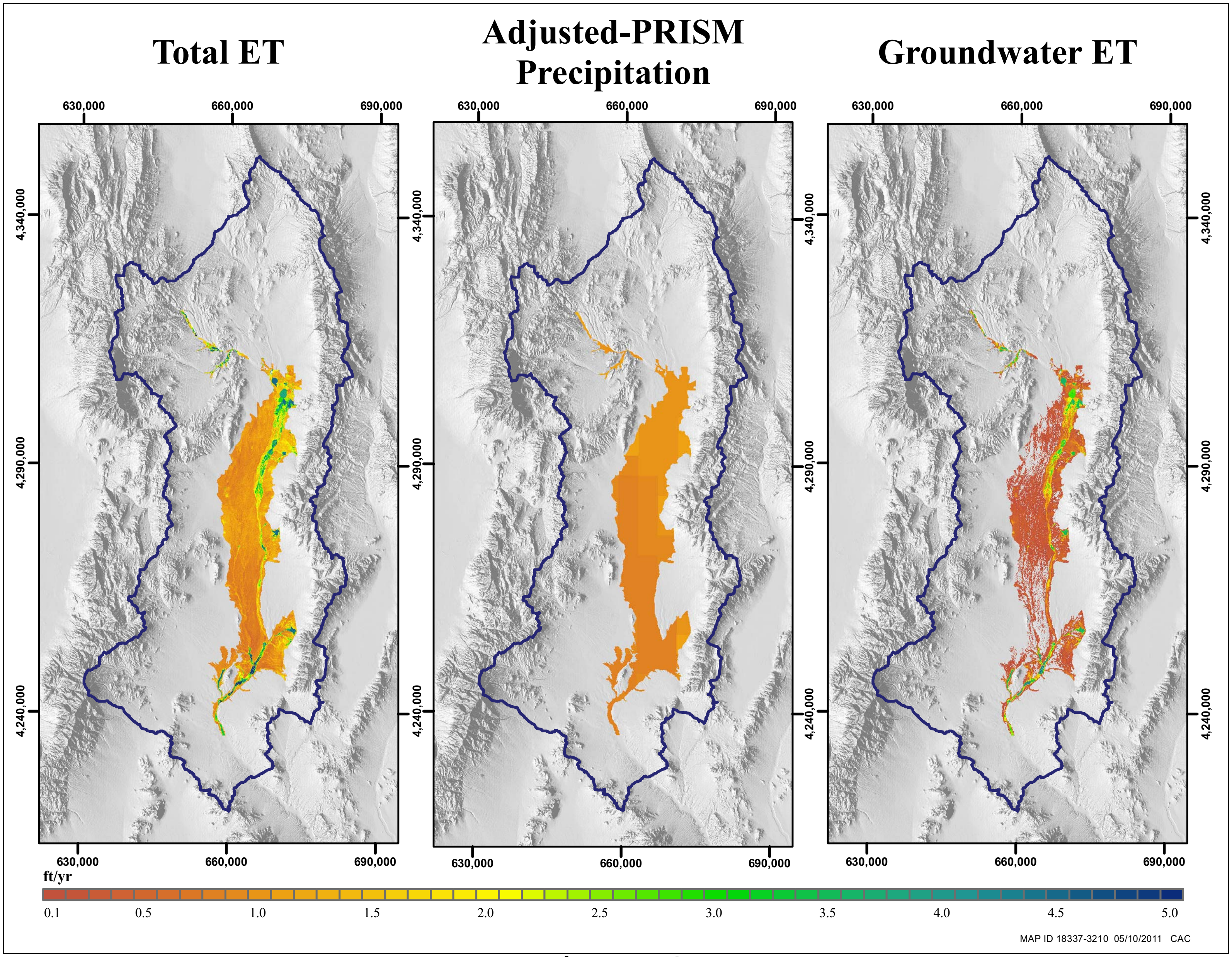


Figure D-12
White River Valley 2006–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

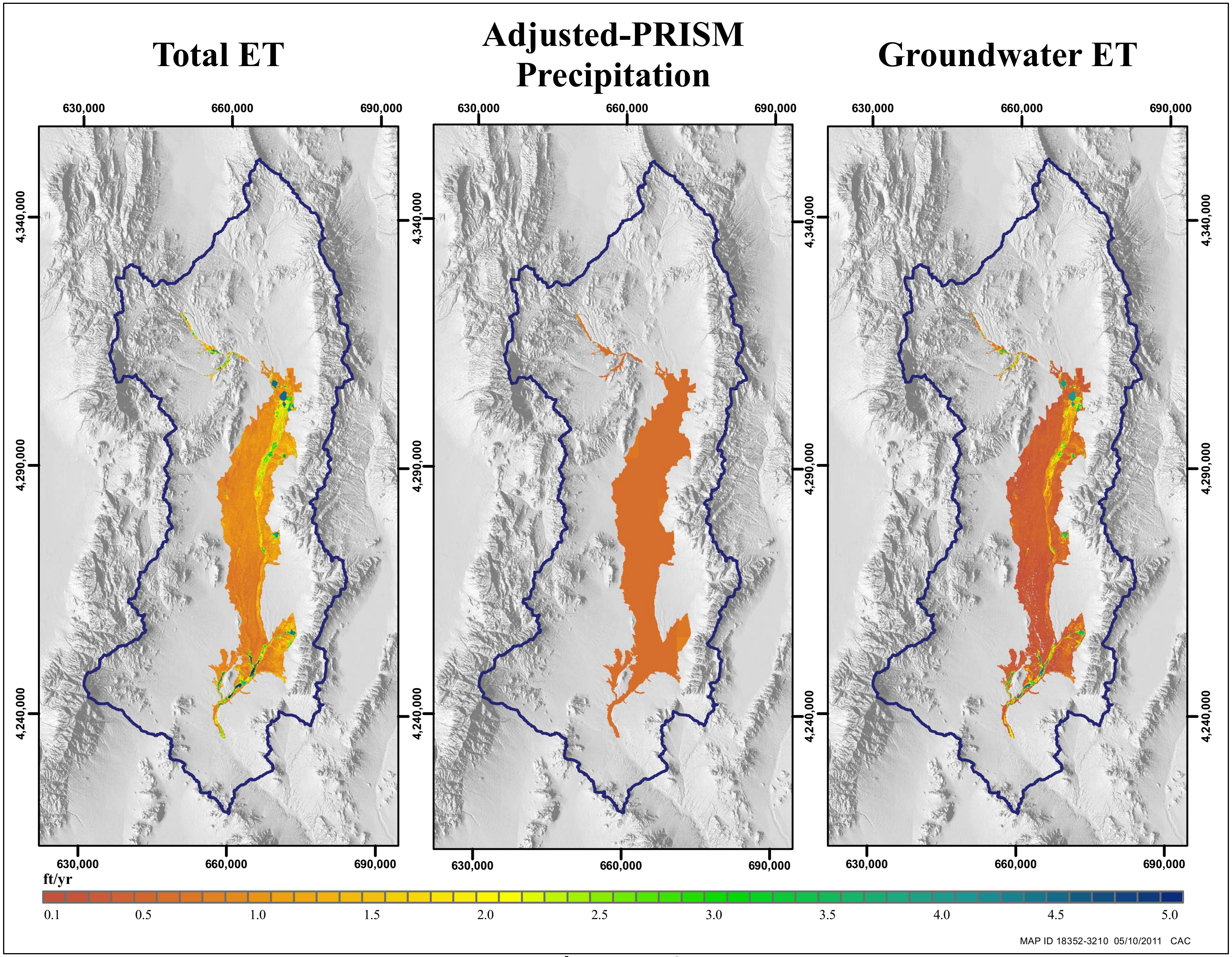


Figure D-13
White River Valley 2007–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

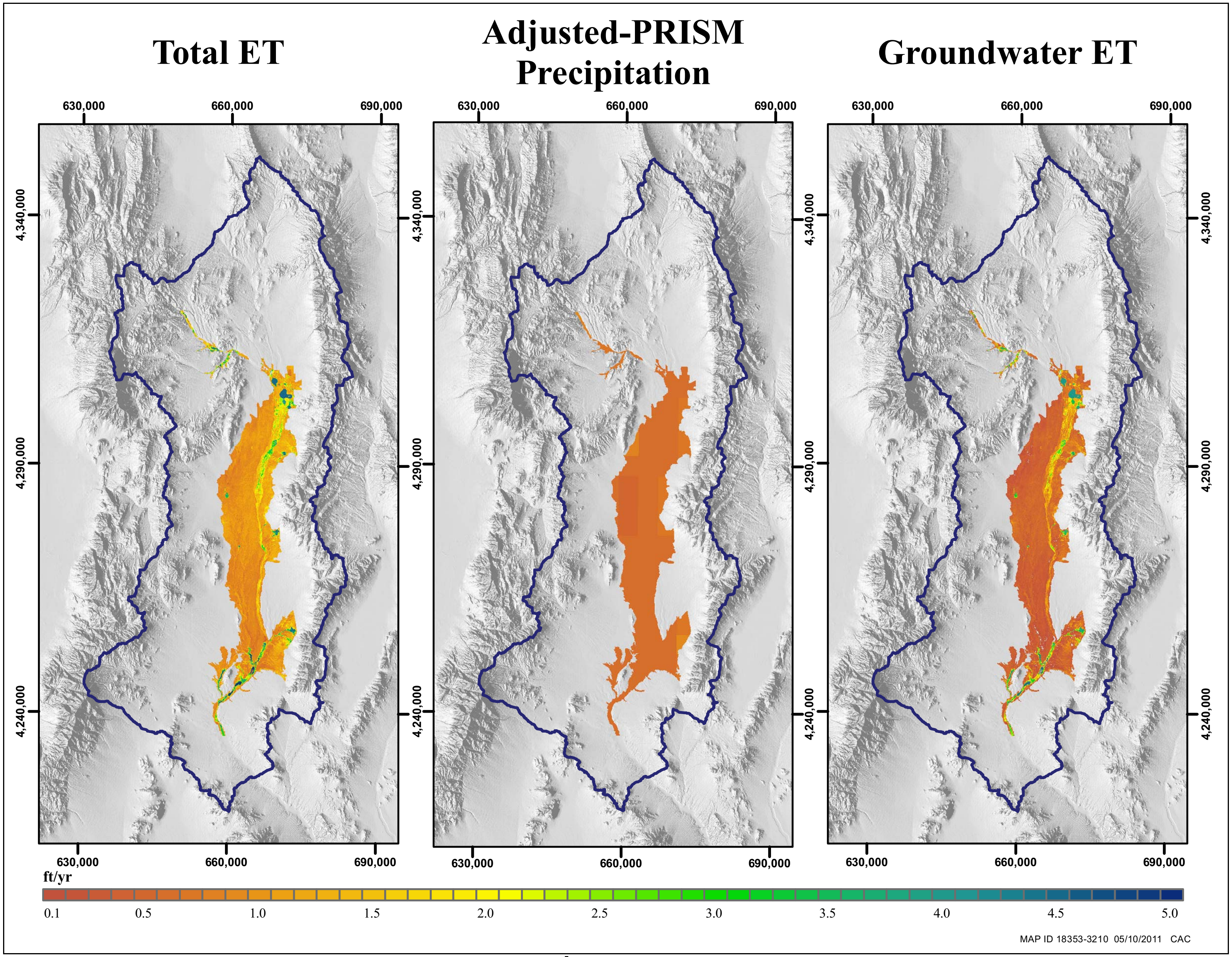


Figure D-14
White River Valley 2008–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

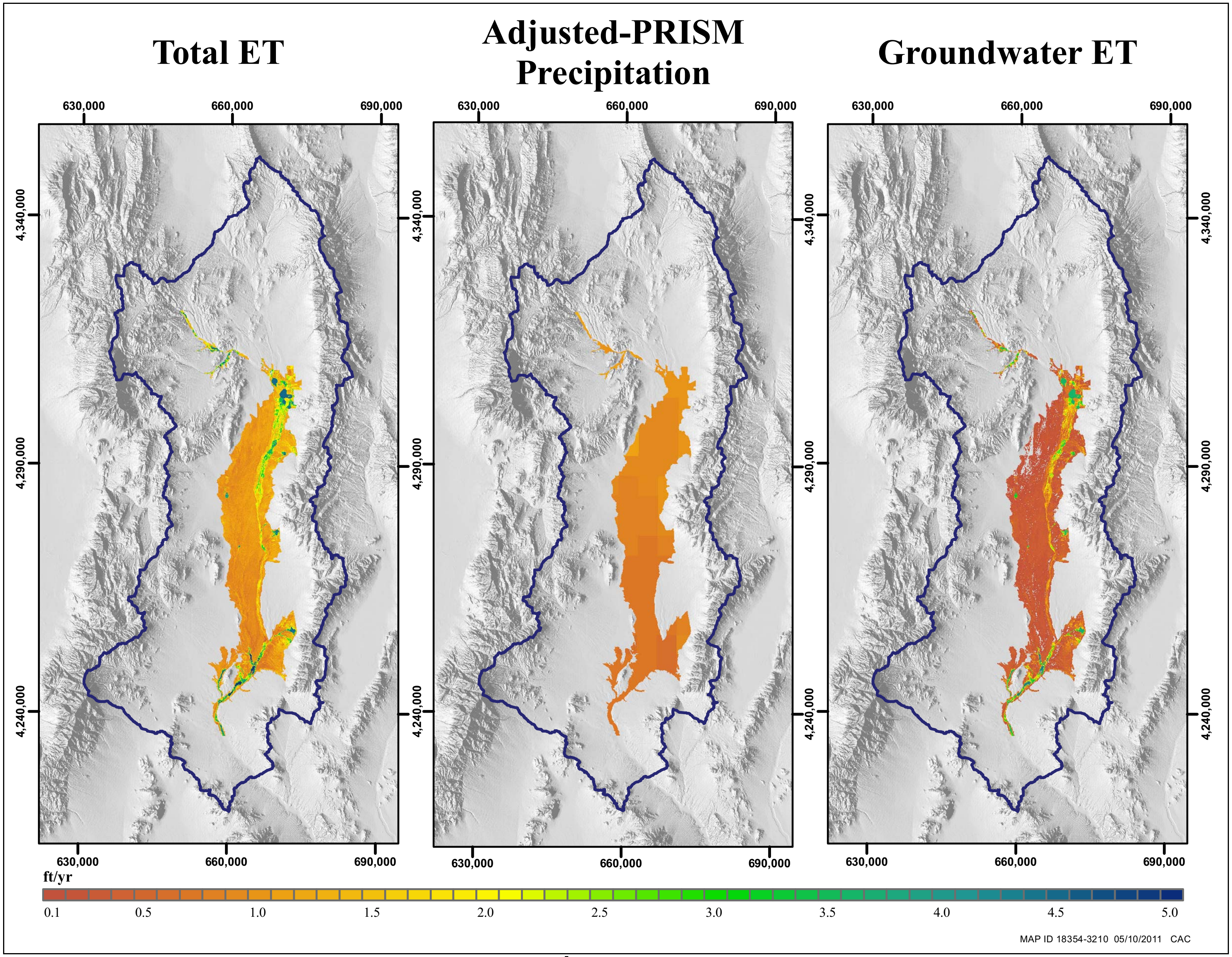


Figure D-15
White River Valley 2009–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

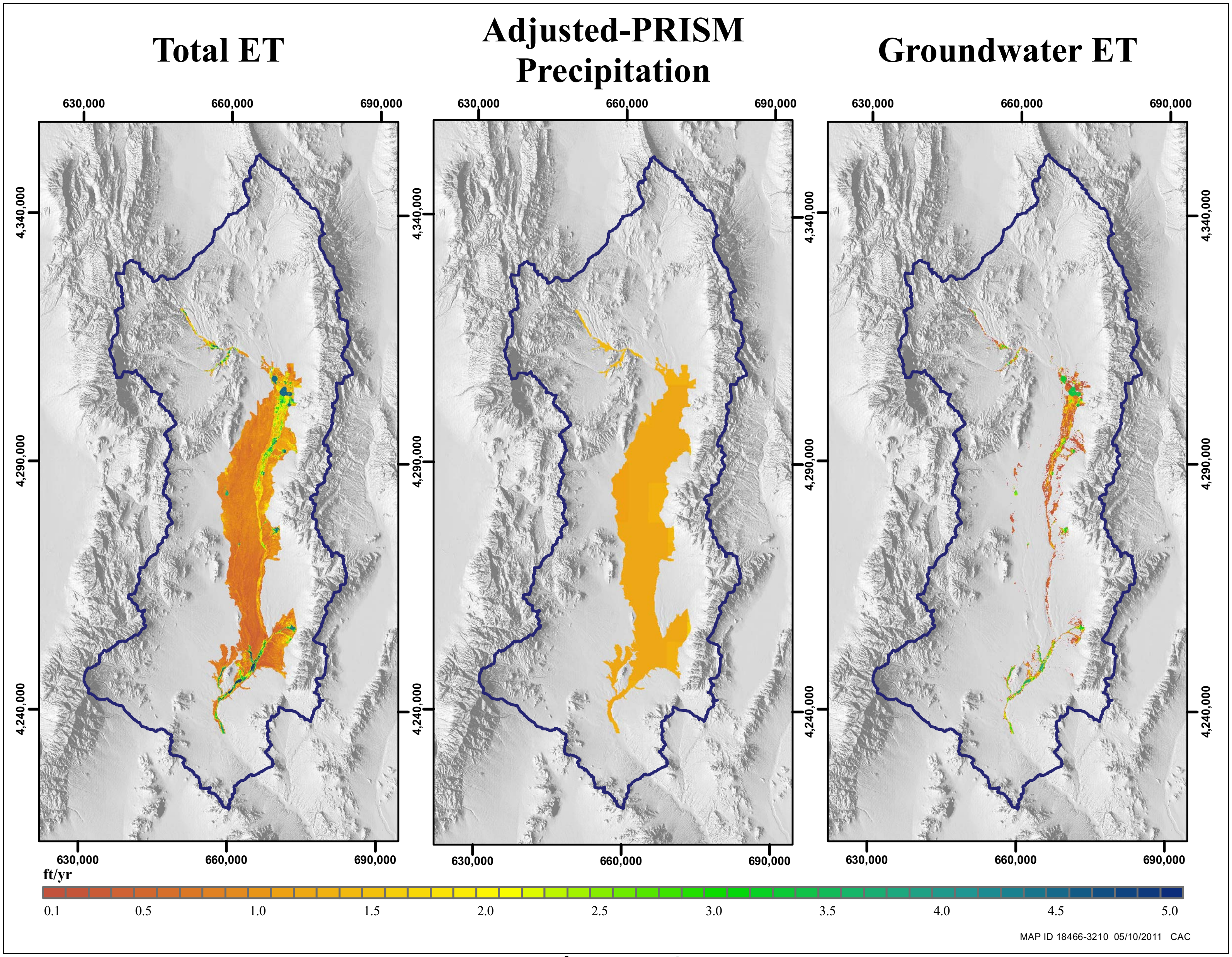


Figure D-16
White River Valley 2010–Annual ET, Adjusted-PRISM Precipitation and Groundwater ET Grids

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Appendix E

External Boundary Flow Estimates

E.1.0 Introduction

This appendix summarizes estimates of interbasin groundwater flow across the hydrographic-area boundary of Spring Valley, and presents the assumptions, data, and calculations used to estimate interbasin groundwater flow across the external boundaries the WRFS. These estimates were used as the basis for some of the Excel® Solver constraints used in the estimation of the recharge efficiencies presented in Appendix F.

E.2.0 Technical Approach and Assumptions

Groundwater flow across the hydrographic-area boundary of Spring Valley and the external boundaries of the WRFS was evaluated by Rowley et al. (2011) based on the permeability of rock units occurring at, near, and beneath the boundaries, the presence of calderas, the framework geometry, and the orientation and presence of significant fault structures that might enhance or inhibit groundwater movement. Using the hydrogeologic framework presented in Rowley et al. (2011), the direction and magnitude of groundwater flow was estimated using the hydraulic heads measured in wells and inferred from spring elevations and aquifer-properties data provided in Section 4.0 and Appendix C, and isotopic data and analysis presented in Thomas and Mihevc (2011). The method used to estimate groundwater flow across basin boundaries and the underlying assumptions are presented in the remainder of this section.

E.2.1 Method Description

For boundary segments identified as flow boundaries and for which all of the necessary data were available, groundwater flow was estimated using Darcy's Law in the following form:

$$Q = (K \times b) \times I \times W \times \left(\frac{365}{43560}\right) \quad \text{(Eq. E-1)}$$

where,

Q = Groundwater flow rate (afy)
K = Hydraulic conductivity (ft/d)
b = Aquifer thickness (ft)
I = Horizontal hydraulic gradient (ft/ft)
W = Width of flow section (ft)

The estimates derived using Equation E-1 are assumed to represent the mean annual groundwater flow volume across the specified boundary as the hydraulic gradient (I), which is the only time-dependent variable, is not expected to vary significantly over time.

E.2.2 Method Application and Assumptions

Simplifying assumptions were made with the objective of calculating reasonable and representative estimates of groundwater flow across specified boundaries of Spring Valley and the WRFS using Equation E-1. These assumptions involve aquifer-property values used in the calculation for the HGUs comprising the flow section. In Equation E-1, this refers to the product of the hydraulic conductivity (K) and aquifer thickness (b), which is equivalent to the transmissivity (T). For some of the groundwater flow calculations, the transmissivity value was derived from estimates of K and b, while for others, the transmissivity value was directly derived from aquifer tests performed in the vicinity of flow sections on wells completed in the HGUs comprising them.

Groundwater flow calculations using estimates of K and b were applied in cases where aquifer-test results were unavailable for wells located in the vicinity of the flow section. In these cases, regional estimates of K were used and the saturated thicknesses of the aquifer(s) comprising the flow section were estimated. Flow sections were defined as intervals extending 2,000 ft below the groundwater table. Aquifer thicknesses within these intervals were estimated from hydrogeologic cross sections constructed along the flow boundaries. This constraint is based on the simplifying assumption that the permeability of aquifers decreases with depth due to the overburden pressure of the overlying rocks. This assumes that with increasing depths, the fractures and pore spaces become more compressed and sealed; thereby, limiting groundwater movement. The implicit assumption is that groundwater flow below the flow section is minimal. This is a simplifying assumption and it is recognized that there are many observations of groundwater temperature, isotopes, and chemistry throughout the basin and range that indicate the hydrogeologic framework permits much deeper circulation of groundwater.

Transmissivity values derived from aquifer tests were applied in groundwater flow calculations where aquifer-test data were available for wells located in the vicinity of the flow boundary and completed within HGUs comprising the flow section. Two of the many underlying assumptions of analytical solutions applied to aquifer-test data to estimate hydraulic properties are that the well is fully penetrating and that the aquifer is isotropic and homogeneous (Kruseman and de Ridder, 2000). These conditions are rarely encountered in the basin and range, particularly in the carbonate aquifer which is very thick, anisotropic and heterogeneous due to fractures caused by extensive faulting. Analytical solutions (assuming flow in porous media) are typically applied to aquifer-test data to approximate the hydraulic properties of the carbonate aquifer, even though many of the assumptions underlying these solutions are violated. Tests of long duration provide more representative approximations than those of shorter duration because more of the aquifer volume is stressed and represented in the estimated values. Shorter test durations represent only the aquifer volume closer to the pumping well (i.e. site-specific rather than average conditions). Therefore, transmissivity values used in flow calculations were selected from aquifer tests of durations greater than or equal to 72 hours to ensure the most representative, or average, values were used.

E.3.0 SPRING VALLEY SUMMARY

Potential groundwater flow across the hydrographic-area boundary of Spring Valley was evaluated by Rowley et al. (2011) who concluded that interbasin flow is unlikely to occur except in four locations which are depicted on Figure 7-1. Three of the four permissible-flow boundaries are located in northern Spring Valley; two at the boundary with Tippett Valley, west and east of the Red Hills, and one at the boundary with Snake Valley to the east. A fourth permissible-flow boundary is located in southeastern Spring Valley along Limestone Hills at the boundary with Hamlin Valley. Descriptions of each flow boundary are presented in the following sections.

E.3.1 Northern Spring Valley and Southern Tippett Valley Boundary

Groundwater flow across the northern boundary of Spring Valley with Tippett Valley is permissible on either side of the Red Hills through potential pathways of fractured carbonate rocks caused by north-south oriented normal faults. However, due to what may be a buried caldera in southern Tippett Valley, just north of the Red Hills, groundwater flow is likely minimal (Rowley et al., 2011). The flow direction is inconclusive because of the lack of hydraulic-head data for the carbonate aquifer; however, the limited data collected from basin-fill wells, coupled with the presence of the possible caldera to the north, suggest the boundary is most likely a groundwater divide.

E.3.2 Northeastern Spring Valley and Western Snake Valley Boundary

Groundwater flow across the northwestern boundary of Spring Valley with Snake Valley is permissible through the younger sediments (QTs) and along an inferred northwest-southeast trending fault; however, the presence of north-south trending faults in this area would impeded any significant groundwater flow in the west-east direction (Rowley et al., 2011). The source of groundwater to this area is most likely derived locally within the northern part of the Snake Range, with perhaps some component from the southern Kern Mountains. Based on the hydrogeologic framework and gravity data, a minor amount of outflow from Tippett Valley might pass through the northeastern part of Spring Valley to this area, but as previously described, this volume would be minor and limited by the buried caldera interpreted in southern Tippett Valley. It is unlikely that groundwater from eastern Spring Valley would flow to this area due to the presence of the Precambrian-Cambrian siliciclastic rocks forming the base of the western range front of the Snake Range, and the associated range-front fault and subsidiary faults that extend to the north and west of the Red Hills. Therefore, it is concluded that there is no groundwater flow from Spring Valley to Snake Valley except for possibly some minor amount of flow from Tippett Valley passing through the northeastern part of Spring Valley to western Snake Valley. This amount is thought to be minor, and the groundwater that occurs in this area is most likely derived from the northern Snake Range and the southern Kern Mountains.

E.3.3 Southeastern Spring Valley and Hamlin Valley Boundary

Groundwater flow across the boundary of Spring and Hamlin valleys is likely through the northern and southern parts of the Limestone Hills, and permissible across the carbonate rocks located in between (Rowley et al., 2011). The Limestone Hills form a range which is a north-south oriented horst of carbonate rocks bounded on each side by range-front and subsidiary faults. Underlying these carbonate rocks are the Precambrian-Cambrian siliciclastic rocks that form the lower confining unit. The thickness of the carbonate rocks is estimated to range between 4,000 and 6,000 ft and, in the north, overlying Tertiary volcanic rocks are present. Groundwater flow is considered likely at the northern and southern parts of the range due to the presence of minor east-west oriented normal faults that cut through the range. Groundwater flow through the range between these locations is permissible given the presence of carbonate rocks; however, this flow is significantly limited by the bounding range-front faults and the low hydraulic conductivity of the bulk properties of the carbonate rocks that comprise the range.

Groundwater flow rates through the northern and southern flow boundaries of the Limestone Hills were calculated using Darcy's Law (Equation E-1) and the following data:

- The hydraulic gradient across the boundaries was estimated at 0.0008866 ft/ft, using local wells located in the vicinity and completed in the carbonate aquifer.

- The hydraulic conductivity value was estimated at 8 ft/d based on aquifer tests performed on SNWA well 184W101 (Prieur et al., 2010).

- The saturated aquifer thickness was assumed to be 2,000 ft for both boundary segments through which most of the flow occurs. Hydraulic conductivity decreases with depth due to overburden pressure.

- The lengths of the northern and southern flow sections were estimated to be approximately 30,000 ft and 6,500 ft, respectively.

The outflow rates estimated for the northern and southern flow boundaries of the Limestone Hills are 3,600 afy and 800 afy, respectively. The total estimate of outflow through the Limestone Hills is 4,400 afy.

E.4.0 WRFS BOUNDARY FLOW

Groundwater flow across external boundaries of the WRFS was evaluated by Rowley et al. (2011), and several boundaries were identified where flow is characterized as likely or permissible based on the hydrogeologic framework. The locations of these boundaries are identified in Figure E-1, and include the boundary with southern Butte Valley-Southern Part (inflow), southwestern Lower Meadow Valley Wash (inflow), Tikaboo Valley South (outflow), Hidden Valley (outflow), and California Wash (outflow). Minor amounts of outflow from southwestern Long Valley to Newark Valley (Harrill et al., 1988, p. 2) and from Garden Valley to Penoyer Valley may occur based on the hydraulic head potential (San Juan et al., 2004; Chapter C, p. 119), but they are not considered in this analysis. Elsewhere, boundary flow is limited by hydrogeologic framework and/or groundwater divides created by the recharge that occurs within the mountain ranges. The WRFS external boundary flow is discussed in the following sections.

E.4.1 Jakes Valley and Butte Valley (Southern Part) Boundary

Rowley et al. (2011) characterized groundwater flow at this boundary as permissible due to the presence of fractured carbonate rocks associated with significant faulting at the northwest boundary. A northeast-trending regional fault in the southern Butte Mountains (Figure E-2) and the western range-front fault of the Egan Range have downthrown the Butte Mountains to form a graben extending from northeastern Jakes Valley into southern Butte Valley to the Cherry Creek Range (Rowley et al., 2011). The significance of the fault and the geometry of the graben are clearly imaged by the gravity data presented in Rowley et al. (2011) and Mankinen and McKee (2011). The graben is comprised of upper Paleozoic carbonate rocks, on top of which lie Cretaceous-Triassic clastic rocks and Tertiary volcanic rocks. Groundwater flow is likely along the northeast-trending fault through the associated fractured bedrock, and permissible within the carbonate rocks of the graben. The surface hydrogeology of the area and a profile of the flow section is presented in Figure E-2.

The length of the flow section is approximately 45,000 ft and it is assumed that the flow occurs predominantly through the saturated carbonate rocks. In the northwestern part of the flow section, greater thicknesses of the Cretaceous-Triassic clastic rocks and Tertiary volcanic rocks are present; therefore, the saturated thickness of carbonate rocks assumed to contribute to the boundary flow is less. At this location the saturated thickness was estimated to be 500 ft, and for the southern part where only the volcanic rocks overlie the carbonate rocks, a saturated thickness of 1,500 ft was estimated. The length of these segments of the flow section are approximately 30,000 ft and 15,000 ft, respectively.

The direction of groundwater flow was evaluated using hydraulic-head data measured in wells located within the graben. These data indicate a hydraulic gradient from Butte Valley to Jakes Valley based on well 178B N20 E61 23AC1 (Map ID 178B-7) located in Butte Valley, and well 174 N18

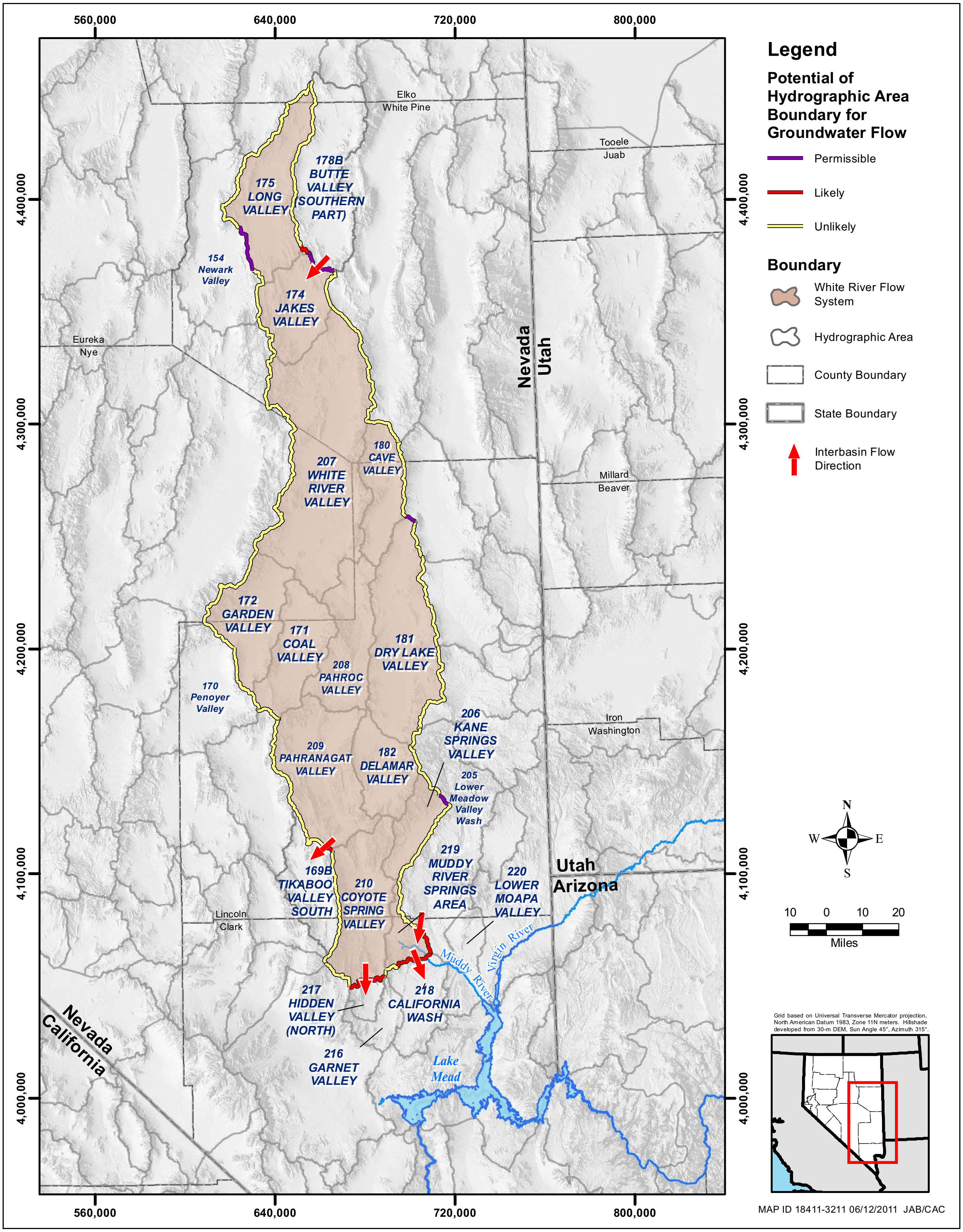

Figure E-1
Locations of Interbasin Flow for the External Boundaries

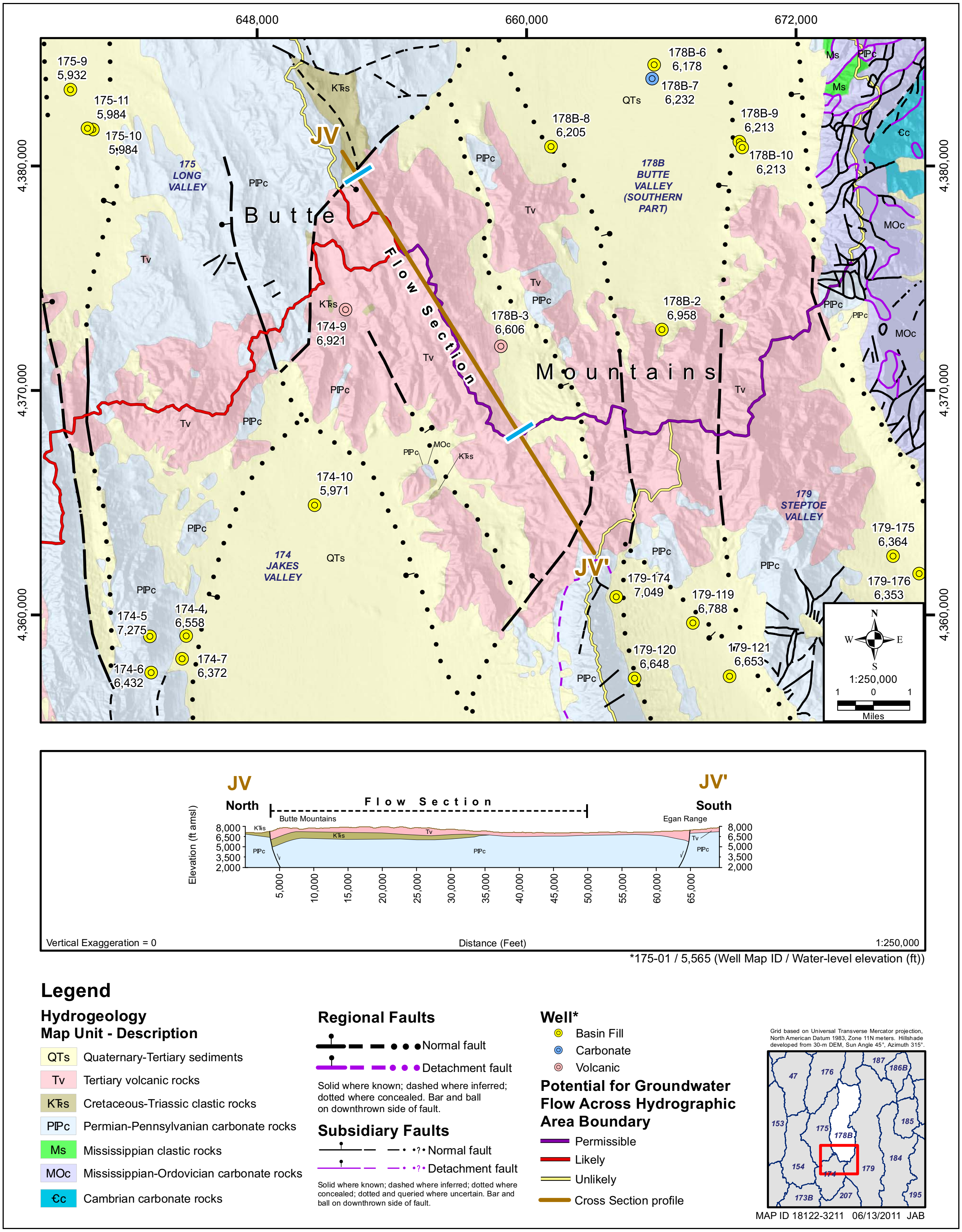

Figure E-2
Interbasin Groundwater Flow from Butte Valley (Southern) to Jakes Valley

E60 17CC 1 (Map ID 174-10) located in Jakes Valley (Figure E-2). The water-level elevations at these wells are 6,232 ft amsl and 5,971 ft amsl, respectively (Appendix C). A distance of 75,000 ft between the two wells was approximated by projecting them to a line oriented parallel to the flow direction and perpendicular to the flow section. Based on this information, a hydraulic gradient of 0.003487 ft/ft was calculated. Wells 178B N19 E61 30B 1 USBLM (Map ID 178B-3) and 174 N19 E60 21 CB 1 (Well Map ID 174-9) were not used in the evaluation of the hydraulic gradient because of their locations within the mountain block between the basins. These wells are completed in volcanic rocks to depths less than 300 ft, and are in excess of 600 ft higher in elevation than the valley floor. Therefore, it is concluded that hydraulic heads measured in these wells are representative of perched or local conditions and not conditions governing groundwater flow across the boundary.

The hydraulic conductivity of the Paleozoic carbonate rocks was derived from the analysis of aquifer tests performed on wells completed in the carbonate aquifer in eastern and southern Nevada. Based on 96 constant-rate tests provided in Section C.4.0 of Appendix C, a mean hydraulic conductivity of 6.16 ft/d for the carbonate aquifer was derived.

Equation E-1 was used to estimate groundwater flow across the boundary of Jakes Valley and Butte Valley. Flow through two segments of the flow section was calculated using a mean hydraulic conductivity for carbonate-rocks of 6.16 ft/d and a hydraulic gradient of 0.003487 ft/ft between the basins. Using a width and thickness of 30,000 ft and 500 ft for the northwestern segment yielded an estimate of 2,700 afy. Using a width and thickness 15,000 ft and 1,500 ft for the southeastern segment yielded an estimate of 4,000 afy. By summing the two estimates, the groundwater flow from Butte Valley to Jakes Valley is estimated to be 6,700 afy. Welch et al. (2007, p. 5) estimated 16,000 afy of groundwater flow from Butte Valley to Jakes Valley as part of the BARCASS.

E.4.2 Lower Meadow Valley Wash and Muddy River Springs Area Boundary

The northern boundary between the MRSA and Lower Meadow Valley Wash hydrographic areas lies within the southern part of the Meadow Valley Mountains where the surface hydrogeology is comprised of upper Paleozoic carbonate rocks (Rowley et al., 2011). These carbonate rocks have been fractured as a result of faulting associated with the east range-front fault and subsidiary faults within the mountain block. Groundwater flow to the south from the Lower Meadow Valley Wash hydrographic area to the MRSA is likely through these fractured carbonate rocks. A portion of this groundwater is consumed by ET, the remainder of which mixes with groundwater from the northern basins of the WRFS and exits the MRSA as spring discharge to the Muddy River and groundwater outflow. The available data is insufficient to derive an estimate of the inflow at this boundary using Equation E-1; however, the magnitude of this flow has been estimated by Kirk and Campana (1988 and 1990), Thomas et al. (1996), and Prudic et al. (1995). The estimate derived by Thomas et al. (1996) using an isotope model was selected for use in this assessment. This estimate of 8,000 afy (Thomas et al, 1996, p. C36) falls within the range estimated by the others, which is 4,500 afy to 13,000 afy reported by Kirk and Campana (1988, p. 29 and 31) and Prudic et al. (1995, p. D71), respectively.

E.4.3 Pahranagat Valley and Tikaboo Valley South Boundary

The east-northeast striking PSZ is comprised of several left-lateral faults that are the primarily control on groundwater flow in the very southern parts of Pahranagat and Delamar valleys, and at the hydrographic area boundary of Pahranagat Valley and Tikaboo Valley South. Figure 7-10 presents the surface hydrogeology of the area and the PSZ with respect to basin boundaries, topographic features, and hydraulic-head data. The main southern splay of the PSZ is the Maynard Lake fault zone which is interpreted to join the main north-south normal fault that defines the western side of the Sheep Range. While the majority of the groundwater in this area is able to flow through the PSZ and into Coyote Spring Valley, it is likely some amount flows laterally along the fault to the southwest and into Tikaboo Valley South. This flow has been postulated by several investigators, but is not estimated as part of this study due to the lack of hydraulic head data within the PSZ and Tikaboo Valley South. The previous estimates range from 3,700 afy (Kirk and Campana, 1988) to 7,000 afy (Thomas et al., 1996). Specifically, Kirk and Campana (1988, p. 36 and 40) reported outflow of 4,400 afy, 4,400 afy, and 3,700 afy for their three flow scenarios. Winograd and Thordarson (1975, p. C92) estimated 6,000 afy of outflow, while Thomas et al. (1996, p. C38) estimated 7,000 afy of outflow to Tikaboo Valley South. For the purposes of this study, the groundwater flow from Pahranagat Valley to Tikaboo Valley was assumed to be the average of these estimates, or 5,100 afy.

E.4.4 Coyote Spring Valley and Hidden Valley Boundary

The Coyote Spring Valley and Hidden Valley boundary was evaluated by Rowley et al. (2011) who concluded that groundwater flow is likely through Cambrian to Permian carbonate rocks that are locally heavily fractured along the western range-front fault of the Arrow Canyon Range to the east, and along numerous faults both east and west of the Elbow Range to the west (Figure E-3). Except for the northern and southern extents of the Arrow Canyon Range, significant groundwater flow through the range is unlikely because the north-south trending range-front fault is a likely barrier to flow in the west-east direction. Thomas and Mihevc (2007, p. 33) evaluated isotopic data resulting from the analysis of groundwater samples collected from wells in Coyote Spring, Hidden and Garnet valleys and California Wash and concluded that groundwater in Garnet Valley has the same isotopic signature as the groundwater in southern Coyote Spring Valley. These conclusions are demonstrated by the deuterium observations of well CSVM-2 in southern Coyote Spring Valley (-97.7 permil), and the carbonate wells in Garnet Valley whose deuterium values range from -97.5 to -97. These values are significantly lighter than the values representing local recharge in the Sheep Range which range from -92 to -81 permil. Based on this information, a flow section was selected along the profile line depicted in Figure E-3, that extends west from the western range-front fault of the Arrow Canyon Range to a normal fault associated with the Las Vegas Range (i.e., southern Elbow Range), a length of approximately 30,000 ft.

Hydraulic-head measurements in wells completed in the carbonate aquifer were evaluated to determine the hydraulic gradient across the flow section. The location of these wells and the corresponding measurements are presented in Figure E-3. A hydraulic gradient was calculated between monitor well CSVM-2 (Map ID 210-32) located in southern Coyote Spring Valley and monitor well GV-1 (Map ID 216-18) located in northern Garnet Valley. The measurements for the wells were 1,823.29 ft amsl (9-14-2010) for CSVM-2, and 1,809.91 ft amsl (9-13-2010) for GV-1.

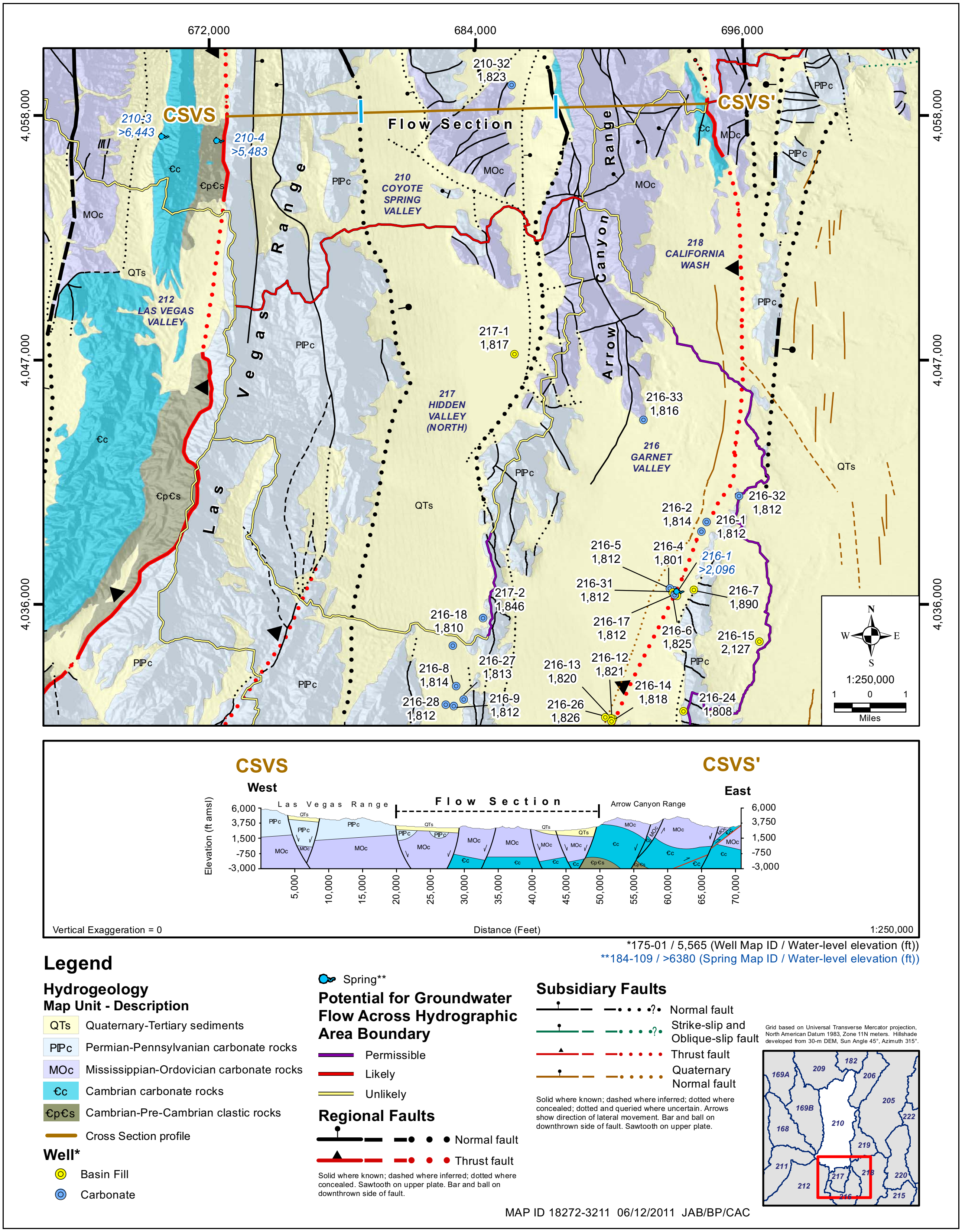

Figure E-3
Interbasin Groundwater Flow from Coyote Spring to Hidden Valley

The distance between the two wells is approximately 83,000 ft, and a hydraulic gradient of 0.00016 ft/ft was calculated.

A mean transmissivity value was derived from aquifer-test results for wells located in the vicinity of the flow section and completed in the carbonate aquifer. These wells and their corresponding transmissivity values are listed in Table E-1, including the test durations and the reporting entity. To ensure the mean value derived from the test data reflects the transmissivity of the carbonate aquifer at larger-scales, only aquifer tests of durations greater than or equal to 72 hours were used in the derivation of the mean. Tests of shorter durations and comparable rates test less volume of the aquifer and therefore yield less representative estimates of aquifer properties (Kruseman and de Ridder, 2000). Aquifer-test results from the following eight wells were included in the derivation of the mean: MX-4, MX-5, RW-1, Harvey Well, ECP-2, TH-2, and Arrow Canyon and observation well EH-4. For wells with more than one reported value (e.g. MX-5), the geometric mean value was derived and used in the estimate. Using these data, geometric mean transmissivity for the carbonate aquifer in this area is 213,035 ft^2/d.

Table E-1
Carbonate-Rock Aquifer Transmissivities

HA	Well	Transmissivity (ft^2/d)	Geometric Mean Transmissivity (ft^2/d)	Test Duration	Reference
210	MX-4	200,136	117,847	77 hours	IT Corporation (1996, App. A)
		204,440		77 hours	Belcher et al. (2001, App. A)
		40,000		5 days	Bunch and Harrill (1984, p. 119)
	MX-5	281,912	321,310	30 days	IT Corporation (1996, App. A)
		1,431,080		30 days	IT Corporation (1996, App. A)
		287,292		30 days	IT Corporation (1996, App. A)
		250,000		30 days	Ertec Western, Inc. (1981, p. 51)
		250,000		80 days	Bunch and Harrill (1984, p. 119)
		168,000		72 hours	Johnson et al. (1998, p. 5)
		290,520		326 hours	Belcher et al. (2001, App. A)
216	RW-1	404,800	404,800	72 hours	SRK Consulting (2001, Fig. 5)
	Harvey Well	411,400	411,400	72 hours	SRK Consulting (2001, Fig. 7)
218	ECP-2	109,500	109,500	7 days	Johnson et al. (2001, App. A, p. 4)
	TH-2	53,820	53,820	7 days	Johnson et al. (2001, App. A, p. 4)
219	Arrow Canyon	312,040	312,040	121 days	Belcher et al. (2001, App. A)
	EH-4	365,840	365,840	121 days	Belcher et al. (2001, App. A)

Using Equation E-1, the groundwater flow from Coyote Spring Valley to Hidden Valley was calculated as the product of the mean transmissivity of the carbonate aquifer (213,035 ft^2/d), the hydraulic gradient (0.00016 ft/ft), and the flow section width (30,000 ft). The estimated groundwater flow is approximately 8,600 afy.

E.4.5 Muddy River Springs Area and California Wash Boundary

Groundwater flow across the boundary at MRSA and California Wash was evaluated by Rowley et al. (2011) who concluded that groundwater flow is likely through carbonate rocks that are locally heavily fractured along the north-south trending range-front faults of the Dry Lake Range, and subsidiary faults to the east of the same orientation (Figure E-4). However, younger east-trending faults in central MRSA, including some that control Arrow Canyon and Battleship Wash just to the south, are likely partial barriers to north-south flow and pathways for flow to the east. Additionally, a west-northwest-trending fault zone, probably with right-lateral motion, formed the broad canyon now followed by State Route 168 and provides a pathway for groundwater flow to the east and southeast (Rowley et al., 2011). These features are presented on Figure E-4, and virtually all of the springs in the MRSA are located at the intersections of these east-, north-, and northwest-trending faults (Rowley et al., 2011).

The orientation of the faulting within the MRSA suggests that flow across the central boundary in the Dry Lake Range is limited by the east-trending lateral faults to the north. Although limited, it is likely there is some flow based on the presence of several upper Pleistocene spring mounds south of the boundary, north of Interstate 15 and west of the old railway stop at Ute, Nevada (Rowley et al., 2011). These features and isotopic data for groundwater samples collected from wells and springs are indicative of groundwater flow to the south and southeast, bypassing the springs. The groundwater observed in these wells has essentially the same isotopic signature as the groundwater observed in wells and springs in the MRSA to the north. Reported deuterium values for wells ECP-1a and TH-1 are -99.0 permil (Johnson et al., 2001), and groundwater in the MRSA ranges from -99.0 to -96.5 permil (Thomas and Mihevc, 2007). At the southeastern boundary, several mapped Quaternary faults south of the boundary likely enhance north-south groundwater flow.

Based on the available hydraulic-head measurements in the MRSA and California Wash, the hydraulic potential across the central boundary is small. The hydraulic head in well UMVM-1 (Well Map ID 219-58) located in MRSA is 1,816.4 (8-18-2010), and 1,816.0 (3-13-2011) in well TH-2 (Well Map ID 218-14) located to the south in California Wash. Because of this minimal potential, the boundary segment within the Dry Lake Range was not included in the flow section (Figure E-4). The flow section only includes the southeastern boundary where groundwater flow is likely and there is a discernible hydraulic gradient. As depicted in Figure E-4, the flow section extends from the eastern range-front fault that is the primary control on the Muddy River Springs, to a normal fault along the eastern edge of the boundary.

The hydraulic gradient was estimated using an average of measurements from 13 wells in the MRSA and an average of measurements from four wells in California Wash. For MRSA, the average value was 1,707 ft amsl, while the average for California Wash was 1,640 ft amsl. The distance between the wells was approximated by projecting the estimated midpoint of the well clusters to a line parallel to the flow direction and perpendicular to the flow section. A distance of 10,400 ft was estimated and used with the hydraulic potential defined by the average heads in each area to calculate a hydraulic gradient of 0.00652 ft/ft.

Based on the profile presented in Figure E-4, the subsurface hydrogeology consists of 2,000 to 4,000 ft of Quaternary-Tertiary sediments overlying Paleozoic carbonate rocks. Consistent with the

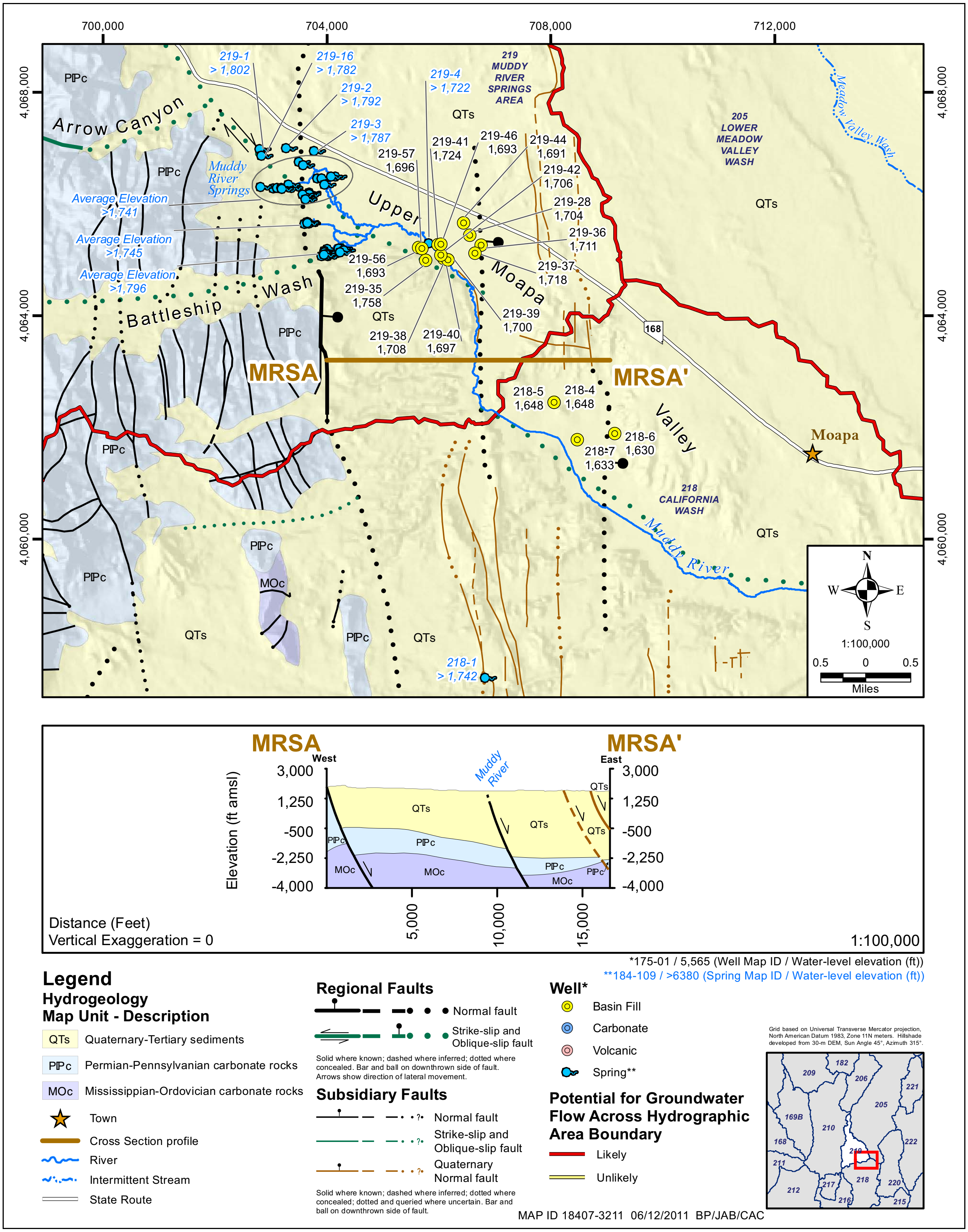

Figure E-4
Interbasin Groundwater Flow from MRSA to California Wash

assumptions discussed in Section E.2.2, only the Quaternary-Tertiary sediments are assumed to contribute to the flow as they comprise the top 2,000 ft of the flow section. These sediments include the Tertiary Horse Spring and Muddy Creek formations. A composite transmissivity for these materials was estimated using reported values from constant-rate aquifer tests performed on wells located and completed in these materials. Results are reported by URS (2001) for tests in Lower Meadow Valley Wash, and by Johnson (1995), Burbey et al. (2006), and Pompeo (2008) for tests performed in the Virgin River Valley. These results are summarized in Table E-2 and provided in detail in Section C.4.0 of Appendix C. The test and observation wells were completed in alluvial materials, as well as in the older Muddy Creek and Horse Spring Formations. Two tests were performed in Lower Meadow Valley Wash, and five in the Virgin River Valley. A geometric mean transmissivity of 11,000 ft^2/d was calculated from the reported values.

Using Equation E-1, groundwater flow across the MRSA and California Wash boundary was estimated using a composite average transmissivity of 11,000 ft^2/d for the basin fill materials, a hydraulic gradient across the boundary of 0.00652 ft/ft, and flow section width 16,500 ft. The resultant value is about 9,900 afy.

Table E-2
Estimate of Transmissivity for Basin-Fill Sediments in Muddy River Springs Area

Location	Well	Transmissivity (ft^2/d)	Geometric Mean Transmissivity (ft^2/d)	Test Duration	Reference
HA 205	Well 3	23,527.8	18,585	168 hrs	URS (2001)
	Well 3	14,680.4			
	MW-1 (Casing A)	7,188	6,998	168 hrs	URS (2001)
	MW-1 (Casing A)	6,813.7			
HA 222 (Virgin River Valley)	WX-31	7,751	9,282	62 days	Burbey et al. (2006)
	WX-31	4,844			
	WX-31	15,071			
	WX-31	7,320			
	WX-31	7,751			
	Unnamed well near WX-31	19,915		NR	
	BVSMW1	5,939	5,829	72 hrs	Pompeo (2008)
	BVSMW2	5,919			
	BVSMW3	5,635			
	HWSMW1	19,465	19,957	72 hrs	Pompeo (2008)
	HWSMW2	20,462			
	HWMW-1	9,130	6,283	72 hrs	Pompeo (2008)
	HWMW-2	8,464			
	HWMW-3	4,735			
	HWMW-4	4,260			
	Well 26	20,000	22,361	48 hrs	Johnson (1995)
	Well 26	25,000			

NR = Not Reported

E.5.0 REFERENCES

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Appendix F

Recharge Efficiencies

F.1.0 INTRODUCTION

Spatial distributions of recharge from precipitation for the Project Basins can be estimated using the groundwater-balance method coupled with a spatial distribution of precipitation, estimates of groundwater ET and interbasin flow, and a relationship between recharge and precipitation. Primary products of the application of this method are relationships between recharge and precipitation which can be used to estimate recharge efficiencies and annual recharge volumes for the Project Basins. Previous estimates of recharge as a function of precipitation are described, followed by the specific objectives, technical approach, method application, and results.

F.2.0 PREVIOUS ESTIMATES

Information available on recharge as a function of precipitation includes reported direct or derived measurements of recharge and precipitation rates for specific watersheds or areas, and recharge-precipitation relationships. This information is presented, followed by a set of related observations.

F.2.1 Recharge-Precipitation Data

A reported estimate of recharge as a function of precipitation is considered to be a "measurement" or a data point if it was derived for a small watershed or area using substantial field and/or laboratory data of related factors. Very few measurements of recharge as a function of precipitation exist within the region in which the Project Basins are located. Several studies do, however, provide measurements of recharge for Nevada, neighboring states, and other states within the continental United States. The most relevant of these studies are briefly summarized in the following text. The corresponding measurements are shown in Figure F-1.

- Winograd (1981, p. 1458 and 1460) used soil-physics techniques to estimate the net infiltration rate through a sequence of thick soil in the northern portion of the Nevada Test Site.

- Flint and Flint (1994, p. 2352, 2353, and 2356) derived a spatially-averaged recharge rate through various types of the volcanic rocks present at the Yucca Mountain site using field and laboratory data, including soil-moisture profiles. The recharge rates were set equal to the estimates of unsaturated hydraulic conductivities for depths greater than the ET zone.

- Osterkamp et al. (1994, p. 505) estimated average-annual volumes of upland recharge, total recharge, runoff, ET and channel loss for watersheds located in the Amargosa River basin in California. Their estimates were derived using the water-balance method combined with field data, a runoff model, and a modified version of an interchannel-runoff model.

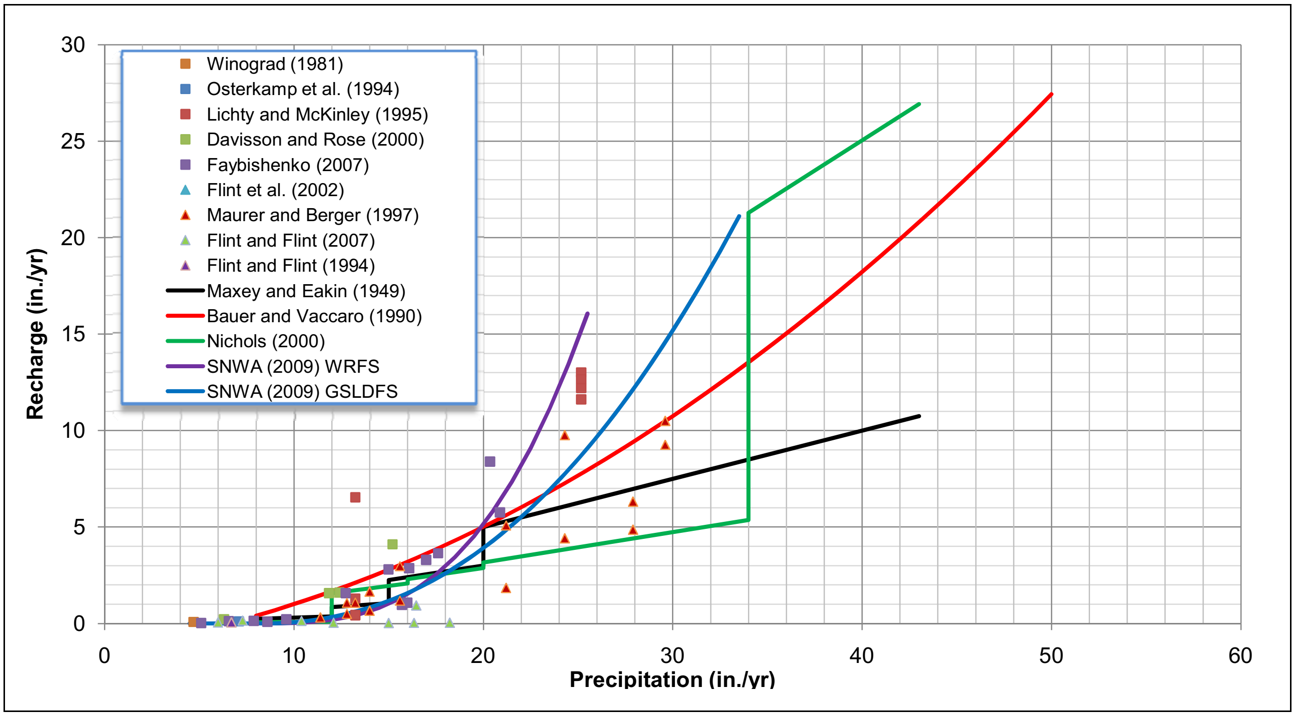


Figure F-1
Recharge-Precipitation Data

- Lichty and McKinley (1995, p. 26) estimated groundwater recharge rates for two small, upland watersheds in central and south-central Nevada. They derived their recharge efficiencies based on the application of a precipitation-runoff model, the PET index-site extrapolation method, and the chloride mass-balance method to volcanic tuffs.

- Maurer and Berger (1997) derived estimates of subsurface outflow from five watersheds in Eagle Valley, Nevada, using two methods. The first method consisted of calculating the subsurface outflow using Darcy's law and head data collected from wells located along the flow sections (Table 7, p. 26). The second method was based on the chloride mass balance and dissolved chloride concentrations in precipitation, groundwater and surface water. The subsurface outflow from the watersheds represents in-place recharge in the mountain block. Maurer and Berger (1997, Table 9, p. 34) also derived water-yield estimates by combining the estimates of subsurface flow with runoff measured by gaging stations for four watersheds and runoff estimated from other watersheds. The water yield represents potential recharge (i.e., mountain block recharge plus runoff).

- Davisson and Rose (2000) estimated recharge for two locations in the Fenner Basin of the eastern Mojave Desert, California, using the watershed water-balance method. Davisson and Rose (2000, p. 12 and 13) calibrated the Maxey-Eakin recharge model to the local conditions of the Fenner Basin in California, using local recharge estimates estimated with field information.

- Flint et al. (2002, Table 1, p. 189) summarized the recharge methods historically used to estimate recharge at the Yucca Mountain site. Included in their report are also the resulting estimates of recharge. Of particular interest are estimates of net infiltration using the chloride mass-balance method and chloride concentrations of pore water in several test holes in the unsaturated zone. Estimates previously derived by Flint and Flint (1994) are consistent with those reported by Flint et al. (2002).

- Faybishenko (2007, p. 85) used a semi-empirical model based on data available from analog meteorological stations to predict future infiltration rates under future changes in climatic conditions at Yucca Mountain, Nevada. This empirical model was tested by estimating current infiltration rates for several sites located within the continental United States and comparing them to the reported estimates of groundwater recharge and percolation rates through the unsaturated zone.

F.2.2 Recharge-Precipitation Relationships

Recharge-precipitation relationships are functions generated using large-scale information, at the basin scale for example, and mass-balance methods either for the saturated or unsaturated zones. Previously-reported relationships include those of Maxey and Eakin (1949), Bauer and Vaccaro (1990), Nichols (2000), and SNWA (2009) (Figure F-1).

- Maxey and Eakin (1949) developed a method to estimate recharge based on the groundwater-balance method. The method includes a relationship between recharge and precipitation, which yields estimates of recharge efficiencies for precipitation zones delineated on the Hardman map (Hardman, 1936). The standard Maxey-Eakin efficiencies were derived by balancing the recharge volume to estimates of discharge volume for 13 basins in Nevada (Maxey and Eakin, 1949, p. 40). This relationship is in the form of a step function as follows: (1) for precipitation less than 8 in., the efficiency is 0; (2) for precipitation between 8 and 12 in., the efficiency is 0.03; (3) for precipitation between 12 and 15 in., the efficiency is 0.7; (4) for precipitation between 15 and 20 in., the efficiency is 0.15; and (5) for precipitation greater than 20 in., the efficiency is 0.25.

- Bauer and Vaccaro (1990, p. 21, 22, and 24) derived estimates of groundwater-recharge rates to the Columbia Plateau regional aquifer system using a deep-percolation model. Recharge rates were simulated for model cells in 53 zones for both predevelopment and current land-use conditioned for the period between 1956 and 1977. The model calculates transpiration, soil evaporation, snow accumulation, snowmelt, sublimation, and moisture evaporation, using information on precipitation, temperature, streamflow, soils, land-use, and altitude. The resulting estimates were used to derive a relationship between recharge and precipitation, which is a second order polynomial.

- Nichols (2000, p. C24 and C54) developed a set of recharge efficiencies for 5 precipitation zones within 16 contiguous basins in Eastern Nevada dominated by carbonate rocks, using the groundwater balance method, together with estimates of precipitation, groundwater ET and interbasin flow. The precipitation distribution was a preliminary version of the 4-km 1961-to-2000 PRISM precipitation map and the groundwater ET estimates were based on newly-collected data. The relationship is presented as a step function as follows: (1) for precipitation less than 8 in., the efficiency is 0; (2) for precipitation between 8 and 12 in., the efficiency is 0.01; (3) for precipitation between 12 and 16 in., the efficiency is 0.13; (4) for precipitation between 16 and 20 in., the efficiency is 0.14; and (5) for precipitation between 20 and 34 in., the efficiency is 0.16; and for precipitation between 34 and 43 in., the efficiency is 0.63.

- SNWA (2009, p. I-8 and I-10) developed relationships between recharge and precipitation for the WRFS and the GSLDFS, using the groundwater-balance method combined with estimates of precipitation, groundwater ET and interbasin flow. The relationship is in the form of a power function.

Maurer and Berger (1997), and Faybishenko (2007) also developed relationships between recharge and precipitation using their respective data sets discussed in the previous subsection and plotted in Figure F-1. The curves representing the two relationships, however, are not shown on the figure.

F.2.3 Observations Based on Recharge-Precipitation Information

Five main observations can be made based on the data and relationships plotted in Figure F-1. They are as follows:

- The available data and previously-reported relationships show that recharge increases with increasing precipitation, following the same general trend.

- The recharge values associated with precipitation values of less than 8 in./yr and even up to 10 in./yr are small and confirm the general assumption that little recharge occurs from precipitation that is less than 8 in./yr (Maxey and Eakin, 1949, p. 40).

- Recharge estimates from the available data points and the relationships fall within a narrow range at the lower precipitation levels. As precipitation rates increase, the number of measurements decrease and the range of recharge estimates widens.

- The Maxey-Eakin relationship (Maxey and Eakin, 1949) follows the same general trend for low to moderate levels of precipitation, but breaks down for precipitation rates greater than 20 in./yr. The more recent investigations (Bauer and Vaccaro [1990], Lichty and McKinley [1995], Maurer and Berger [1997], Nichols [2000], Faybishenko [2007] and SNWA [2009]) indicate that, contrary to the Maxey-Eakin method (1949), recharge efficiencies can be much larger than 25 percent for precipitation values above 20 in.

- The recharge measurements made by Lichty and McKinley (1995) are considered to be the best field measurements available for the higher precipitation rates.

F.3.0 OBJECTIVES

The objective is to derive a relationship between recharge and precipitation and use it to estimate recharge efficiencies and mean annual potential recharge for Spring, Cave, Dry Lake, and Delamar valleys. Although the mean annual volume of recharge for Spring Valley could be derived by simply applying the groundwater balance method directly to the annual budget components, the objective here is to also generate a spatial distribution of the potential recharge. Spring Valley is a nearly closed basin and will be treated as such. However, the other three Project Basins do not have significant groundwater discharge by ET, rather, they discharge groundwater through the subsurface to adjacent downgradient basins located in the same flow system, the WRFS. Therefore, a similar objective for the whole flow system must be reached first by deriving a method to estimate recharge efficiencies and potential recharge for the WRFS, from which potential recharge distributions for the three Project Basins can then be extracted.

F.4.0 APPROACH

The approach followed to develop a method for estimating recharge efficiencies and potential recharge consists of applying the groundwater-balance method to Spring Valley and the WRFS, and implementing it in the Excel® Solver. The theory, its implementation in the Excel® Solver, and the data requirements are described in the following text.

F.4.1 Theory

A relationship expressing recharge efficiencies as a function of precipitation can be derived from the equation representing the groundwater-balance for a given basin or flow system.

F.4.1.1 Groundwater-Balance Method

The groundwater-balance method is based on fundamental concepts of hydrology and is a standard approach for estimating unknown groundwater-budget components (e.g., recharge) using estimates of other budget components that can be reasonably measured (e.g., precipitation, ET). This method is more reliable for closed groundwater basins (i.e., basins with no boundary flow). It can, however, yield reasonable results when applied to a basin or flow system where the net amount of boundary flow is either known within a small range of uncertainty, or known to be small relative to the total budget for that basin or flow system.

Under natural conditions, the total recharge for a given basin or flow system is equal to the sum of the estimates of groundwater ET and outflow, less any inflow to the basin or flow system. This relationship is expressed as follows:

$$R_T = ET_{gw} + Outflow - Inflow \qquad \text{(Eq. F-1)}$$

where,

R_T = Total recharge (afy)
ET_{gw} = Total groundwater ET (afy)
Inflow = Total groundwater inflow (afy)
Outflow = Total groundwater outflow (afy)

F.4.1.2 Recharge Efficiencies

Recharge efficiency, by definition, is the ratio of recharge to precipitation. Recharge may be expressed as a function of effective precipitation. For this analysis, recharge as a function of effective precipitation, is assumed to follow a form of the power function of Kumar and Seethapathi (2002, p. 7). The equation is as follows:

$$R = a(P-8)^b \qquad \text{(Eq. F-2)}$$

where,

R = Recharge rate (in./yr)
a = Power function constant
b = Power function exponent
P = Precipitation rate (in./yr)
$P - 8$ = Effective precipitation (in./yr)

For this analysis, it is assumed that precipitation contributes to recharge starting at 8 in./yr where the effective precipitation and recharge are assumed to be zero. The 8 in./yr threshold value is based on the work of Anderson et al. (1992, p. B33). The volume of precipitation below 8 in./yr is assumed to account for losses to soil-moisture deficits and ET. Recharge increases with increasing effective precipitation. This threshold value is supported by the available data (Figure F-1). This equation is also similar to that of Contor (2004, p. 3) and Anderson et al. (1992), except that these authors express recharge as a function of total precipitation rather than effective precipitation.

Recharge efficiencies may be calculated by dividing each side of Equation F-2 by precipitation, *P*, to yield the following equation:

$$Eff = \frac{[a(P-8)^b]}{P} \qquad \text{(Eq. F-3)}$$

where,

Eff = Recharge efficiency or *R/P* as a fraction
a = Power function constant

b	=	Power function exponent
P	=	Precipitation rate (in./yr)
$P - 8$	=	Effective precipitation rate (in./yr)

The primary parameters are the coefficients of the power functions represented by Equation F-2 and Equation F-3 (i.e., the constant *a* and the exponent *b*). The derived power functions between recharge efficiencies and precipitation are designed to yield balanced groundwater budgets for Spring Valley and the WRFS.

F.4.2 Implementation in Excel® Solver

The groundwater-balance method was implemented in the Excel® Solver to derive estimates of recharge efficiencies and spatial distributions for the Project Basins.

The Excel® Solver is designed to solve optimization problems. The solver finds optimal solutions to numerical problems such as the one at hand, in which the main variables requiring a solution are the coefficients in the power functions expressing the recharge efficiencies for Spring Valley and the WRFS. The solver finds an optimal value for a formula in one cell of the worksheet called the target cell. The solver works with a group of cells that are related, either directly or indirectly, to the formula in the target cell. Values in these cells are called parameters, which the solver adjusts to produce the desired result defined by the target-cell formula. Constraints can be added to restrict the values of the parameters the solver uses. Additional information on the Excel® Solver, including examples, can be found in the Excel® 2007 version help menu and/or the "Microsoft® Excel® 2007 Bible" (Walkenbach, 2007). To initialize and run the solver, the target cell, parameters, constraints, and initial conditions must first be defined. The application of the Excel® Solver to the problem at hand (i.e., find optimal solutions of the power function coefficients that yield recharge distributions for Spring Valley and the WRFS) is explained later in this section.

F.4.3 Information Requirements

The implementation of this method in the Excel® Solver was completed using the PRISM precipitation grid and estimates of groundwater discharge. Specific information is as follows:

- Delineated potential recharge areas within the basin or the flow system
- One-inch precipitation intervals within the basin or the flow system
- Mean precipitation rates for each 1-in. precipitation interval
- Relationship between recharge and precipitation (equation)
- Mean annual groundwater ET volume estimates for the basin or the flow system
- Mean annual boundary inflow and/or outflow volumes for the basin or the flow system
- Additional information on the recharge-precipitation relationship.

F.5.0 Method Application

The selected method requires that recharge efficiencies for Spring Valley and the WRFS be generated first. To reduce the uncertainty introduced by interbasin flow within the WRFS, this flow system was handled as a single basin. The detailed process, including the delineation of potential recharge areas, the precipitation distribution, the mean annual groundwater ET volumes, parameters, constraints, and implementation in the Excel® Solver are described in Appendix G.

F.5.1 Solution Process

The details of the solution process are depicted in the flow chart shown in Figure F-2. The overall approach consists of three main steps which are as follows:

1. Gather necessary data and information on precipitation, groundwater ET and interbasin flow.

2. Analyze the data and information to identify potential interpretations of the various data types.

3. Select reasonable interpretations and generate associated products needed to execute the Excel® Solver.

4. Set up the solver using these products (i.e. the spatial precipitation distribution in potential recharge areas, estimates of groundwater ET, and estimates of external boundary inflow and outflow for Spring Valley and the WRFS).

5. Use the Excel® Solver to estimate the power function coefficients for Spring Valley and the WRFS as a whole (single basin). This step, simultaneously, produces recharge efficiencies that are used to generate spatial recharge distributions.

F.5.2 Delineation of Areas of Potential Recharge

For the purpose of this analysis, areas of potential recharge are defined as areas where most of the in-place recharge occurs and mountain-front runoff is generated. The recharge that may result from infiltration of mountain-front runoff is not distributed to the actual areas where it may occur. Potential recharge is assumed to occur in all parts of a given basin or flow system except (1) on the valley floor(s), (2) in groundwater discharge areas, and (3) in areas where the depth of precipitation is less than 8 in. The potential recharge areas for Spring Valley and the WRFS are presented in Figures F-3 and F-4.

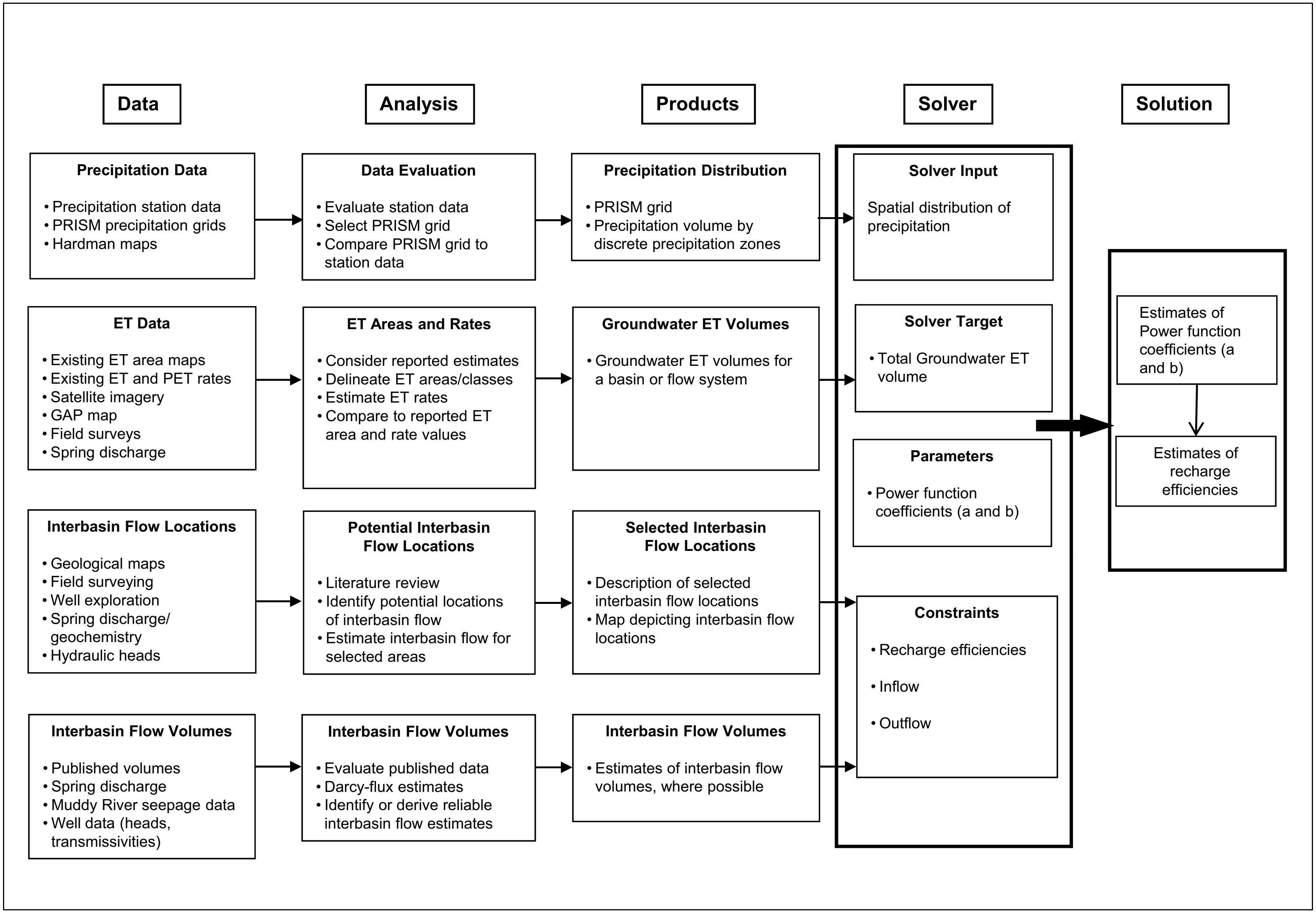


Figure F-2
Flow Chart Showing Solution Process Using Microsoft Excel® Solver Application

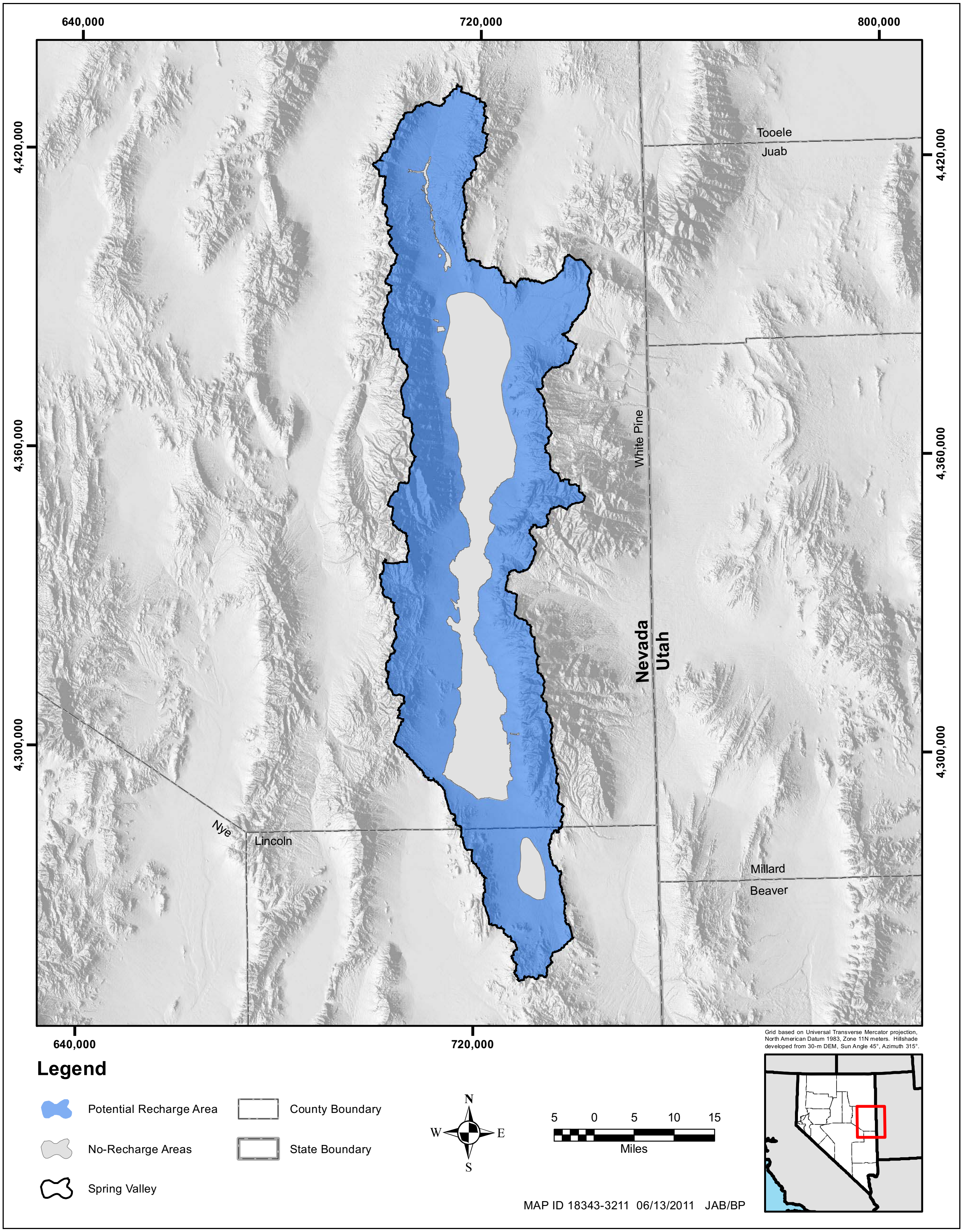


Figure F-3
Areas of Potential Recharge in Spring Valley

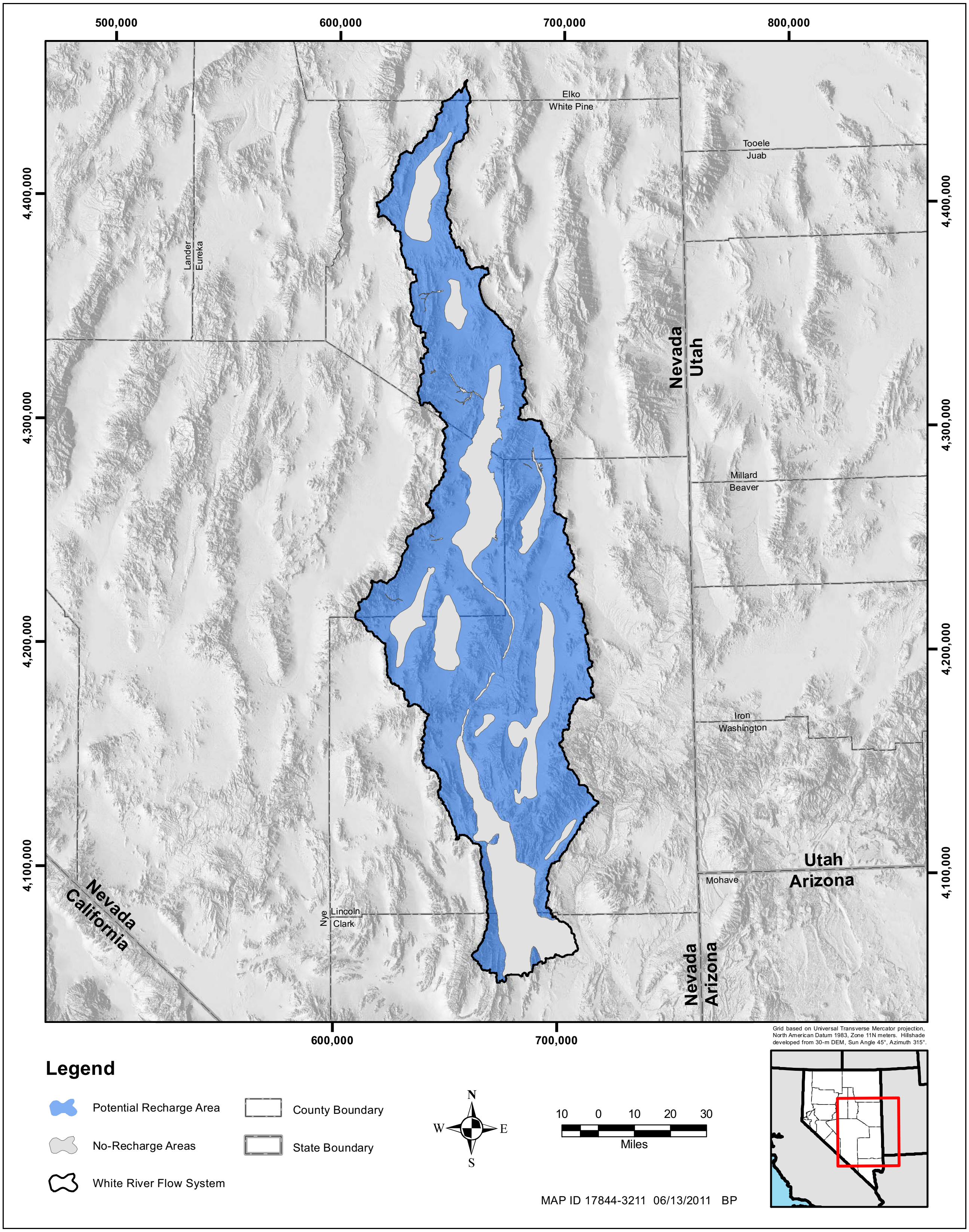


Figure F-4
Areas of Potential Recharge within the White River Flow System

Valley floors were delineated using the USGS DEM (USGS, 2001), and were subsequently excluded from the areas of potential recharge. Land-surface slopes were calculated using the DEM grid, and the low and relatively flat areas of basins were identified and excluded if the slopes were less than 2 percent. Alluvial fans were not included in the delineation of the valley floor areas because they are typically comprised of coarse-grained material that can accommodate recharge if the depth of precipitation is significant (i.e., greater than 8 in.).

Groundwater-ET areas were also excluded from the areas of potential recharge. This is consistent with the calculation of estimated groundwater ET where the precipitation is deducted from the total ET estimate. Removing the precipitation volume necessarily leads to the removal of any recharge that may occur there. The assumption is that precipitation on discharge areas is evapotranspired.

Areas where precipitation is 8 in./yr or less were also excluded from the areas of potential recharge. This is because it was assumed that a minimum of 8 in./yr of precipitation is necessary before groundwater recharge may occur. The first 8 in./yr of precipitation are assumed to satisfy the soil-moisture deficit and losses to the atmosphere (ET) (Anderson et al., 1992, p. B33). This assumption is consistent with the Maxey-Eakin method (1949, p. 40) which assumes that recharge is zero below 8 in. of precipitation. The published estimates of recharge shown in Figure F-1 confirm that for precipitation rates less than 8 in./yr, recharge rates are negligible at the basin scale. Thus, areas receiving less than 8 in. of precipitation within a given basin are not considered to be areas of potential recharge.

The union of the valley floors, groundwater discharge areas, and areas receiving 8 in./yr or less of precipitation are called “no-recharge areas,” for the purpose of this report. As stated before, in-place recharge from precipitation may actually occur in these areas, depending on the local conditions, but it is known to be relatively small (Figure F-1).

F.5.3 Precipitation Data

The 800-m PRISM precipitation grid (Version 3) serves as the basis for the solver calculations and the derivation of the spatial distribution of recharge. The spatial distributions of precipitation based on the PRISM grid for Spring Valley and for the WRFS are shown in Figures F-5 and F-6.

The PRISM grid was contoured to generate 1-in. precipitation intervals starting from a minimum value of 5 in. for WRFS and 8 in. for Spring Valley to the maximum values occurring within the basin and flow system. A mean precipitation value was calculated for each interval as the average of the PRISM grid cells located within the interval. The precipitation intervals were then exported to Excel in the form of a table containing the precipitation rate and corresponding area for each 1-in. interval for Spring Valley and for the WRFS, separately. These tables form the basis of the calculations performed by the solver and are included in the solver files (Appendix G). “No-recharge areas,” as defined in the previous section (Figures F-3 and F-4), were excluded from the recharge calculations by assigning a zero recharge efficiency to portions of the 1-in. intervals intersecting them.

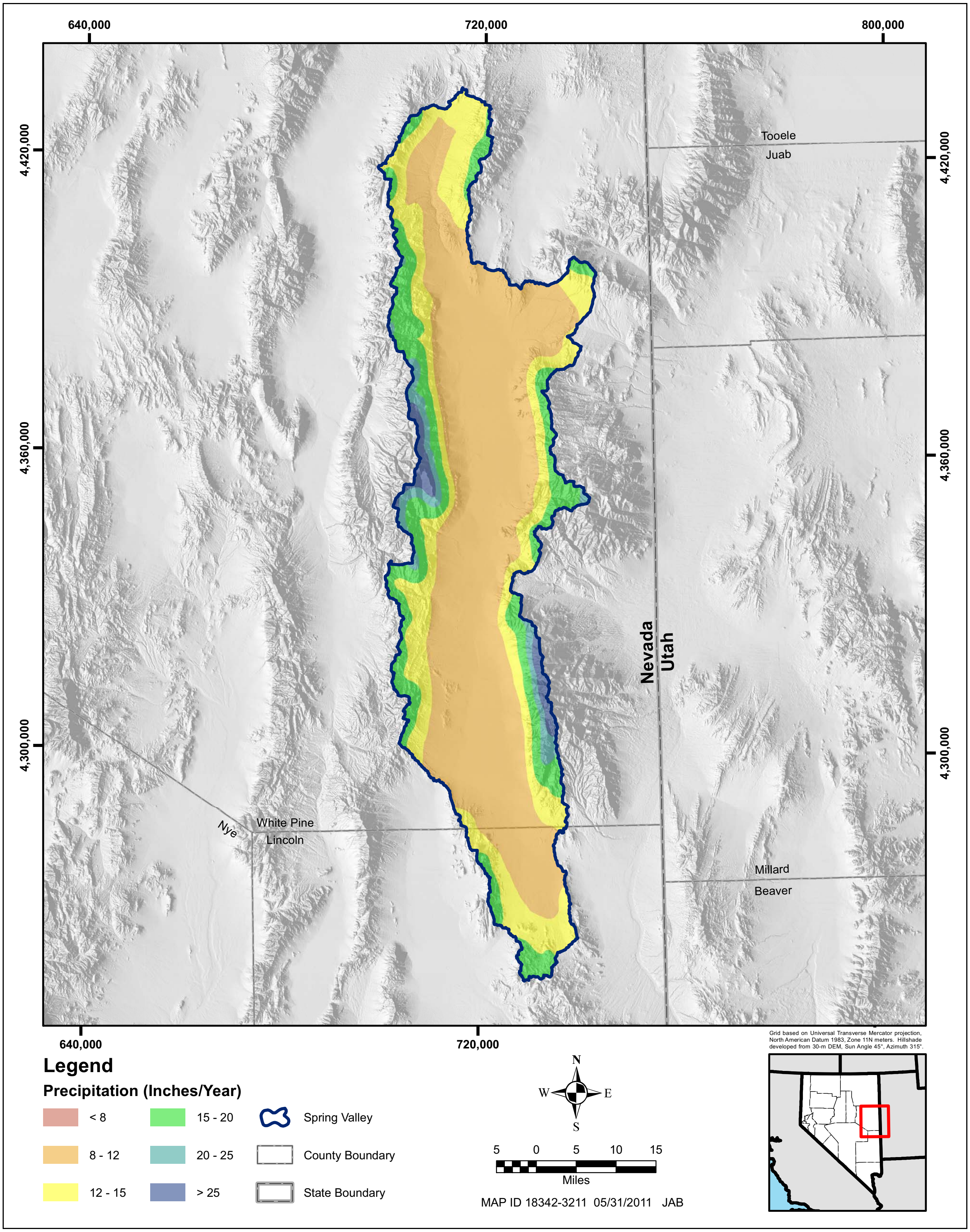


Figure F-5
Precipitation Distribution in Spring Valley

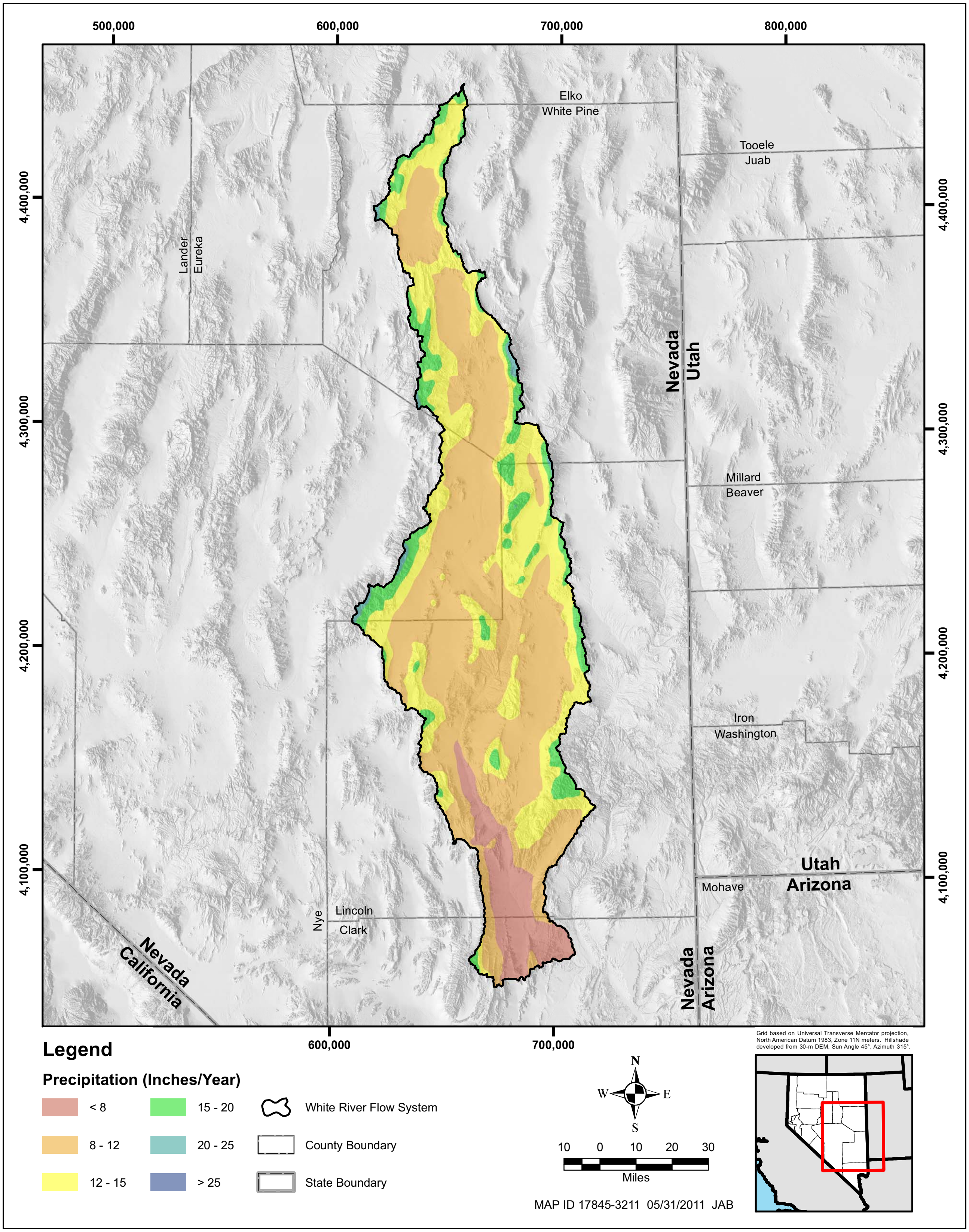


Figure F-6
Precipitation Distribution in the White River Flow System

F.5.4 Solver Target ET_{gw}

In the solver, the target is represented by the estimated value of groundwater ET for the basin or flow system. The target cell contains a formula relating groundwater ET to the other components of the budget; this formula is Equation F-4 rearranged in the following form:

$$ET_{gw} = R_T + Inflow - Outflow \qquad \text{(Eq. F-4)}$$

where,

ET_{gw} = Total groundwater ET (afy)
R_T = Total recharge (afy)
Inflow = Total groundwater boundary inflow (afy)
Outflow = Total groundwater boundary outflow (afy)

The target value for ET_{gw} for Spring Valley is 94,800 afy. This estimate was derived from new data collected during field investigations conducted between 2006 and 2010 (Section 5.0 and Appendix D).

The target value for ET_{gw} for the WRFS is 105,800 afy. This value represents the estimated total annual volume for all basins of the WRFS. The estimate for White River Valley was obtained from new field investigations conducted between 2006 and 2010 (Appendix D), whereas, the groundwater ET estimates for all other basins of the WRFS as defined in this study (Eakin, 1966, p. 252), were obtained from SNWA (2009, p. 7-17). As two methods were presented in that report, the values used here were derived using Method 1, a method in which the ET rate for a given area was estimated as the annual ET rate measured at an ET-measurement site adjusted by the PET ratio of the two locations (SNWA, 2009).

F.5.5 Solver Parameters

Parameters represent variables that require a solution. For this analysis, the only parameters are the coefficients, a and b, in the power function expressing recharge efficiencies as a function of precipitation (Equation F-3). The parameter solutions are calculated through an optimization process in which the coefficients, and therefore, the recharge efficiencies are adjusted within predefined constraints described in Section F.5.5.2, to ensure that Equation F-4 is optimally solved.

Considering that the solution to the problem depends on many variables but only a few of them are reasonably known, the solution is nonunique and many possible representations exist. For example, the solver may identify solutions that are mathematically feasible but not reasonable given what is understood about the physical aspects of the basin's aquifer system or the flow system. It is, therefore, important to provide reasonable initial estimates for unknown parameters as was done in this case.

Equation F-3 was used in the solver for direct calculation of the recharge efficiencies. The primary parameters are the coefficients of Equation F-3 (i.e., the constant *a* and the exponent *b*). These coefficients require reasonable initial estimates as the optimization process may yield other solutions that may not be reasonable. Details on how initial estimates of these two parameters were derived are provided in the following subsection.

F.5.5.1 Initial Estimates for Coefficients of Power Function

Information available to derive reasonable initial estimates for the two coefficients of the power function, *a* and *b*, includes reported measurements of recharge as a function of precipitation in the region and recharge-precipitation relationships derived by previous investigators (Figure F-1).

It would be preferable to derive an approximate recharge-precipitation relationship directly from the measurements. However, the measurements available for the region of interest are insufficient to develop such a relationship, particularly at precipitation levels larger than 20 in./yr. Recharge-precipitation relationships derived by previous investigators were shown to follow the general trend exhibited by the available measurements (Figure F-1). However, the relationships developed by Maxey and Eakin (1949), Bauer and Vaccaro (1990), and Nichols (2000) are the best candidates to derive initial estimates for the parameters of the power function represented in Equation F-2. Of the three relationships, the one developed by Nichols (2000) was selected because of the following reasons:

- Nichols (2000) study covers a large area that comprises the northern basins of the WRFS where most of the precipitation occurs, Spring Valley, and basins with precipitation rates larger than those observed in the WRFS.
- Nichols (2000) groundwater ET estimates are based on field measurements of ET rates and satellite imagery of the groundwater discharge areas.
- Nichols (2000) spatial precipitation distribution is based on a more comprehensive data set and a model that includes the major physical processes that affects it: the 4-km 1961-1990 PRISM precipitation grid (Daly et al., 1994).
- Nichols (2000) recharge efficiencies display an exponential increase with precipitation, which closely matches the best available data at higher precipitation rates (Lichty and McKinley, 1995). The exponential increase is more consistent with the physics of water infiltration in the unsaturated zone. Under unsaturated conditions, the infiltration rate equals the unsaturated hydraulic conductivity, which increases exponentially with the degree of saturation until full saturation is reached. At that point, the infiltration rate equals the vertical saturated hydraulic conductivity, which corresponds to the absolute maximum infiltration rate. On the mountain block, the infiltration rate is limited by the precipitation rate and full saturation is never reached.

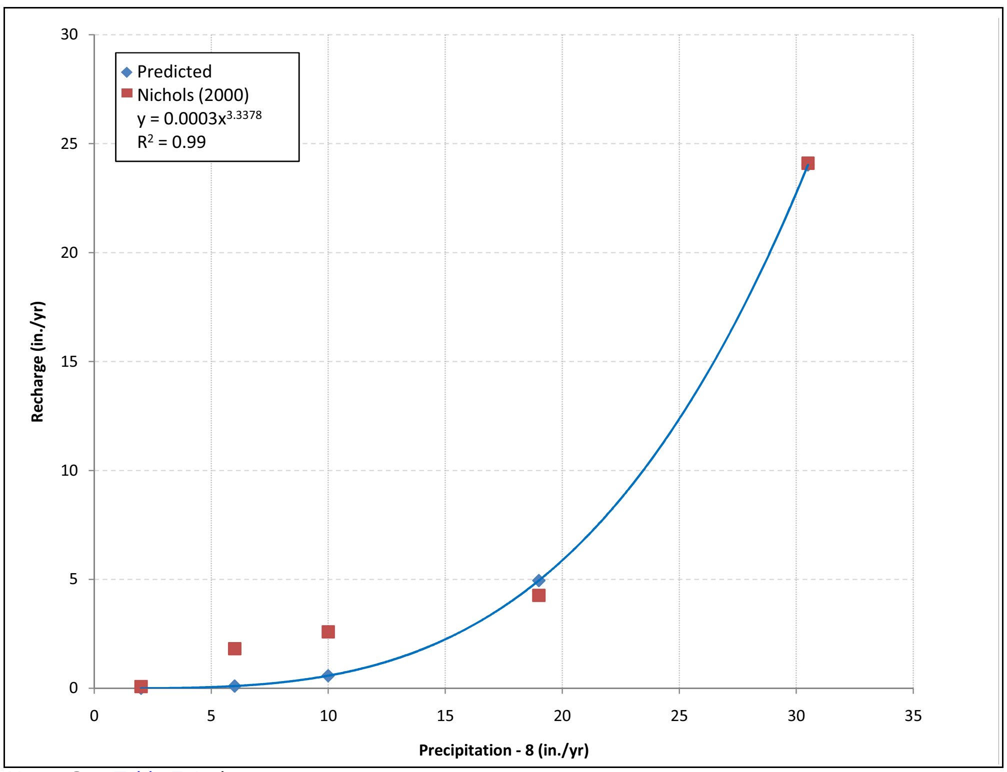
The step-function relating recharge efficiencies to precipitation (Table C-12 on p. C24 in Nichols, 2000) was used to derive the initial estimates for the two coefficients of the power function, a and b of Equation F-2. The precipitation ranges were split into the two values defining the range (Table F-1). A mean precipitation value was then calculated for each precipitation range, and a mean recharge value was calculated by multiplying it by the corresponding recharge efficiency (Table F-1).

Table F-1
Information Used to Derive Initial Estimates of a and b (Nichols, 2000)

Precipitation Zone (in./yr)	Precipitation Rate			Recharge Efficiency (% precipitation)	Recharge Rate (in./yr)
	Minimum (in./yr)	Maximum (in./yr)	Mean (in./yr)		
8-12	8	12	10.0	0.8	0.08
12-16	12	16	14.0	13.0	1.82
16-20	16	20	18.0	14.4	2.59
20-34	20	34	27.0	15.8	4.27
34-43	34	43	38.5	62.6	24.10

The resulting point data were fit with a power function in the form of Equation F-2 using the curve-fitting capability of SigmaPlot 11 (Figure F-7). The corresponding values of the *a* and *b* coefficients are as follows:

- Power function constant: $a = 0.0003$
- Power function exponent: $b = 3.3378$



Note: See Table F-1 above.

Figure F-7
Power Function Fit to Nichol's (2000) Precipitation-Recharge Step Function

F.5.5.2 Constraints

Constraints were placed on the parameters that control the spatial distribution of recharge and on the external boundary flow of Spring Valley and the WRFS.

F.5.5.2.1 Constraints on Recharge Parameters

Constraints designed to control the spatial distribution of recharge were specifically placed on the coefficients of the power function and the recharge efficiencies.

Power Function Coefficients

Based on the current state of knowledge of the process of infiltration of precipitation into the geologic media, recharge is known to generally increase with precipitation. Therefore, the coefficients in Equation F-3 must be positive, for example:

- Power Function Constant, *a* is positive.
- Power Function Exponent, *b* is positive.

Recharge Efficiencies

A constraint is imposed on the maximum recharge efficiency. The maximum recharge efficiency cannot be greater than 1, but the exact maximum recharge efficiencies for Spring Valley and the WRFS are unknown and are most likely much less than 1.

As potential recharge exhibits a strong and consistent relationship with precipitation (Figure F-1), it is considered to be mainly a function of precipitation. Therefore, recharge efficiency is also mainly a function of precipitation. The maximum recharge efficiency values for Spring Valley and the WRFS are different because the maximum precipitation levels are different. Estimates of these constraints are based on the existing information.

Recharge efficiencies reported for the largest precipitation rates above 20 in./yr were extracted from the reports described in Section F.2.0 and are briefly described in the following text.

- Maxey and Eakin (1949, p. 40) reported a maximum recharge efficiency of 0.25 for the precipitation zone greater than 20 in/yr. based on the Hardman (1936) precipitation map. Subsequent studies, that of Lichty and McKinley (1995, p. 26) for example found recharge efficiencies could be much larger.

- Lichty and McKinley (1995, p. 26) reported four recharge measurements for a maximum precipitation rate of 25.16 in./yr. The four recharge measurements were averaged and divided by the precipitation rate to yield a maximum recharge efficiency of 0.49 for two small basins located in central Nevada.

- Maurer and Berger (1997, p. 34) estimated a recharge rate of 10.5 in./yr for a maximum precipitation rate of 29.6 in./yr. This corresponds to a maximum recharge efficiency of 0.355 in./yr.

- Nichols (2000, p. C54) estimated a maximum recharge efficiency of 0.63 percent for precipitation values equal or greater than 34 in./yr in Ruby Valley in northern Nevada.

- Faybishenko (2007, p. 85) estimated a maximum recharge efficiency of 0.41 in./yr for a maximum precipitation rate of 20.35 in./yr.

Based on this information, the maximum recharge efficiency values for Spring Valley and the WRFS were estimated as follows:

- For the WRFS, the maximum recharge efficiency was selected to be 0.49 based on the measurement made for a similar precipitation value of 25.16 in./yr by Lichty and McKinley (1995, p. 26).

- For Spring Valley, a maximum recharge efficiency was interpolated for the maximum precipitation of about 33 in. using two pairs of precipitation-recharge values: (25.16, 0.49) from Lichty and McKinley (1995, p. 26), and (34, 0.63) from Nichols (2000, p. C54). The resulting maximum efficiency for Spring Valley is 0.60.

F.5.5.2.2 Constraints on External Boundary Flow

All inflow and outflow values used in the solver were specified as fixed constraints in the solver. The locations of these flow boundaries are shown in Figure F-8 for Spring Valley and Figure F-9 for the WRFS. The flow rates were estimated using Darcy flux calculations, whenever possible. The detailed estimates are presented in Appendix E and summarized in the following text.

For Spring Valley, only one external flow boundary was used: outflow from the southeastern boundary of Spring Valley to Hamlin Valley. The annual volume of outflow was estimated at 4,400 afy, using Darcy's equation (Appendix E).

For the WRFS, the external boundary flows are as follows:

- The inflow across the boundary between Butte Valley South and Jakes Valley was estimated at 6,700 afy using Darcy's law (Section E.4.1).

- The inflow from Lower Meadow Valley Wash to Muddy River Springs Area was estimated at about 8,000 afy (Section E.4.2).

- Outflow from Pahranagat Valley to Tikaboo Valley (South) along the PSZ was estimated at 5,100 afy (Section E.4.3).

- The outflow from the southeastern end Coyote Spring Valley to Hidden Valley was estimated at 8,600 afy, using Darcy's law (Section E.4.4).

- Outflow from the Muddy River Springs Area: The outflow from the Muddy River Springs Area corresponds to outflow from the southern end of the flow system as defined in this study. This outflow has two components: (1) the flow that feeds the Muddy River Springs Area

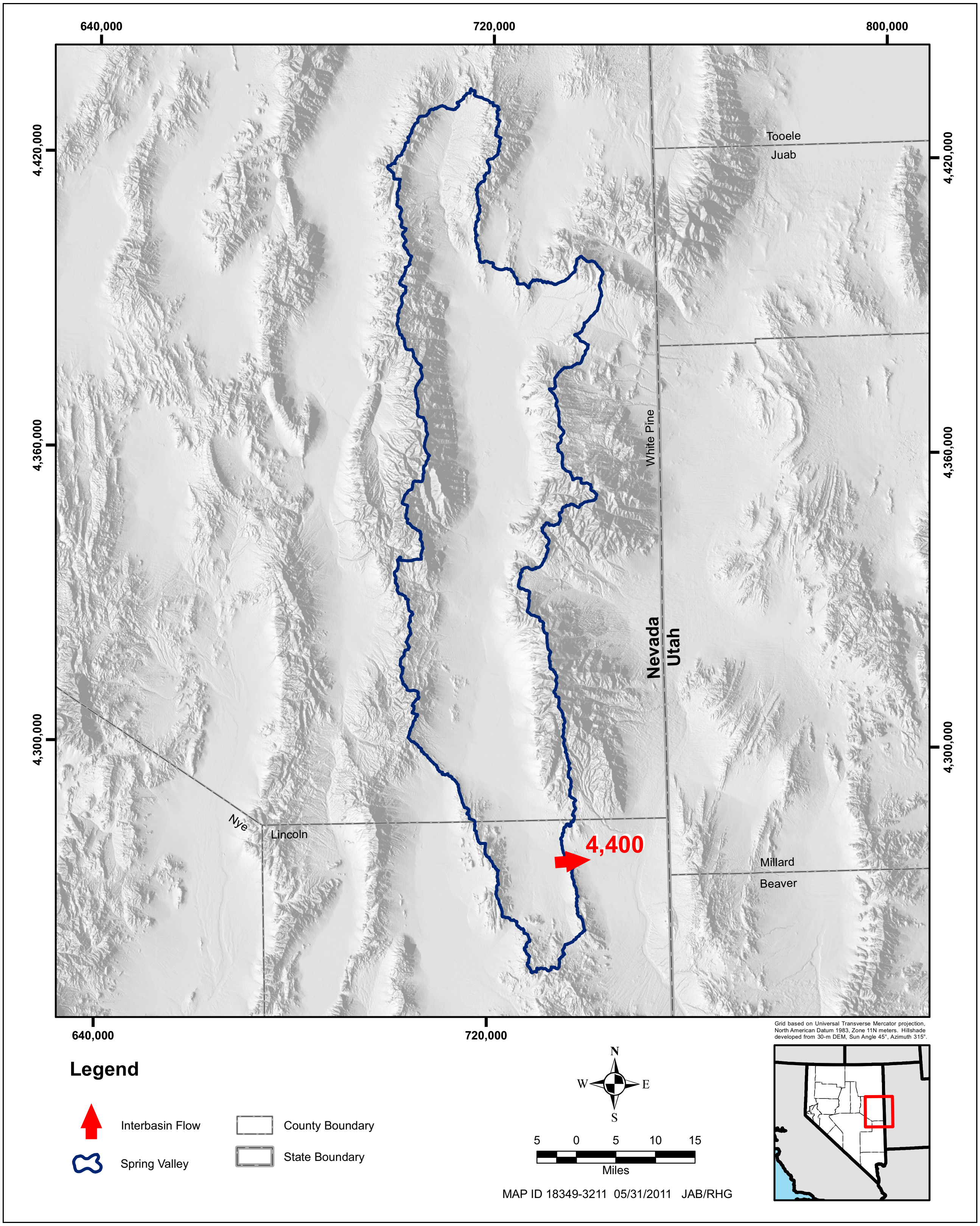


Figure F-8
Locations and Volumes of Interbasin Flow (in afy) for Boundary Segment Used as Constraint for Spring Valley

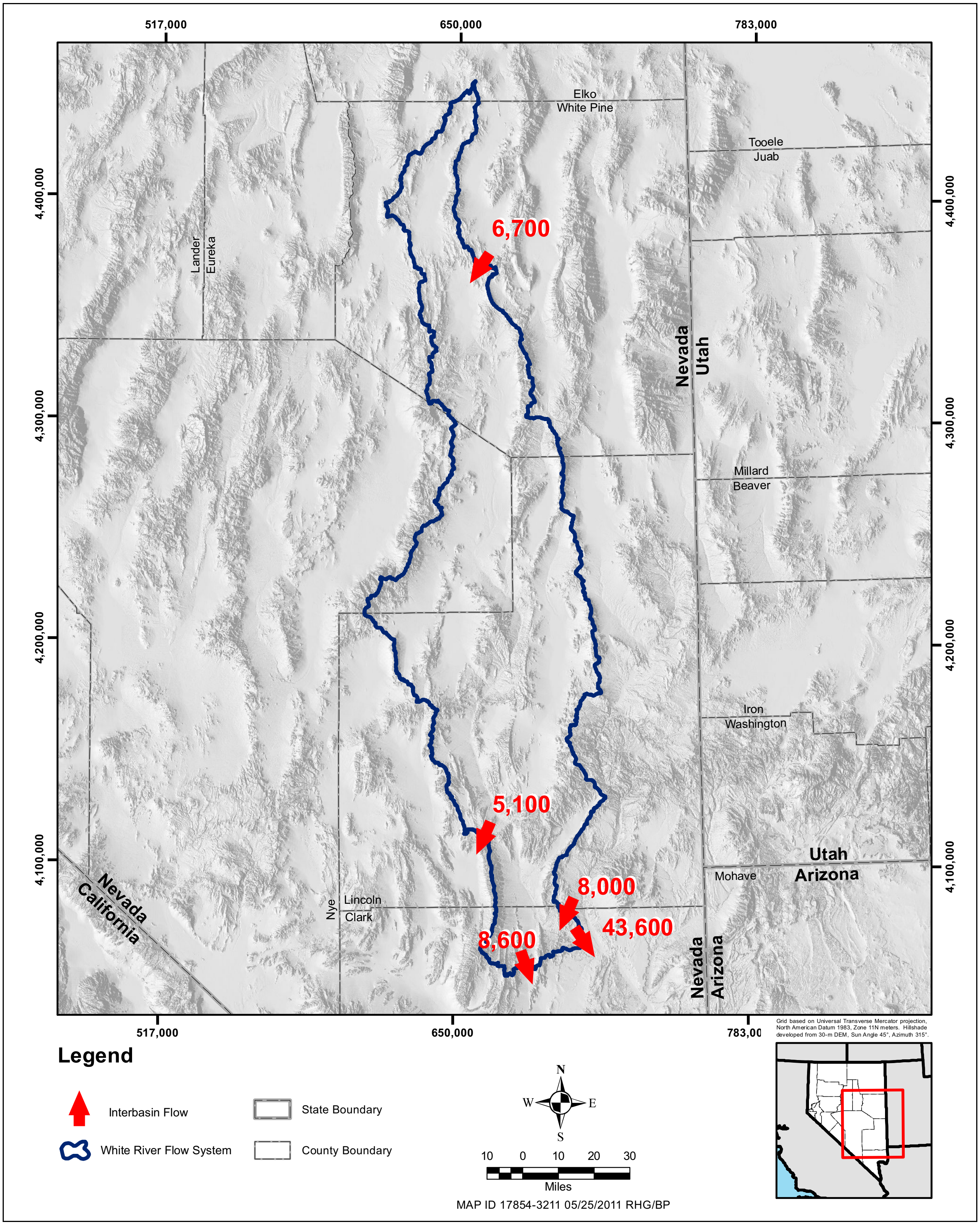


Figure F-9
Locations and Volumes of Interbasin Flow (in afy)
for Boundary Segments Used as Constraints for the WRFS

including the seeps, as measured in the Muddy River at the Moapa gage, and (2) subsurface outflow within the valley fill located below the Muddy River at the southern boundary of Upper Moapa Valley (MRSA). The first component of this outflow was set to 33,700 afy of groundwater discharge to the Muddy Springs as estimated by Eakin (1964, p. 14). The second component of this outflow was estimated at about 9,900 afy using Darcy's equation (Section E.4.5).

F.6.0 SOLUTION PROCESS

The solver was used to inversely solve for the recharge efficiencies of Spring Valley and the WRFS using the target-ET estimates, the parameters, and the constraints described in Section 5.0. Because there is more than one unknown parameter, the derived solution is not unique. To converge to a solution, the solver uses successive values of all parameters while seeking a solution. Values of the primary parameters and the power-function coefficients, *a* and *b*, are used to calculate recharge for each 1-in. precipitation interval encompassed within the potential recharge areas. This recharge value is then divided by precipitation to obtain a recharge efficiency, which in turn, is used to calculate recharge volumes. Once the calculated recharge volume yields a total groundwater-ET value that matches the target value, a solution is reached.

F.7.0 SOLUTIONS

The details relating to the solutions are described in this subsection, including the recharge-precipitation relationship, and Project Basin recharge distributions and groundwater budgets.

F.7.1 Recharge-Precipitation Relationships

The solutions for the coefficients of Equation F-2 are as follows:

1. a = 0.0339 and b = 1.97 for Spring Valley,
2. a = 0.0046 and b = 2.76 for the WRFS.

The corresponding calculated recharge rates were plotted against the corresponding precipitation rates for both Spring Valley and the WRFS. A graph of the relationships derived for Spring Valley and the WRFS is presented on Figure F-10. Relationships derived by Maxey-Eakin (1949) and other authors are included in Figure F-10 for comparison.

As shown on Figure F-10, all relationships have the expected general trend of increasing recharge with increasing precipitation, and the relationships developed by this study for Spring Valley and the WRFS fall within the range defined by the others. All relationships shown in Figure F-10 are similar to each other at the lower precipitation rates but somewhat diverge at larger rates. The relationships derived by this analysis follow the same general trend as the other relationships for the low to mid precipitation rates. At the higher precipitation rates, the relationships derived as part of this study

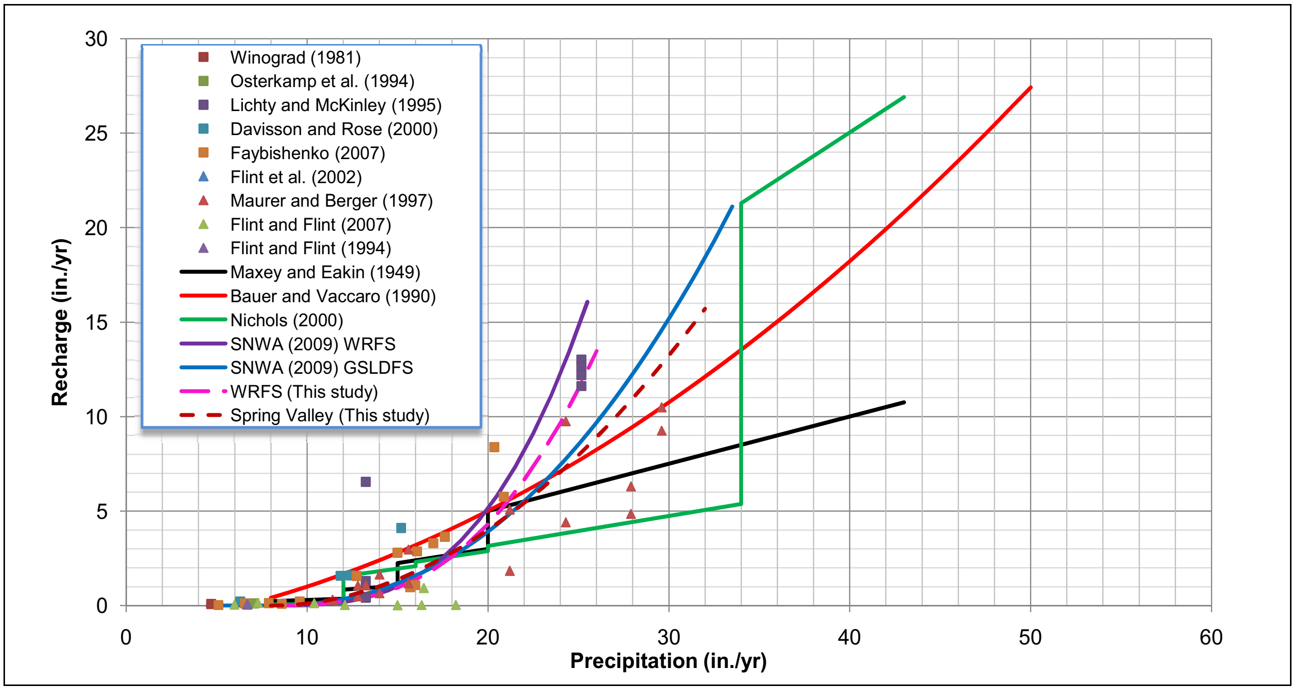


Figure F-10
Recharge-Precipitation Relationship Developed for Spring Valley and the White River Flow System

diverge from the Maxey-Eakin (1949) relationship and are more consistent with the relationships derived by Bauer and Vaccaro (1990), Nichols (2000) and SNWA (2009).

F.7.2 Recharge Efficiencies

Recharge efficiencies derived for the 1-in. set of precipitation intervals used in the solutions for Spring Valley and the WRFS are presented in this subsection.

The recharge efficiencies derived for Spring Valley are listed in Table F-2. The efficiencies for Spring Valley range from 0.17 percent for the 8 to 9 in./yr precipitation interval to 60 percent for the maximum precipitation interval of 33 to 34 in./yr. The basin-wide average recharge efficiency, calculated as the total recharge (99,200 afy) divided by the total precipitation (1,119,700 afy), including precipitation on areas classified as no-recharge areas, is about 9 percent.

The recharge efficiencies derived for the WRFS are listed in Table F-3. The efficiencies for the WRFS range from about 0.02 percent for the 8 to 9 in./yr precipitation interval to 49 percent for the maximum precipitation interval of 25 to 26 in./yr. The total recharge and precipitation for the whole flow system are 148,400 and 4,639,000 afy, respectively, resulting in an system-wide average recharge efficiency of about 3 percent.

Table F-2
Recharge Efficiencies for 1-in.
Precipitation Intervals for Spring Valley

1-in. Precipitation Interval	Mean Precipitation Rate (in./yr)	Recharge Efficiency (Fraction of Precipitation)
8-9	8.65	0.0017
9-10	9.55	0.0084
10-11	10.55	0.0203
11-12	11.46	0.0342
12-13	12.49	0.0524
13-14	13.49	0.0721
14-15	14.48	0.0933
15-16	15.48	0.1158
16-17	16.54	0.1406
17-18	17.52	0.1644
18-19	18.56	0.1906
19-20	19.65	0.2184
20-21	20.53	0.2416
21-22	21.69	0.2722
22-23	22.74	0.3002
23-24	23.49	0.3207
24-25	24.83	0.3573
25-26	25.65	0.3797
26-27	26.52	0.4039
27-28	27.64	0.4352
28-29	28.72	0.4653
29-30	29.63	0.4909
30-31	30.29	0.5096
31-32	31.52	0.5444
32-33	32.37	0.5685
33-34	33.47	0.6000

Table F-3
Recharge Efficiencies for 1-in.
Precipitation Intervals for the WRFS

1-in. Precipitation Interval	Mean Precipitation Rate (in./yr)	Recharge Efficiency (Fraction of Precipitation)
5-6	5.78	0.0000
6-7	6.48	0.0000
7-8	7.50	0.0000
8-9	8.65	0.0002
9-10	9.55	0.0016
10-11	10.55	0.0057
11-12	11.46	0.0123
12-13	12.49	0.0230
13-14	13.49	0.0371
14-15	14.48	0.0547
15-16	15.48	0.0760
16-17	16.54	0.1024
17-18	17.52	0.1305
18-19	18.56	0.1642
19-20	19.65	0.2032
20-21	20.53	0.2381
21-22	21.69	0.2877
22-23	22.74	0.3361
23-24	23.49	0.3735
24-25	24.83	0.4443
25-26	25.65	0.4900

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Appendix G

Description of Excel Recharge-Efficiency Excel® Solver Files

G.1.0 INTRODUCTION

The purpose of this appendix is to describe in detail the calculations conducted in support of the data analyses related to the recharge efficiencies of Spring Valley and the WRFS, which includes Cave, Dry Lake, and Delamar valleys.

G.2.0 OBJECTIVES OF CALCULATIONS

The objective of the calculations was to derive recharge efficiencies for Spring Valley and the WRFS using the groundwater-balance method, which could then be used to calculate spatial distributions and annual recharge volumes for the each Project Basin. The descriptions are organized based on the Excel® files containing the calculations and provided in electronic form with this report. These files consist of two Excel® files containing the recharge efficiency solutions for Spring Valley and the WRFS that were derived using the Excel® Solver. For hard copies of the report, the Excel® files are included on the DVD enclosed with the document.

The files are provided for the sole purpose of documentation of the analyses. In essence, the Excel® Solver files contain calibrated groundwater budget models for Spring Valley and the WRFS. Any changes to the target values, the initial estimates of the parameters, or the constraints may change the solution or yield no solution at all if the solver is executed. Consequently, the reader should not alter the contents of the files unless they thoroughly understand their setup and have good knowledge about the groundwater budgets of Spring Valley and the WRFS.

The Excel files containing the recharge-efficiency solutions are named: "SNWA-Spring-Valley-Recharge-Efficiencies" and "SNWA-WRFS-Recharge-Efficiencies" The file contents and the solution process are described in the following text.

G.3.0 FILE CONTENTS

Each solution file includes four worksheets which are named and described as follows:

- Worksheet 1: "1-Explanation"
- Worksheet 2: "2-Groundwater-ET&Boundary-Flux"
- Worksheet 3: "3-Precipitation-Recharge"
- Worksheet 4: "4-Solver-Solution"
- Worksheet 5: "5-References"

G.3.1 Worksheet 1 - "1-Explanation"

The "explanation" worksheet contains a brief description of the file and its contents.

G.3.2 Worksheet 2 - "2-Groundwater-ET&Boundary-Flux"

This worksheet contains a table listing the annual groundwater-ET and boundary-flux volumes for the basin or flow system. The annual volume of groundwater ET is used as the target and the boundary fluxes as constraints in the solver (see Section G.3.4).

G.3.3 Worksheet 3 - "3-Precipitation-Recharge"

This worksheet fulfills two roles: (1) it contains the precipitation data which serve as input to the solver, and (2) it contains the recharge calculations performed by the solver during the solution process. All calculations are performed by built-in formulas using the solution derived in worksheet 4. This worksheet should, therefore, not be altered by the user. A description of the table contents is provided, followed by an explanation of the process used to generate them.

G.3.3.1 Worksheet 3 Contents

Each row in the table contains information for the mean precipitation value of 1-in. precipitation intervals, or zones, grouped by areas of recharge and no recharge and sorted by the mean precipitation. Specifically, the table contains the following information:

- 1-in. Precipitation Interval – This is the actual range of the 1-in. precipitation zone or interval.
- Mean Precipitation Rate – This is the mean precipitation value of the 1-in. precipitation interval (in inches) in the 800-m PRISM grid. The calculation process of the mean precipitation rates is described in Section G.3.3.2.
- Area – This is the area (in acres) of a 1-in. precipitation interval. The generation process is described later in this section.
- Area Excluded from Potential Recharge Areas? Yes or No. Occasionally, the precipitation intervals overlapped areas defined as no-recharge areas. They were, therefore, excluded from the potential recharge areas and assigned recharge efficiencies of zero during the calculations.
- Precipitation Volume – This field contains the volume of precipitation for a 1-in. interval (in afy), and is obtained by multiplying the mean precipitation rate by the area.
- Recharge Efficiency – The values in this field are extracted from the recharge efficiency table calculated during the solution process using the power function and the selected precipitation "values." The recharge efficiency table is located in the "Solver-Solution" worksheet and is described later in this section.

- Recharge Volume – This field contains the recharge volume of a 1-in. precipitation interval (in afy), and is the product of the "Precipitation Volume" and the "Recharge Efficiency."

G.3.3.2 Generation of Precipitation Data

The precipitation data serves as the basis for the solver calculations and the derivation of the spatial distribution of recharge. The precipitation values in the table were generated using ArcMap 10 as follows:

1. The process was initiated from the 800-m PRISM grid (Figure G-1A).

2. The 800-m PRISM grid was contoured to generate 1-in. contour lines (Figure G-1B). Two consecutive contour lines represent a 1-in. precipitation interval.

3. The 1-in. precipitation intervals were converted to polygons (Figure G-1C).

4. The actual precipitation value for each 1-in. precipitation interval is average of all PRISM grid values within the interval. So the average precipitation is the same for all corresponding 1-in. precipitation intervals. The average is close to the middle value of the 1-in. precipitation interval for the relatively flat areas, and is less than the middle value for the areas with positive slope (Figure G-1D).

5. "No-recharge areas," which include the union of the valley floors, the less-than-8-in.-precipitation areas, and the groundwater-ET areas, were then assigned recharge efficiencies of zero.

6. A table of precipitation "values" was generated starting from the minimum to the maximum precipitation rate of the basin or flow system.

   - WRFS: Minimum precipitation of 5.8 in.; maximum precipitation of 25.7 in.
   - Spring Valley: Minimum precipitation of 8.7 in.; maximum precipitation of 33.5 in.

7. The surface areas of each precipitation interval were calculated using the operation "Calculate Geometry" in ArcMap 10.

8. The 1-in. PRISM precipitation interval attribute table was then exported to Excel and added to the file in Worksheet "3-Precipitation-Recharge" The precipitation interval, its average rate, and its area are located in columns 1through 3 of this table.

G.3.4 Worksheet 4 - "4-Solver-Solution"

Worksheet 4 is the core of the Solver. Worksheet 4 requires the precipitation-recharge table in Worksheet 3, described in Section G.3.3. Without the precipitation data and the recharge calculations in Worksheet 3, the Solver will not function. This worksheet is organized in three principal areas: (1) Area 1 - Main Solver Area, (2) Area 2 - Recharge Efficiency Calculations, (3) Area 3 - Map

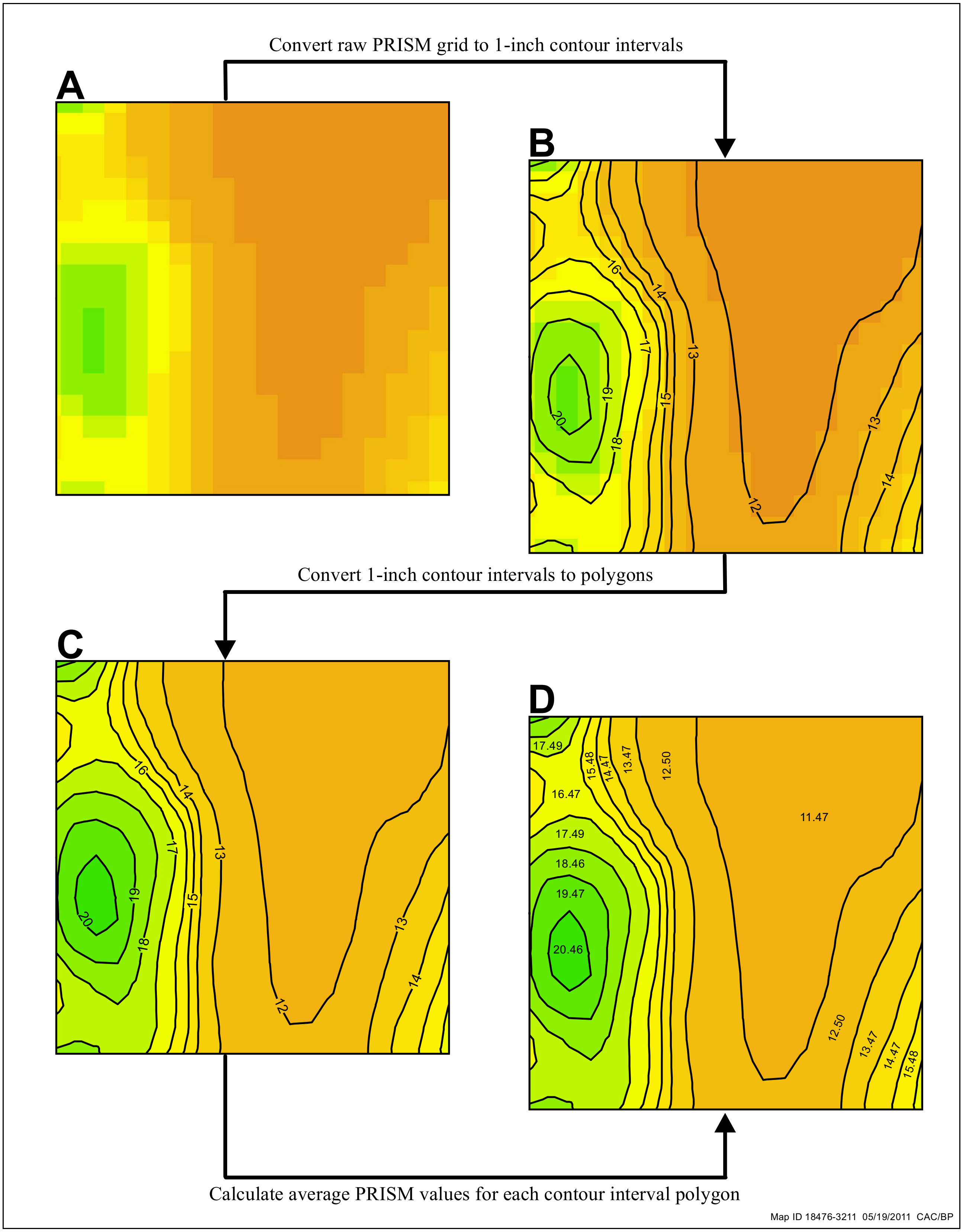

Figure G-1
Generation Process of One-Inch Precipitation intervals

showing groundwater mass balance, and (4) Area 4 - Map Label Information. Each of these areas is described in the following text.

G.3.4.1 Area 1 - Main Solver Area

This main solver area contains the target cell, parameter cell, and a list of the constraints used. The parameters are the two coefficients of the power function. Appropriate initial estimates for the two parameters are also provided here. Constraints were imposed on these parameters, but also on selected flow terms which are also listed in this area. The target, parameters and constraints are color-coded and the color codes are provided within this area.

The target is represented by the estimated value of total groundwater ET. The target cell contains a formula relating groundwater ET to the other components of the budgets; this formula is as follows:

$$ET_{gw} = R_T + Inflow - Outflow \qquad \text{(Eq. G-1)}$$

where,

ET_{gw} = Total groundwater ET for Spring Valley or the WRFS (afy)
R_T = Total natural recharge for Spring Valley or the WRFS (afy)
Inflow = Total groundwater inflow to Spring Valley or the WRFS (afy)
Outflow = Total groundwater outflow from Spring Valley or the WRFS (afy)

For Spring Valley, the target value for "ET_{gw}" is 94,800 afy. The estimate of "*Inflow*" to Spring Valley is minor and not considered in the Spring Valley Solver. The "*Outflow*" occurs at the southeastern boundary of Spring Valley to Hamlin Valley, and is estimated at 4,400 afy.

For the WRFS, the target value for "ET_{gw}" and the estimate of "*Inflow*" are 105,800 and 14,700 afy, respectively. The inflow of the 14,700 afy is sum of the inflow of 6,700 afy from Butte Valley South to Jakes Valley, and 8,000 afy from Lower Meadow Valley Wash to the MRSA. The estimate of "*Outflow*" is estimated at 57,300 afy and occurs across three segments of the WRFS boundary: (1) 5,100 afy out of Pahranagat Valley through the PSZ; (2) 8,600 afy from southern Coyote Spring Valley to Hidden Valley; and (3) 43,600 afy from the southern boundary of the MRSA (combination of the 33,700 afy of spring discharge within the MRSA, and subsurface outflow of 9,900 afy through basin-fill sediments).

The initial parameter estimates used for both Spring Valley and the WRFS are as follows:

- Power function constant: $a = 0.0003$
- Power function exponent: $b = 3.3378$

The constraints used for Spring Valley are as follows:

- Recharge efficiency < or = 0.60
- Inflow = 0 afy

- Outflow = 4,400 afy

The constraints used for the WRFS are as follows

- Recharge efficiency < or = 0.49
- Inflow from Butte Valley South to Jakes Valley = 6,700 afy
- Inflow from Lower Meadow Valley Wash to MRSA = 8,000 afy
- Outflow from Pahranagat Valley to Tikaboo Valley South = 5,100 afy
- Outflow from Coyote Spring Valley to Hidden Valley = 8,600 afy
- Outflow from MRSA to California Wash = 43,600 afy

G.3.4.2 Area 2 - Recharge Efficiency Calculations

Area 2 of the solution sheet has a table containing the 1-in. precipitation intervals and the corresponding recharge efficiencies calculated using the power-function coefficients listed as parameters in the main Excel® Solver area described above. For each precipitation interval, the recharge efficiency is calculated as the recharge rate expressed as the power function divided by precipitation as follows:

$$Eff = \frac{[a(P-8)^b]}{P} \qquad \text{(Eq. G-2)}$$

where,

Eff	=	Recharge efficiency or *R/P* as a fraction
a	=	Power function constant
b	=	Power function exponent
P	=	Precipitation (in./yr)
P – 8	=	Effective precipitation (in./yr)

These efficiencies utilize whatever values of *a* and *b* are stored in the parameter cells: initial estimates or the final values derived by the solver. As described in the previous subsection, a constraint is imposed on the maximum recharge efficiency. Its value depends on the maximum precipitation level (see Appendix F).

G.3.4.3 Area 3 - Map Showing Groundwater Budget

The groundwater budget is presented on a map located in Area 3 of this worksheet. The variable components of the groundwater budget are automatically updated when the solver is executed and an optimal solution is found by the solver.

G.3.4.4 Area 4 - Map Label Information

This area consists of a table containing the coordinates and labelling information for the map presented in Area 3. The components of the groundwater budget listed in the table are automatically updated when the solver is executed and displayed on the map in Area 3 of the worksheet.

G.3.5 Worksheet 5 - "5-References"

This worksheet contains a list of references cited in the Excel file.

G.4.0 SOLUTION PROCESS

The WRFS solver file is used as an example. The solver is activated by clicking "Solver" under the Excel menu item "Tools" from the solution sheet (Worksheet 4). At this point, the "Solver Parameters" window pops up (Figure G-2). In its upper part, the window displays information about the objective of the solver. This information includes the specification of the target cell (Cell D4) and an option for the objective function specifying whether the solver is to maximize, minimize, or equate the objective function to a target value. When the equality option ("Value of") is selected as it is in this case, a target value must be specified. In this case, a value of "105,800" is specified, representing the total GW ET in afy for the WRFS calculated in Worksheet 2.

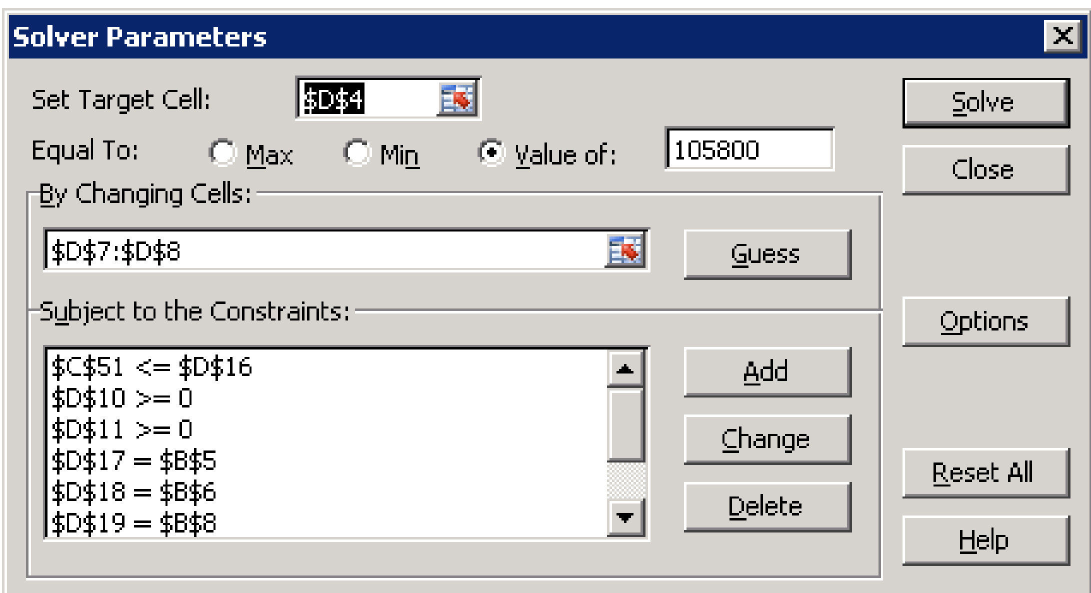

Figure G-2
Excel® Solver Window - Example: White River Flow System

Under the objective function information, the cells where the parameters are located in the worksheet are provided under "By Changing Cells." In this case the parameter cells range from D7 to D8 During the solution process, the solver iteratively changes the values in these cells until the objective is achieved, in this case, until the value in the target cell equals the specified target value of 105,800 afy.

Under the parameter information, a list of the constraints is provided to the solver to constrain the solution under the title "Subject to the Constraints." Each row in the list consists of a cell address in the solution worksheet, a logical operator, and a value. The logical operator may be set to "Equal," "Less than or equal," or "Greater than or equal." The constraints on the solution allow the solver to narrow the domain of feasible solutions for problems with many unknowns.

In the right-hand side of the solver window are a "Solver" button to execute the solver, a "close" button to close the window, an "options" button to specify the solution method and convergence criteria, a "Reset" button, and a "Help" button. Once the "Solve" button is activated, the user is presented with various options for keeping or resetting the solution, saving scenarios, and reporting results. The novice user should use the default options.

Plates

PLATE 1. MAJOR GEOLOGIC AND HYDROLOGIC FEATURES AND CONTROLS ON THE AQUIFER SYSTEM OF SPRING VALLEY AND VICINITY

PLATE 2. MAJOR GEOLOGIC AND HYDROLOGIC FEATURES AND CONTROLS ON THE AQUIFER SYSTEM OF CAVE, DRY LAKE AND DELAMAR VALLEYS AND VICINITY