Conceptual Model of Groundwater Flow for the Central Carbonate-Rock Province: Clark, Lincoln, and White Pine Counties Groundwater Development Project

November 2009

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Suggested citation:
Southern Nevada Water Authority, 2009, Conceptual model of groundwater flow for the Central Carbonate-Rock Province—Clark, Lincoln, and White Pine Counties Groundwater Development Project: Southern Nevada Water Authority, Las Vegas, Nevada, 416 p.

PREFACE

This report was prepared by the Southern Nevada Water Authority. The U.S. Geological Survey served as technical advisor to the Bureau of Land Management in the review of this report.

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ACRONYMS

3D	three-dimensional
AGU	agricultural unit
ANCOVA	analysis of covariance
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
CDF	cumulative density function
CI	confidence interval
COV	coefficient of variation
CRFS	Colorado Regional Ground-Water Flow System
CWP	Cooperative Water Project
DEM	digital elevation model
DMV	dense meadowland vegetation
DOE	U.S. Department of Energy
DRI	Desert Research Institute
DST	drill-stem test
DSV	dense shrubland vegetation
DVFS	Death Valley Flow System
DVRFS	Death Valley Regional Flow System
DWV	dense woodland vegetation
EIS	environmental impact statement
ET	evapotranspiration
GIS	geographic information system
GSLDFS	Great Salt Lake Desert Flow System
GVFS	Goshute Valley Flow System
HA	hydrographic area
HGU	hydrogeologic unit
K	hydraulic conductivity
LVVSZ	Las Vegas Valley Shear Zone
LVVWD	Las Vegas Valley Water District
MSAVI	Modified Soil Adjusted Vegetation Index
MSV	moderate shrubland vegetation
MVFS	Meadow Valley Flow System

ACRONYMS (CONTINUED)

MWV	moderate woodland vegetation
NA	not applicable
NAD83	North American Datum of 1983
NCDC	National Climatic Data Center
NDVI	Normalized Difference Vegetation Index
NDWR	Nevada Division of Water Resources
NE	not estimated
NED	National Elevation Dataset
NPU	non-phreatophytic unit
NRCS	Natural Resources Conservation Service
NTS	Nevada Test Site
NWIS	National Water Information System
NWR	National Wildlife Refuge
OWU	open water unit
PET	potential evapotranspiration
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RASA	Regional Aquifer-System Analysis
RMU	regional modeling unit
SEBAL	Surface Energy Balance Algorithm for Land
SNJV	Stoller-Navarro Joint Venture
SNOTEL	SNOwpack TELemetry
SNWA	Southern Nevada Water Authority
SWReGAP	Southwest Regional Gap Analysis Project
UGS	Utah Geological Survey
UNLV	University of Nevada, Las Vegas
UNR	University of Nevada, Reno
USAF	U.S. Air Force
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
WRCC	Western Regional Climate Center
WRFS	White River Flow System
WY	Water Year

ABBREVIATIONS

°C	degrees Celsius
°F	degrees Fahrenheit
ac	acre
afy	acre-feet per year
amsl	above mean sea level
bgs	below ground surface
cfs	cubic feet per second
cm	centimeter
ft	foot
ft^2	square feet
ft^3	cubic feet
gpm	gallons per minute
hr	hour
in.	inch
km	kilometer
km^2	square kilometer
m	meter
m^2	square meter
mi	mi
mi^2	square mile
yr	year

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1.0 INTRODUCTION

The purpose of this report is to describe the development of a conceptual model of groundwater flow within the Central Carbonate-Rock Province (CCRP) of Nevada and Utah. The extent of the Project study area (i.e., the regional model area) is shown in Figure 1-1. The groundwater flow model supports the Southern Nevada Water Authority's (SNWA) Clark, Lincoln, and White Pine Counties Groundwater Development Project (hereinafter referred to as the Project), including the acquisition of water rights from the Nevada State Engineer and rights-of-way from the Bureau of Land Management (BLM). This conceptual model was developed and used to construct and calibrate a regional numerical groundwater flow model. The numerical model was used as part of the environmental analysis for the Project. Specifically, the numerical model was used to simulate groundwater development scenarios to evaluate the range of potential water-related effects of the Project's groundwater production at the regional scale. All work relating to BLM issuance of rights-of-way was subjected to review by a panel assembled by BLM. Summary descriptions of the Project background, relevant previous and on-going investigations, purpose and scope, and the BLM review process are presented in this section, followed by a description of the contents of this report.

1.1 Project Background

To reduce reliance on Colorado River water resources and buffer the impacts of long-term droughts on the Colorado River system, SNWA has identified plans to develop in-state non-Colorado River water resources (SNWA, 2004). These additional resources will augment the current water resource portfolio identified in the SNWA Water Resource Plan (SNWA, 2008b). The Project will develop and convey groundwater rights and applications held by SNWA in five basins in eastern Nevada. Figure 1-2 shows the project basins and proposed points of diversion.

The Project consists of groundwater production, conveyance and treatment facilities, and power conveyance facilities, most of which will be located on federal lands managed by BLM. Consequently, in 2004, SNWA applied to BLM for rights-of-way to construct, operate, and maintain the Project facilities. BLM issuance of these rights-of-way is a federal action, which must comply with the National Environmental Policy Act of 1969, the Endangered Species Act of 1973, and other federal regulations. BLM has determined that preparation of an Environmental Impact Statement (EIS) is required to assess the potential effects that may result from permitting the rights-of-way, including the potential indirect effects of the proposed groundwater development. This conceptual model of groundwater flow was prepared in support of the development of the numerical groundwater flow model, which was used in the EIS process for the analysis of the potential indirect effects of the Project.

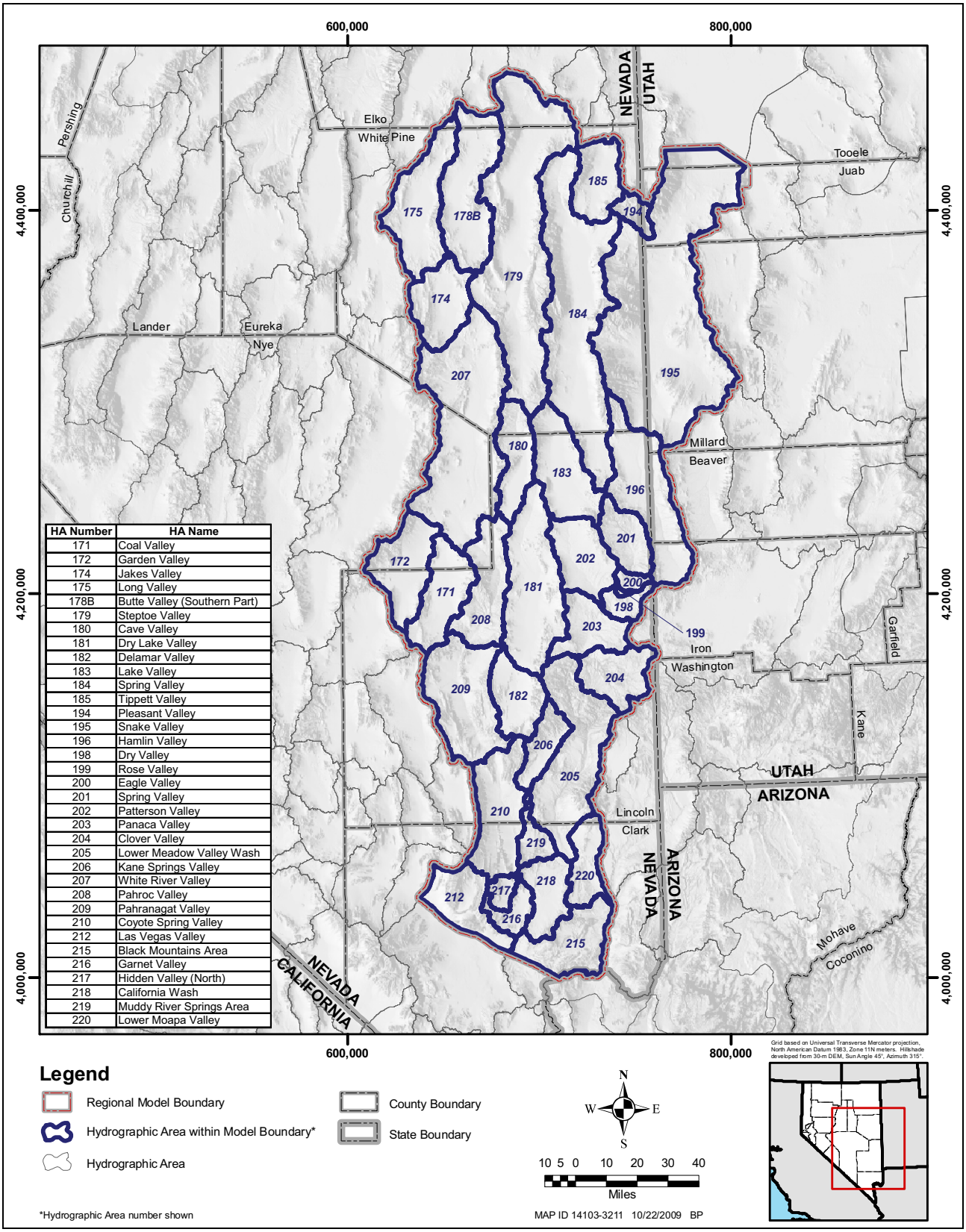


Figure 1-1
Location of Study Area

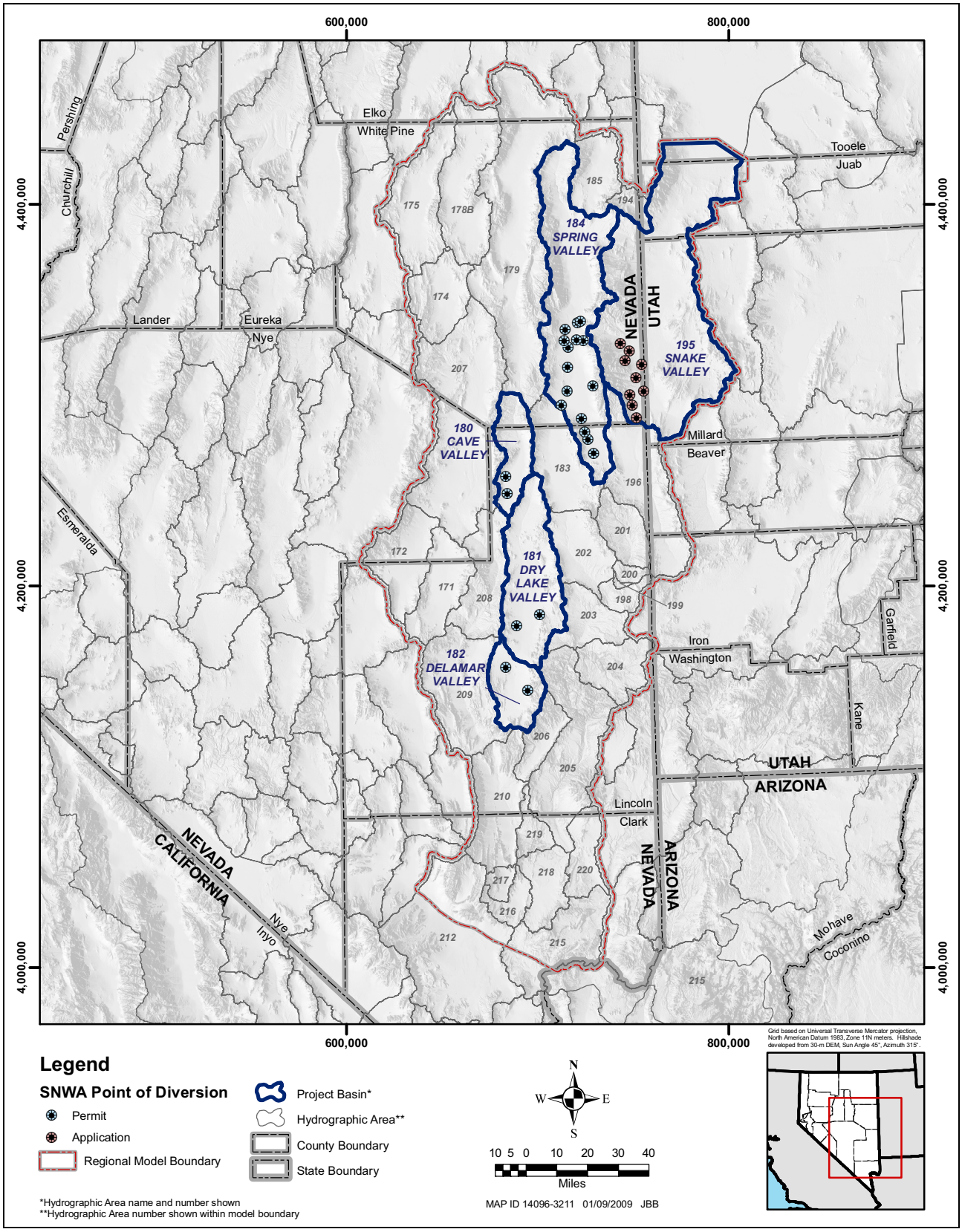


Figure 1-2
Location of Project Basins and Points of Diversion

1.2 Relevant Investigations

Many documents reporting the findings of various studies were reviewed to support development of the numerical model. A large number of them contain information that is relevant to the conceptual model described in this report. Of particular interest are major studies that provide information on the geology and/or hydrology of the study area or portions of it. Such studies are briefly described in this section. Others are called out as appropriate in this report. Major investigations of interest include the following:

- Nevada Division of Water Resources (NDWR)/U.S. Geological Survey (USGS) Reconnaissance Investigations
- U.S. Air Force (USAF) MX Missile-Siting Investigation–Water Resources Program Study
- Great Basin Regional Aquifer-System Analysis (RASA) Study conducted by the USGS
- Studies conducted by the Las Vegas Valley Water District (LVVWD)/SNWA, including those in cooperation with other agencies
- Basin and Range Carbonate Aquifer System Study (BARCASS) conducted by the USGS in cooperation with other agencies
- Groundwater and surface-water evapotranspiration study in hydrographic areas of the Southern Colorado Regional Ground-Water Flow System (CRFS) (DeMeo et al., 2008)

Information derived from recent or on-going studies, such as BARCASS or work conducted by SNWA and cooperating agencies, was given the highest consideration, as these studies incorporate more recent data and analysis methods.

1.2.1 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, 1963a). 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. A more detailed description of the Maxey and Eakin (1949) method is provided in Section 9.1.1.1. An index of the hydrographic areas (HA) of Nevada and the associated publications is presented in Rush (1968a).

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.

1.2.2 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 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 valleys. 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).

1.2.3 Great Basin Regional Aquifer-System Analysis Study

The Great Basin 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 upon fewer deep-flow regions. The Reconnaissance Series provides the basic estimates of recharge and discharge for this regional flow model.

1.2.4 LVVWD/SNWA/Co-operator Studies

Work conducted by LVVWD, SNWA, and co-operators in the study area includes past studies and on-going data collection efforts. Selected studies of interest have been documented in the following reports:

- 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's Office in 1989 as part of its CWP.

- Reports prepared to support the water-rights hearings and EIS activities include (1) a USGS report containing estimates of groundwater budgets for selected basins of the study area (Nichols, 2000); (2) a LVVWD report on water resources and groundwater modeling of the White River and Meadow Valley flow systems (LVVWD, 2001); (3) an SNWA report on water resources evaluation for Spring Valley (SNWA, 2006); and (4) an SNWA report on water resources evaluation for Cave, Dry Lake, and Delamar valleys (SNWA, 2007).

- A multiple-volume report, *Baseline Characterization Report for Clark, Lincoln, and White Pine Counties Groundwater Development Project* (SNWA, 2008a), prepared by SNWA for BLM describes the baseline conditions for the Project study area in support of the EIS.

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 study area. Some are being conducted in cooperation with other agencies, such as USGS, DRI, and 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. The current status of the well installation and testing activities and the ET studies is provided in Appendix A.

1.2.5 BARCASS

BARCASS was a study created 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

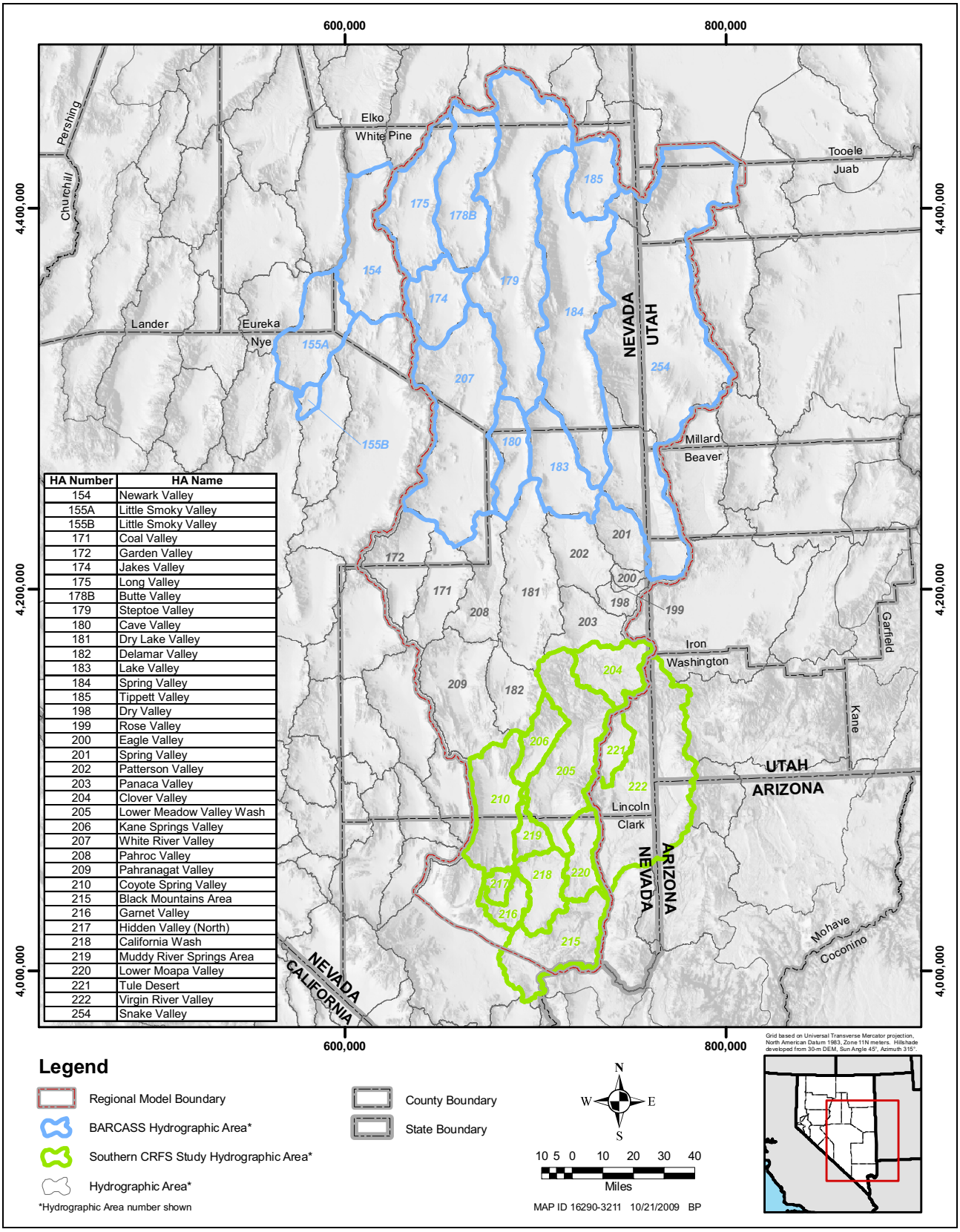
area coincides with the northern portion of the study area described in this report (Figure 1-3). Twelve hydrographic areas in the Great Basin were included in BARCASS. Of those twelve, Long, Butte, Steptoe, Spring, Tippett, Snake (including Pleasant and Hamlin), Lake, White River, and Jakes valleys are included within the scope of this study. BARCASS includes the most recent evaluation of ET within the northern part of the study area (Moreo et al., 2007; Smith et al., 2007; Welch et al., 2008).

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

- Summary report (Welch et al., 2008)
- 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)

1.2.6 Southern Colorado Regional Groundwater Flow System ET Study

USGS, in cooperation with the National Park Service, BLM, and the U.S. Fish and Wildlife Service, recently conducted a study to quantify the amount of groundwater and surface-water ET in the southern part of the Colorado Regional Groundwater Flow System, Nevada, Utah, and Arizona (DeMeo et al., 2008). Their study area includes 12 hydrographic areas and a portion of two others (Figure 1-3): Clover Valley (HA 204), Kane Springs Valley (HA 206), Lower Meadow Valley Wash (HA 205), Tule Desert (HA 221), Coyote Spring Valley (HA 210), Virgin River Valley (HA 222), Muddy River Springs Area (HA 219), Hidden Valley (North) (HA 217), Garnet Valley (HA 216), California Wash (HA 218), Lower Moapa Valley (HA 220), and the part of the Black Mountains Area (HA 215) north of Las Vegas Valley and the Lake Mead shear zones. All of these basins, except Tule Desert and Virgin River Valley, are located in the CCRP model area (Figure 1-3). The methodology followed by DeMeo et al. (2008) to delineate the ET areas is similar to that of BARCASS (Welch et al., 2008). Their ET rates are based on a combination of newly collected and reported data. The newly collected data consist of micrometeorological measurements at four sites. The four sites were located on the Virgin River floodplain (dense woodland), along the Muddy River (moderate woodland), in Rainbow Canyon (moderate shrubland), and in Lower Meadow Valley Wash (dense shrubland).



HA Number	HA Name
154	Newark Valley
155A	Little Smoky Valley
155B	Little Smoky Valley
171	Coal Valley
172	Garden Valley
174	Jakes Valley
175	Long Valley
178B	Butte Valley
179	Steptoe Valley
180	Cave Valley
181	Dry Lake Valley
182	Delamar Valley
183	Lake Valley
184	Spring Valley
185	Tippett Valley
198	Dry Valley
199	Rose Valley
200	Eagle Valley
201	Spring Valley
202	Patterson Valley
203	Panaca Valley
204	Clover Valley
205	Lower Meadow Valley Wash
206	Kane Springs Valley
207	White River Valley
208	Pahroc Valley
209	Pahranagat Valley
210	Coyote Spring Valley
215	Black Mountains Area
216	Garnet Valley
217	Hidden Valley (North)
218	California Wash
219	Muddy River Springs Area
220	Lower Moapa Valley
221	Tule Desert
222	Virgin River Valley
254	Snake Valley

Figure 1-3
Location of BARCASS and Southern CRFS ET Study Areas

1.3 Purpose and Scope

This section describes the overall purpose and scope of the hydrologic evaluation conducted in support of the EIS process and explains the purpose and scope of the conceptual model presented in this report.

1.3.1 Overall Purpose and Scope

The purpose of the hydrologic evaluation was to compile and analyze the available hydrogeologic information to support the EIS process and to develop the analytical tools to assist in the analysis of the indirect effects associated with the proposed groundwater withdrawal.

The hydrologic evaluation included the development of a regional three-dimensional (3D) numerical model of the flow systems underlying the study area. Each of the flow systems underlying the study area consists of three subsystems identified by their depth and the lengths of their flow paths: regional, intermediate, and local as described by Tóth (1963) and Freeze and Cherry (1979). See Section 5.2.1 for a description of these subsystems. The numerical model included the regional and intermediate portions of the flow system and served as a tool for performing preliminary regional-scale simulations of the effects of groundwater withdrawal. The simulation results, in turn, were used to preliminarily evaluate the potential water-related effects on the environment. As monitoring and testing data become available in the future, the model will be improved and used as a water-resource management tool.

The overall scope of work of the hydrologic evaluation included four major steps:

1. The preparation of a report documenting the baseline conditions within the study area titled *Baseline Characterization Report for Clark, Lincoln, and White Pine Counties Groundwater Development Project* (SNWA, 2008a).

2. The development of a conceptual model of groundwater flow in the flow systems underlying the study area. All components of this conceptual model, except for historical groundwater use and its effects on the flow system, are documented in this report.

3. The development of a numerical model calibrated to available observations. This step included the analysis of historical groundwater use and its effects on the flow systems and is documented in a report titled *Transient Numerical Model of Groundwater Flow for the Central Carbonate-Rock Province Clark, Lincoln, and White Pine Counties Groundwater Development Project* (SNWA, 2009b).

4. The use of the resulting transient model to evaluate future water-use scenarios, including groundwater withdrawals from the proposed SNWA wells, which are documented in a report titled *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, 2009a).

The study area extends over parts of Lincoln, White Pine, and Clark counties in Nevada and over Tooele, Juab, Millard, Beaver, and Iron counties in Utah encompassing the five project basins: Cave Valley (HA 180), Dry Lake Valley (HA 181), Delamar Valley (HA 182), Spring Valley (HA 184), and Snake Valley (HA 195) (Figure 1-1). The study area also includes basins where the water conveyance pipelines will be constructed to move the water from the project basins to the intended place of use in Las Vegas Valley. Originally, the eastern boundary of the model area coincided with the boundary of Snake Valley. During the course of this work, the model boundary was extended to include the portion of Fish Springs Flat that comprises Fish Springs.

1.3.2 Purpose and Scope of the Conceptual Model

The purpose of the conceptual model was to assemble the available hydrogeologic information into simplified components that provide a complete description of the flow system. The main components of the conceptual model are as follows:

- Hydrogeologic framework and hydraulic properties
- Groundwater occurrence and movement
- Predevelopment water budget
  - Groundwater discharge to the surface
  - Subsurface interbasin flow
  - Precipitation recharge
- Historical water use

All components of the conceptual model listed above, except historical water use, are described in this document. The historical water use and its effects are described in the numerical model report (SNWA, 2009b). In this hydrologic evaluation, the conceptual model served as an intermediate step in the development of the numerical model. Its components form the basis of the numerical model.

The conceptual model was developed for the flow systems underlying the Project study area (Figure 1-1). The scope of work included the evaluation, analysis, and simplification of the information contained in the baseline report (SNWA, 2008a) and additional information from various sources described in the document.

1.4 BLM Review Process

A Hydrology Technical Group was assembled by BLM in the early stages of the technical work conducted in support of the EIS. The primary objective of this group was to provide technical advice and recommendations to BLM, so they could ensure that the hydrologic data analysis and numerical model development satisfy the analysis requirements of the EIS.

The BLM Hydrology Technical Group members are as follows:

- BLM (Nevada, Utah, and Denver regional offices)
- USGS
- ENSR/AECOM (EIS consultant)

- Nevada State Engineer's Office (Observing)

The Hydrology Technical Group review process included meetings and conference calls to discuss and resolve technical issues. It also included formal reviews of preliminary reports and work products, including data compilation and analysis, and modeling files or results. This group conducted the report reviews and provided review comments to SNWA and Earth Knowledge, Inc., a consultant to SNWA. ENSR/AECOM was selected by BLM as a third-party contractor to assist in the preparation of the EIS. The Nevada State Engineer's Office participated in the technical meetings but in an observation capacity only.

1.5 Document Contents

This report consists of 12 sections and 9 appendixes. A brief description of the contents of each is provided.

Section 1.0 is this introduction.

Section 2.0 is a general description of the study area, including physiography, climate, soil and vegetation, and land and water uses.

Section 3.0 provides a description of the general approach to modeling groundwater flow in the study area and the specific approach used to conduct the hydrologic evaluation and develop the conceptual model. The description includes the method used to derive estimates of the water budgets for the flow systems and their basins.

Section 4.0 provides a description of the hydrogeologic framework model.

Section 5.0 describes the occurrence and movement of groundwater within the study area.

Section 6.0 describes available methods of deriving spatial distributions for precipitation and presents previously reported precipitation volumes.

Section 7.0 describes groundwater discharge, including groundwater ET and the springs that are relevant to the groundwater flow system at the regional scale.

Section 8.0 presents the directions and relative volumes of interbasin groundwater flow.

Section 9.0 presents methods used to estimate potential recharge and discusses the estimates of recharge and predevelopment groundwater budgets.

Section 10.0 presents the derived predevelopment groundwater budget.

Section 11.0 provides a summary of the contents of this report.

Section 12.0 provides a list of references cited in this report.

Appendix A provides the status of selected ongoing SNWA field data collection activities.

Appendix B presents maps of the extent and topography of all regional modeling units (RMUs).

Appendix C describes the hydraulic property data analysis.

Appendix D contains precipitation station data.

Appendix E contains literature ET data, including a compilation of phr eatophyte rooting depths, ET station data, and the data analysis conducted to derive potential evapotranspiration (PET) rates.

Appendix F contains the details of the groundwater ET and interbasin flow volume calculations, including the ET and precipitation rates used in the analysis, the groundwater ET volume calculations, and the details of the Monte Carlo simulations conducted to estimate the uncertainty of groundwater ET and interbasin flow estimates.

Appendix G presents the relevant spring discharge data and an analysis of the geothermal gradient for the study area, which was used to derive initial estimates of the springs' source depths.

Appendix H provides additional information in support of interbasin flow estimates.

Appendix I describes the recharge and groundwater budget calculations using the Excel® Solver.

2.0 STUDY AREA DESCRIPTION

The study area for the conceptual model was selected to encompass the five project basins and other neighboring basins (Figure 2-1). Each project basin is described in SNWA (2008a). This section provides a general overview of the physiographic setting, climate, soil and vegetation, geologic setting, groundwater flow systems, and land and water-use status of the study area.

2.1 Physiography

The study area is located within the Basin and Range Province described by Fenneman (1931) (Figure 2-1) and consists of a series of parallel to subparallel, north-trending mountain ranges separated by elongated alluvial valleys. According to Rowley and Dixon (2000), this region has undergone the most severe structural extension of the continental crust of any location in the world. The alluvial valleys are further classified by Heath (1984) as being in the Alluvial Basins Groundwater Region of the western United States. The study area is also part of the Carbonate-Rock Province of eastern Nevada and western Utah described by Plume and Carlton (1988) (Figure 2-1).

2.2 Climate

The climate within the study area is variable and influenced by the large range in latitude, variations in 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 study area have large daily and annual variations because the clear skies of Nevada allow for heating of the ground in the day and radiant cooling at night. Mean daily temperatures across the area (from Las Vegas to Ely) vary by approximately 20°F. 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 study area 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 amount of precipitation varies across the area with Ely, Nevada, receiving an annual average of 9.7 in., while Las Vegas receives an annual average of 4.4 in. (WRCC, 2008). The study area lies within the northeast, south-central, and extreme south climatic divisions defined by Houghton et al. (1975). Precipitation within each of the basins is generally least on the valley floor and greatest in the mountains. For much of the study area, annual precipitation ranges from 8 to 12 in. with the precipitation increasing with increasing elevation. 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. These conditions have prevailed in

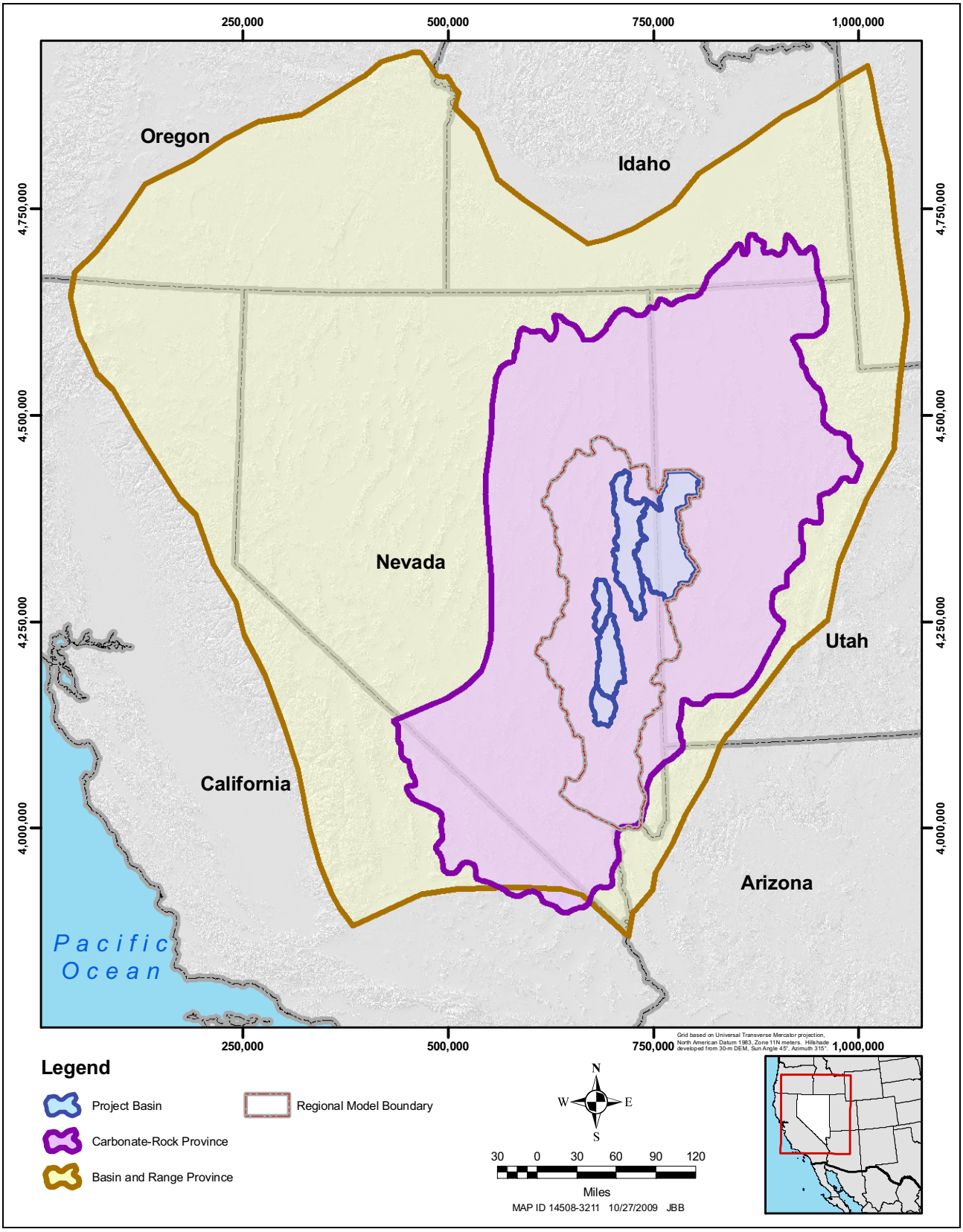


Figure 2-1
Location of Study Area within the Basin and Range Province

historic time, but during the pluvial episodes of the Pleistocene Epoch, the climate was much wetter and temperatures were 48°F to 55°F cooler (Tuttle, 1990).

Wind speed and direction are controlled by prevailing storm tracks and orographic effects induced by the basin and range topography. Evaporation rates within the study area are controlled by low humidity, abundant sunshine, and dry winds. The Las Vegas area is the warmest and driest part of the study area and has the lowest relative humidity. The annual evaporation rates range from approximately 45 to 72 in./yr (Houghton et al., 1975). Available records (Eakin, 1963a and b; Rush, 1964; Hood and Rush, 1965; Rush and Kazmi, 1965) suggest that evaporation from May through September accounts for most of the annual total evaporation in each of the valleys in the study area.

2.3 Soil and Vegetation

Generally, the basins of the study area (in the Great Basin) have thick sequences of fill material resulting from thousands of years of erosion from the surrounding mountains and volcanic activity in the area. Some of these valleys are occupied by playas (temporary lakes), which normally have a very high salt concentration as a result of evaporation.

The study area encompasses parts of the Mojave Desert and the Great Basin ecological systems. The exact boundary between the Mojave Desert and the Great Basin is vague, but the two systems can be distinguished by the occurrence of different vegetation communities and plant species.

The Mojave Desert scrub, or creosote bush scrub, is the dominant vegetation community within the Mojave Desert. The occurrence of this vegetation community is one of the main characteristics distinguishing the Mojave Desert from the Great Basin. Although, creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*) dominate this community, the Mojave Desert is a diverse landscape with a variety of other shrubs, yuccas (*Yucca spp.*), cholla (*Opuntia spp.*), and cacti.

The valley floors of the Great Basin are typical of a xeric sagebrush-shrubland community with big sagebrush (*Artemisia tridentata*) as the dominant species, which also distinguishes the Great Basin from the Mojave Desert. Big sagebrush is not typically found in the Mojave Desert. Common companions include greasewood (*Sarcobatus vermiculatus*), green and rubber rabbitbrush (*Chrysothamnus viscidiflorus* and *Chrysothamnus nauseosus*), snakeweed (*Gutierrezia sarothrae*), spiny hopsage (*Grayia spinosa*), and littleleaf and gray horsebrush (*Tetradymia glabrata* and *Tetradymia canescens*). More saline-tolerant species include shadscale (*Atriplex confertifolia*), saltgrass (*Distichlis spicata*), and winterfat (*Ceratoides lanata*). Greasewood also occurs on and around playas or in salt-encrusted soils. Riparian species, such as cottonwood (*Populus fremontii*), willow (*Chilopsis linearis*), tules (*Scirpus spp.*), and cattails (*Typha spp.*), occur within the spring complexes. The pinyon-juniper community dominates the higher elevations of the Great Basin, and the dominant trees are pinyon pine (*Pinus monophylla*) and Utah juniper (*Juniperus osteosperma*). Shrubs in this community can include snakeweed, green and rubber rabbitbrush, western serviceberry (*Amelanchier alnifolia*), various currants, and gooseberries and snowberry (*Symphoricarpos spp.*) (Mozingo, 1987).

Most 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. This 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 study area will be described in further detail in Section 7.0 of this report.

2.4 Geologic Setting

A brief description of the geology of the area, including the units present and the main structural events, is included in this section. The detailed descriptions, including maps and cross sections, may be found in Volume 1 of SNWA (2008a).

The geology of the study area is dominated by a thick sequence of Paleozoic carbonates overlying Proterozoic to early Cambrian quartzites and shales above a Precambrian metamorphic core complex. The total thickness of the Paleozoic carbonates is between 30,000 and 33,000 ft in parts of the study area (Tschanz, 1960; Tschanz and Pampeyan, 1961). Occasional shale and quartzite units are interbedded with the carbonates. Tertiary volcanic rocks are commonly found above the pre-Cenozoic sediments. These volcanic rocks erupted from several caldera complexes and are locally intruded by cogenetic plutons. Preceding, intermixed with, and postdating the volcanic rocks are volcaniclastic sedimentary units, which generally thicken toward the southern part of the model area. These Cenozoic sediments include Oligocene to Miocene limestone and Oligocene to Holocene 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, is of Quaternary age, and is largely in stream channels and playa areas. Three most recent episodes produced present-day topography and geologic features controlling groundwater flow. The three events are as follows:

1. The Late Devonian to Late Mississippian Antler compressive deformation resulted in a number of thrust faults and created a highland to the northwest of the study area. Erosion of the highland resulted in Mississippian shales, sands, and gravels deposited within the study area.

2. The Late Jurassic to early Tertiary Sevier compressive deformation thrust western facies Paleozoic carbonates and related sediments over eastern facies continental and near-shore sediments, most of which are Permian to Jurassic in age.

3. The Cenozoic basin-range extensional deformation began with the formation of detachment faults over uplifted areas, commonly areas of Jurassic and Tertiary 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.

The Paleozoic carbonate rocks have little primary porosity and permeability but have developed secondary permeability through fractures and faults resulting from repeated folding and faulting events. Groundwater is transmitted through these openings. Some of the fractures have been enlarged by dissolution as water moves through them. The high spring discharges in parts of Pahranagat Valley, White River Valley, and the Muddy River Springs Area, as well as the cave system in Snake Valley, demonstrate groundwater movement in solution openings and fracture systems, at least locally in parts of the study area.

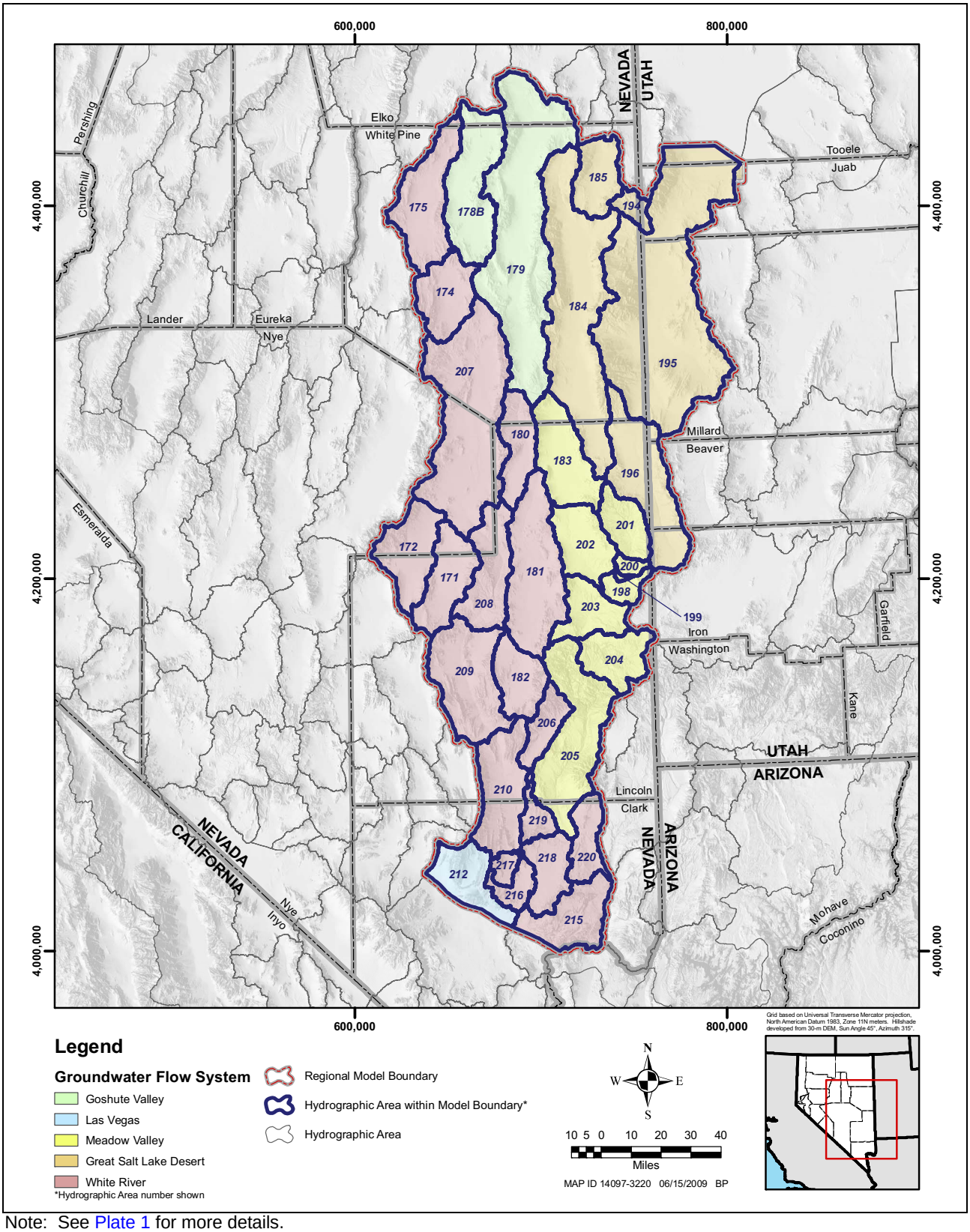
The primary permeability of the Paleozoic clastic and Tertiary volcanic rocks exposed in some of the surrounding mountains in the area is also very low. The rocks' transmissive properties are enhanced through secondary fracturing, which in some cases provide a network of openings through which water moves (Eakin, 1963c).

The unconsolidated sand and gravel of the valley fill in some of the valleys are capable of transmitting large amounts of groundwater. In some of the valleys where silty clay and clay dominate, however, water may be transmitted very slowly.

2.5 Groundwater Flow Systems

The basis of a flow system is interbasin flow. The first recognition of interbasin flow in the study area 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 rainfall 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. The dry playas are found in some valleys of the northern study area. The groundwater table of these dry playas 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 study area discharge groundwater internally through phreatophytic ET. In addition, it is also recognized that, at depth, some amount of water following a groundwater gradient and permeable section flows from this basin to the lower basins.

Five groundwater flow systems are entirely or partially within the study-area domain (Figure 2-2 and Plate 1). These flow systems are finite three-dimensional bodies, bounded by the top of the saturated zone at the top, low hydraulic-conductivity geologic units at the bottom, and variable hydrogeologic features, corresponding to the hydrographic-area boundaries of the peripheral basins, on the sides. Flow into or out of the flow systems may occur through any of the boundaries. As will be discussed in Section 5.0, the boundaries of the flow systems in the study area are subject to interpretation. The five flow systems, as depicted in Plate 1, have been interpreted for this study to support the simplified version of the conceptual model. Most of the flow system boundaries, but not all, correspond to the



Note: See Plate 1 for more details.

Figure 2-2
Regional Flow Systems within Study Area

interpretation of Harrill et al. (1988) in U.S. Geological Survey Hydrologic Investigations Atlas HA-694-C. These flow systems are as follows:

- Goshute Valley Flow System (GVFS)
- Great Salt Lake Desert Flow System (GSLDFS)
- Las Vegas Flow System
- Meadow Valley Flow System (MVFS)
- White River Flow System (WRFS)

The top boundary of the flow systems of interest is assumed to correspond to the top of the saturated zone, not including perched groundwater. In general, recharge occurs at the higher-altitude areas of the top boundary (mountains), and discharge occurs at lower-altitude areas of the top boundary (the valley bottoms). Water from precipitation recharges the system through the top surface as direct infiltration of precipitation on the mountain block or as infiltration of mountain-front runoff on the alluvial aprons and valley bottoms. Groundwater discharges from the flow systems through the top boundary via evaporation from open water bodies fed by groundwater and/or by groundwater ET.

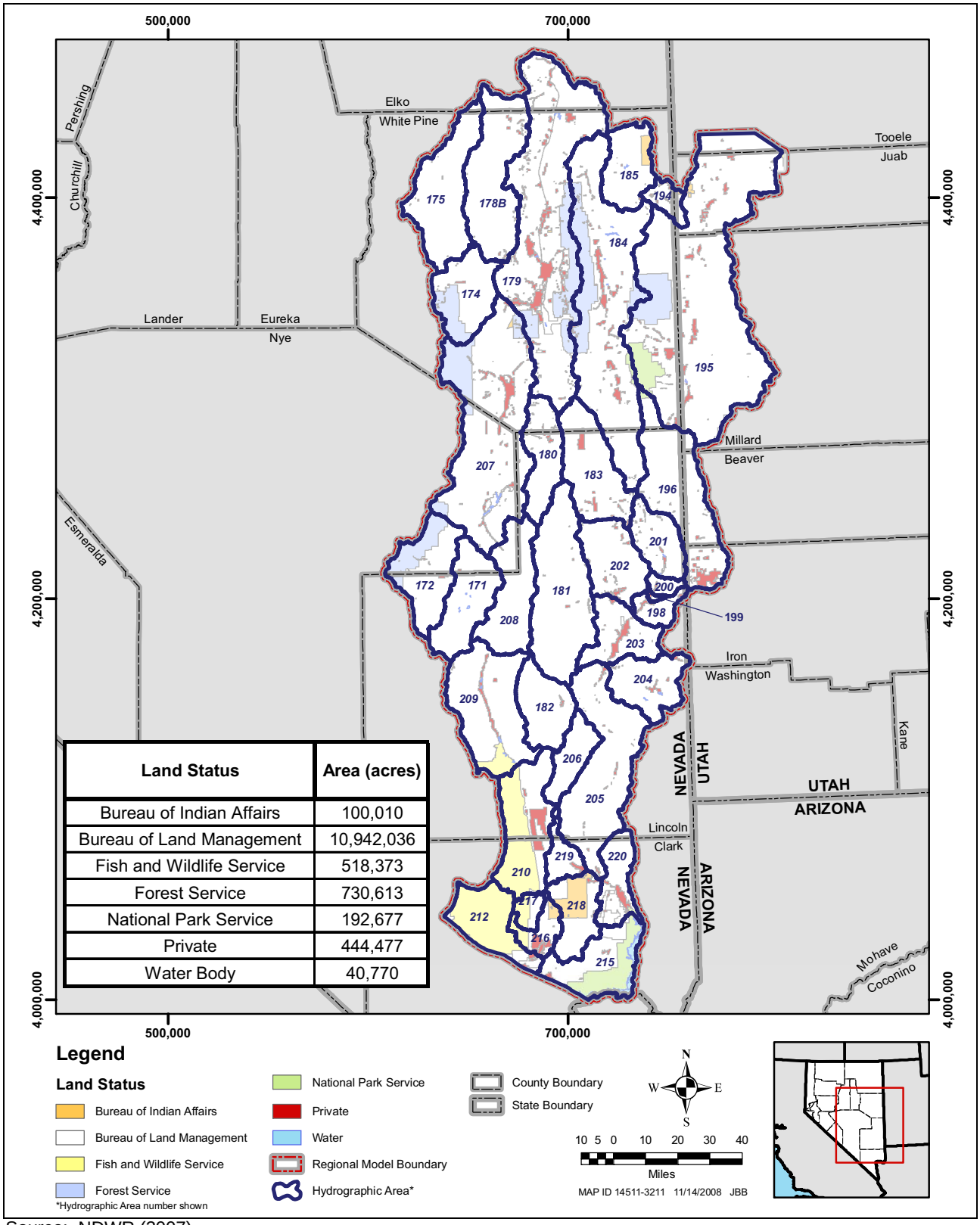
The bottom boundary of the flow systems is assumed to correspond to that part of the flow systems where groundwater flow is either unlikely or negligible. For this study, a depth of -10,000 ft amsl was selected as a cutoff for the bottom of the flow systems. The resulting flow domain includes most of the aquifers occurring within the study area. Some deep portions of the carbonate aquifer were cut off in some areas. This simplification should not affect the model of regional flow because this depth most probably represents the maximum depth of groundwater circulation; at depths greater than 10,000 ft amsl, groundwater circulation is unlikely. Others have used similar cutoff depths to represent the bottom of groundwater flow models in this region. For example, Faunt et al. (2004) used a cutoff depth of -4,000 m amsl (-13,000 ft amsl) in the model of the Death Valley Regional Flow System (DVRFS) (in Faunt et al., 2004). DOE (1997) used the same cutoff value of -4,000 m amsl in its regional model of the Nevada Test Site (NTS), an earlier version of the DVRFS model. This cutoff depth was supported by low estimates of horizontal hydraulic conductivities extrapolated from relationships of hydraulic conductivity versus depth (IT, 1996). IT (1996, n.p.) states "for depths of 3,000 m and more, the extrapolated hydraulic conductivity (*K*) values are less than 10^{-7} m/day, which are representative of virtually impermeable media."

Under ideal conditions, the lateral boundaries of the flow systems should correspond to natural hydrologic boundaries. This may be feasible for small local flow systems where the boundaries may be identified by aquifer testing, but it is not feasible for large flow systems such as those underlying the study area. In this case, the lateral boundaries of the groundwater flow systems of the study area (Figure 2-2) were generally selected to correspond to hydrographic-area boundaries. An exception is the southern end of the western boundary where the flow system was extended to the Las Vegas Valley Shear Zone (LVVSZ), including a portion of Las Vegas Valley. The LVVSZ is considered to be impermeable to transverse groundwater flow. A preliminary identification of permeable boundary segments was reported in SNWA (2008a). The locations of the permeable boundary segments were revised and finalized during the estimation of annual lateral boundary flow volumes, which are described in Section 8.0.

2.6 Land and Water-Use Status

Current land-status patterns in the study area are shown on Figure 2-3. Population density of the area is very low, so urban and commercial land uses are very limited. Over 90 percent of the land in the study area is owned by the Federal government through the Department of Interior bureaus; private ownership accounts for less than 4 percent. Irrigation cropland and rangeland are the two largest land-use activities in the area and occur predominantly in the valley bottoms. Cropland irrigation is mostly undertaken around the communities while rangeland activities are spread throughout the valleys on both government-owned and private lands.

According to the Nevada State Engineer (Smales and Harrill, 1971), the first major water use in Nevada coincides with the mining boom starting in 1849. Most of the water was diverted from streams to nearby mills to process the mining ores. Some water was used for irrigation purposes to support the mining community. From 1849 to 1860, the mining community was the main water user in Nevada. The livestock industry began in Nevada around 1870. Irrigation by surface water to produce forage crops began to increase starting then. Water use continued to expand in Nevada with the building of dams and reservoirs starting in 1903. Major water needs continued to be satisfied by surface water up to the early 1940s when the state began experiencing notable growth. At that time, groundwater use became more significant. However, prior to that time, by 1937, Boulder Dam (now Hoover Dam) had been completed, and Lake Mead had been filled. Spring flow records at the Muddy, Rogers, and Blue Point springs indicate that filling the lake has not significantly affected the majority of the flow system of the study area. Thus, although Lake Mead is man-made, approximate predevelopment conditions are assumed to prevail up to 1945 and include Lake Mead.



Source: NDWR (2007)

Figure 2-3
Land-Status Patterns within Study Area

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3.0 TECHNICAL APPROACH

A description of the technical approach used to develop the groundwater flow model is presented in this section. The general approach is described first, followed by the approach used for developing the conceptual model.

3.1 General Approach

The general approach for the model development consisted of the following steps:

1. Development of a three-dimensional conceptual model for the flow systems of the study area, including estimates of groundwater-budget components (e.g., precipitation, recharge, groundwater discharge by ET, and interbasin inflow and outflow).

2. Development of a numerical model for the flow systems of the study area, including:

   - Construction of the numerical model based on the conceptual model.

   - Calibration of the numerical model to predevelopment steady-state conditions and transient conditions that span from 1945 to 2004.

3. Simulation of alternate groundwater development scenarios using the transient numerical model to evaluate:

   - Effects of proposed pumping.
   - Cumulative effects of historical groundwater use and proposed pumping.

The approach followed to develop the conceptual model (Step 1) is described in the remainder of this section. The specific approaches followed to complete Steps 2 and 3 are described in the corresponding reports (SNWA, 2009a and b) that document the CCRP model development and use (see Section 1.3.1).

3.2 Conceptual Model Development

The CCRP conceptual model was developed following the standards designed for groundwater flow modeling by the American Society for Testing and Materials (ASTM, 1996). The conceptual model consists of several conceptual submodels, each of which describes a set of abstractions of the physical components and processes of the flow system. The conceptual submodels are based on extensive reviews of previous scientific investigations and the available geologic and hydrologic data compiled and evaluated. The conceptual submodels work together as one conceptual model to provide a

simplified interpretation of the flow systems that are the basis of the numerical groundwater flow model. These submodels consist of the following:

- Simplified hydrogeologic framework
- Groundwater occurrence and movement
- Predevelopment groundwater budget
- Historical groundwater use and effects

During development of the conceptual model, an extensive effort was spent on compiling available data and collecting additional data to support the conceptualization process. These efforts, along with a summary of the conceptualization process, are described within this section. Historical groundwater use and effects are described in the numerical model report (SNWA, 2009b).

3.2.1 Data Compilation, Collection, and Evaluation

The conceptual model described in this report was based on extensive reviews of previous scientific investigations and the available geologic and hydrologic data. These investigations include detailed and reconnaissance-level geologic, hydrologic, and geochemical investigations of the project basins and adjacent basins (Figure 1-2). A summary of studies that are relevant to this study is presented in Section 1.2 and throughout this report.

Substantial data collection efforts were also completed. Data collection activities during the 2003 to 2008 field seasons included drilling and testing SNWA monitor and test wells, geologic mapping, vegetation mapping, water-chemistry sampling, depth-to-groundwater measurements, and stream flow measurements. These data augmented existing hydrologic, geologic, and chemistry databases compiled by SNWA. Additionally, data compilation and collection efforts have been enhanced through cooperative agreements between SNWA and the University of Nevada, Reno (UNR), 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 routing. These efforts are documented in various technical reports, including SNWA (2008a), and this report.

These data were evaluated to determine 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 developed as part of BARCASS were given priority and were incorporated in the conceptual model as appropriate. The results of the data evaluation and analyses are documented in SNWA (2008a) and are summarized in this report.

3.2.2 Simplified Hydrogeologic Framework

The hydrogeologic framework was developed through simplification of the geologic framework described in Volume 1 of SNWA (2008a). The development process consisted of four steps: (1) development of a geologic framework, (2) simplification into a hydrogeologic framework,

(3) simplification into an RMU model, and (4) assignment of hydraulic properties to the RMUs and significant structures. Steps 1 and 2 are described in SNWA (2008a). The final simplification process (Step 3) consisted of grouping units based on their hydraulic properties and structural positions. The development of the simplified hydrogeologic framework is described in more detail in Section 4.0 of this report.

3.2.3 Groundwater Occurrence and Movement

Groundwater occurrence and movement were deduced from the available data, particularly the following data types:

- Simplified hydrologic framework (discussed in previous subsection)
- Potentiometric head and water-level data under natural conditions
- Locations of major surface-water features (springs and streams)
- Distributions and rates of groundwater recharge from precipitation
- Locations of groundwater ET areas under natural conditions
- Locations of interbasin inflow and outflow under natural conditions

The interpretation of groundwater occurrence and movement within the flow system of the study area is described in Section 5.0. The information used to derive this interpretation originates from many sources. Detailed information on potentiometric levels and surface water, including streams and springs, is described in SNWA (2008a). Relevant information is summarized in this report as appropriate.

3.2.4 Predevelopment Groundwater Budget

A quantitative estimate of the predevelopment water budget is very important to the development of a groundwater flow model. The estimated budget represents predevelopment, long-term, mean annual conditions and includes precipitation recharge, groundwater discharge by ET and/or springs, and interbasin inflow and outflow. Given that precipitation recharge cannot be measured directly, it must be estimated in some manner. The three principal methods to estimate recharge include groundwater-balance methods, soil-water-balance methods, and chloride mass-balance methods.

Groundwater-balance methods yield estimates of recharge by balancing the total discharge against recharge and subsurface inflows for a system. Examples of such methods include Maxey and Eakin (1949) and variations on that method, such as those converting the traditional step function to a power function. Power functions have also been developed to describe the relationship between precipitation and recharge in Idaho, India, and Arizona. Soil-water-balance methods focus on the processes that control net infiltration through the uppermost layers of surficial materials in a given area and have been used in Nevada through the development of the INFIL and Basin Characterization Model (BCM) models. The chloride mass-balance method yields estimates of groundwater recharge in arid and semiarid environments, based on annual precipitation and known chloride concentrations of precipitation and groundwater in targeted aquifers. Each of these three principal methods will be described in greater detail in Section 9.0.

For the purpose of this study, the groundwater-balance method was selected. In this method, the total recharge to the system (precipitation recharge plus inflow) is equated to the total discharge from the system (groundwater ET plus outflow), and unknown components of the budget are estimated using trial-and-error or optimization methods. The optimization method as implemented in the Excel® Solver was used in this study (Section 3.2.4.4). Groundwater ET is estimated independently and is treated as a known quantity in the groundwater-balance method. Recharge is expressed as the sum of the product recharge efficiencies and precipitation volumes over a series of discrete zones. Assuming that precipitation is known, the recharge efficiencies are the primary unknown variables in the groundwater-balance method. However, other budget components that cannot be measured or estimated with sufficient confidence (interbasin flow rates in this case) may also be treated as unknown variables in the groundwater-balance method. However, constraints derived from the information available on the unknown variables (recharge efficiencies and interbasin flow volumes) are essential to finding a reasonable solution. The process used for development of the groundwater budgets is presented in Figure 3-1.

Groundwater budgets were derived for four flow systems of the study area (GVFS, MVFS, GSLDFS, and WRFS). No separate solution was sought for the small portion of Las Vegas Valley located within the model area. Recharge for this area was calculated using the solution derived for the nearest flow system, namely the WRFS.

3.2.4.1 Spatial Distribution of Precipitation

An estimate of the spatial distribution of precipitation is needed to estimate groundwater ET and the spatial distribution of recharge. The precipitation distribution for this study was derived using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) method (Daly et al., 1994, 1997, 1998, 2008). The PRISM method incorporates important physical processes and uses state-of-the-art spatial methods for determining the precipitation distributions. The precipitation distribution over the study area was extracted from the 800-m PRISM grid, and the quality of this distribution was evaluated. The distribution was integrated by hydrographic area to obtain yearly precipitation volumes for all basins in the study area, and the resulting volumes were compared to previous estimates. One-inch precipitation bands within predefined potential recharge areas were extracted from the PRISM grid for use in the Excel® Solver. Details describing the PRISM precipitation distribution are presented in Section 6.0.

3.2.4.2 Groundwater Discharge to the Surface

Groundwater discharges to the surface primarily through the process of ET and spring flow. Groundwater may also discharge to the surface directly into streams through the process of upward leakage. Estimates of groundwater ET were made using the simplifying assumption that the volume of groundwater ET discharging from a given ET area is equal to the volume of total ET reduced by the volume of precipitation on that area. Groundwater ET was estimated using two methods. Method 1 was developed as part of this study and was applied to most of the southern basins of the study area. Method 2 was used and described by Welch et al. (2008) and DeMeo et al. (2008) and was applied to all northern basins and two southern basins of the study area. These methods are presented in Section 7.0.

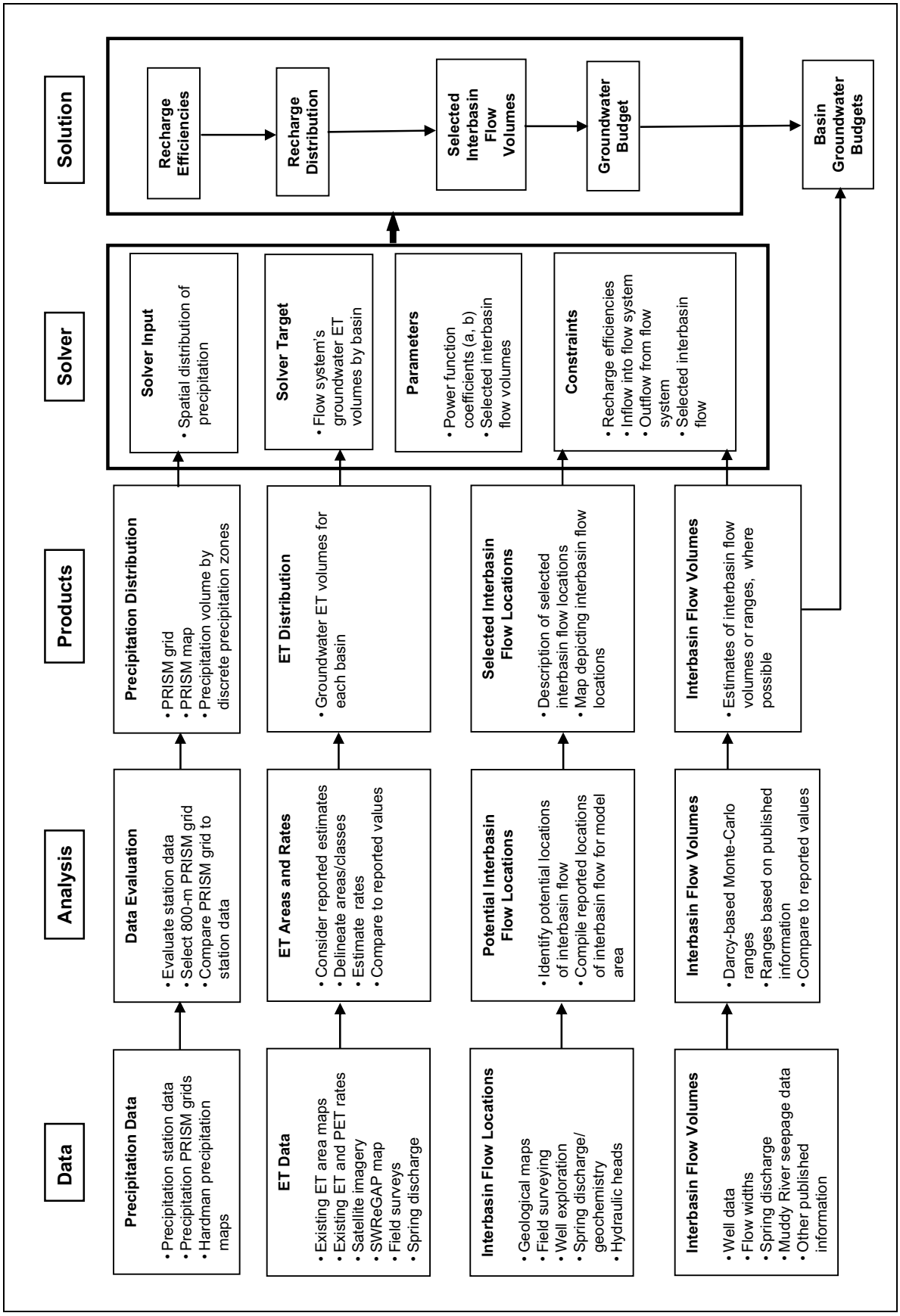


Figure 3-1
Process Used to Derive Groundwater Budgets for the Flow Systems of the Study Area

For Method 1, potential areas of groundwater ET were delineated and classified, and published ET rates were compiled and evaluated. Appropriate rates were selected, adjusted to local PET conditions, and applied to the delineated potential groundwater ET areas in each basin. The PRISM precipitation grid was then used to remove the ET associated with precipitation as the source.

For Method 2, potential areas of groundwater ET were delineated and classified similarly to Method 1 but with more detail. Groundwater ET rates were derived from the literature and/or field measurements and were multiplied by the corresponding potential groundwater ET areas to obtain estimates of annual volumes of groundwater ET.

3.2.4.3 Interbasin Groundwater Flow

Locations and volumes of interbasin flow are needed to constrain the groundwater-budget solutions. The selected flow-routing configuration, presented in Section 8.0, matches the interpretation of Harrill et al. (1988) for the most part. Flow ranges for each permeable boundary segment were estimated for each flow system. Constraints on interbasin flow volumes were developed using spring and stream flow gage records and groundwater elevations. Interbasin flow volumes across the external lateral boundaries of the model domain were estimated using Darcy's equation and Monte Carlo simulations. This method consisted of conducting multiple calculations of flux across a given flow-boundary segment to derive stochastic estimates of the flux. Interbasin flow for selected basin boundaries was also estimated by the Excel® Solver along with available information from the literature. The interbasin flow estimates are described in Section 8.0.

3.2.4.4 Recharge Estimation

The groundwater-balance method was used to estimate recharge for each flow system, using estimates of other budget components that can be measured within the bounds of reasonable uncertainty (e.g., precipitation, groundwater discharge to the surface). A relationship between recharge efficiencies and precipitation was derived that yielded a balanced groundwater budget for the flow system. This was completed using the spatial distribution of precipitation and estimates of groundwater ET and outflow previously discussed.

The groundwater-balance method was implemented using the Excel® Solver (Appendix I). The Excel® Solver is designed to find optimal solutions to numerical problems in which the main variables requiring a solution are the recharge efficiencies for a given flow system. The resultant recharge efficiencies were applied to the precipitation distribution to derive a recharge distribution. Using the recharge distribution, recharge estimates for each basin were calculated and used to develop the groundwater budget for the entire flow system and each of its basins. A different set of efficiencies was derived for each of the four flow systems in the study area.

For this analysis, it was assumed that only precipitation rates at or above 8 in./yr contribute to groundwater recharge (effective precipitation). The volume of precipitation below 8 in./yr is assumed to account for losses to soil-moisture deficits and ET (Anderson et al., 1992). The method described above was applied to each of the flow systems within the study area, except Las Vegas, and is described in detail in Section 9.0 and Appendix I.

4.0 HYDROGEOLOGIC FRAMEWORK

The Central Carbonate-Rock Province encompasses the entire study area and provides a degree of hydraulic connectivity between the many hydrographic areas composing the flow systems of the study area. A simplified hydrogeologic framework model of the flow systems underlying the study area was constructed to support the conceptualization of groundwater flow within these flow systems. The corresponding hydrogeologic surficial map and cross sections are presented in Plates 2 and 3. The area of the hydrogeologic framework model is slightly larger than the area of the conceptual model of groundwater flow (Plate 1). This section is organized as follows:

1. Construction of hydrogeologic framework model (SNWA, 2008a)
2. Improvements made after SNWA (2008a) was published
3. Construction of simplified hydrogeologic framework model (i.e., an RMU model)
4. Description of simplified hydrogeologic units (RMUs)
5. Identification of significant structural features
6. Description of hydraulic properties

4.1 Construction of Hydrogeologic Framework Model

The construction of the hydrogeologic framework model is described in detail in SNWA (2008a). The approach consisted of developing a detailed geologic framework and then simplifying it into a hydrogeologic framework. These two major steps are summarized in the following text.

4.1.1 Geologic Framework

The available published and unpublished geologic information was collected, compiled, and reviewed by geologists with extensive mapping experience within the study area. Relevant information included geologic maps, cross sections, and reports. In addition, information derived from boreholes, geophysical studies, and geologic field work was also considered. From this information and expert interpretations, a detailed geologic framework model was developed that consists of (1) surficial geologic maps in digital form (north and south) and descriptions of the geologic units; (2) a map of the major faults in digital form and a detailed description of the history of the area; and (3) several geologic cross sections in digital form (north and south) tied into the geologic maps. Detailed descriptions of this step may be found in Volume 1 of SNWA (2008a).

4.1.2 Hydrogeologic Framework

The geologic framework was simplified into a hydrogeologic framework by combining geologic units of similar hydraulic properties and spatial extent into hydrogeologic units (HGUs), which may be classified as aquifers, aquitards, or intermediate units. The geologic cross sections were also

simplified to represent hydrogeologic cross sections. The areal extent of each HGU was then defined based on the hydrogeologic maps and cross sections. The hydrogeologic maps and cross sections were also used to identify major structural features that may control groundwater flow. Detailed descriptions of the hydrogeologic framework, including a surficial map and cross sections, may be found in Volume 1 of SNWA (2008a).

4.2 Improvements Made after SNWA (2008a) Was Published

Improvements made to the hydrogeologic framework after completion of SNWA (2008a) included (1) a more detailed evaluation of the geology of the Fish Springs Range to better understand the relationship between Fish Springs and Snake Valley, (2) the addition of new gravity data for Snake Valley, and (3) the reinterpretation of major structural features in the southern basins. These improvements were incorporated into the simplified hydrogeologic model described later in this section.

4.2.1 Detailed Hydrogeology of Fish Springs Range

During the CCRP model development, the eastern boundary of the flow domain was extended to include the portion of Fish Springs Flat that comprises Fish Springs. As a result, a more detailed evaluation of the hydrogeology of the Fish Springs Range, which separates Fish Springs from Snake Valley, was conducted.

The Fish Springs Range in Utah (Plate 4) is a 5-mi-wide, 20-mi-long, north-trending, jagged horst that rises abruptly from its base at less than 4,900 ft elevation to a height of 8,500 ft. It is bounded on the west by the northern extension of Tule Valley (Stephens, 1977), which is separated by scattered, mostly unnamed low hills from north-draining Snake Valley farther west. The two valleys join each other west of the northern Fish Springs Range as they enter the southwestern end of the broad Great Salt Lake Desert (Gates and Kruer, 1981), the ultimate sink of the Great Salt Lake Desert groundwater flow system (Harrill et al., 1988).

The Fish Springs Range is bounded on the east by Fish Springs Flat (Bolke and Sumsion, 1978), which separates Fish Springs range from the Dugway Range, Thomas Range, and Drum Mountains to the east. Fish Springs Flat drains north into the Great Salt Lake Desert. Both Tule Valley and Fish Springs Flat are dominated by deposits of pluvial Pleistocene Lake Bonneville (Plate 4) (Sack, 1990; Oviatt, 1991). An east-west county line, between Juab County to the south and Tooele County to the north, passes a half mile north of the Fish Springs Range; this line is the southern end of the Dugway Proving Ground (Clark et al., 2007), a large military base. The northern end of Fish Springs Flat, largely south of the county line and the Dugway Proving Ground, contains a large (26,000 afy) (Bolke and Sumsion, 1978) spring complex consisting of Fish Springs and other springs of slightly saline water. This spring complex and discharge area, about 4.5 mi east-west by 6 mi north-south, has been set aside as the Fish Springs National Wildlife Refuge (NWR) managed by the U.S. Fish and Wildlife Service.

The Fish Springs Range is made up largely of moderately west-dipping Middle Cambrian to Middle Devonian carbonate rocks (Kepper, 1960; Hintze, 1980a and b; Morris, 1987). These rocks of the

lower carbonate aquifer rest on Lower Cambrian siliciclastic (basement confining zone) rocks that are exposed only in a few places on the eastern side of the range and underlie the range. All rocks in the range are intensely faulted by north-striking basin-range faults, with the range-front faults on both sides of the range being the largest. The range-front fault zone on the eastern side is of especially large displacement, and the basin beneath Fish Springs Flat is probably at least 3,000 ft thick (Plate 4), although the exact thickness is unknown. This main north-south fault zone, which uplifted the range, is still active and has a component of Holocene and late Pleistocene movement (Black et al., 2003). This zone not only formed many youthful fault scarps but also localized the springs of the Fish Springs complex. Many of these springs are warm, indicating deep circulation of groundwater in the fractures of the fault zone. Just north of the NWR, one northeast-trending string of springs is termed Wilson Health Springs (Hintze, 1980a) because it was the site of a former commercial spa. These springs, now on the Dugway Proving Ground, include several fumaroles, whose constructional edifice of spring deposits is evident. These hot springs further document the deep circulation of groundwater, here along a northeast-striking fault zone.

North-striking attenuation faults and thrust faults are mapped in the Fish Springs Range (Hintze, 1978, 1980a and b). More importantly, east-striking, oblique-slip faults also have been mapped throughout the range (Hintze, 1980a and b). Some large displacements appear to control the small Fish Springs lead-silver mining district, formerly mined on the western side of the northern part of the range (Olivera, 1975; Christiansen, 1977). A concentrated series of such east-striking faults occurs at Sand Pass, which separates the southern end of the Fish Springs Range from the northern end of the somewhat higher and larger House Range. This east-striking fault zone makes up the Sand Pass transverse zone, first noticed by Stoeser (1993) and later recognized by Rowley (1998) and Rowley and Dixon (2001) to extend as far east as the Wasatch front and to continue west to define the northern side of the east-trending Kern Mountains of Nevada. Stoeser (1993) noted that the zone is the southern boundary for the major east-west Tintic-Deep Creek volcanic belt in Utah, which is of Tertiary age. At Sand Pass, the southern end of the Fish Springs Range is about 2 mi west of the northern end of the House Range, suggesting left-lateral offset of the ranges along the transverse zone. In addition, small intrusions are present at the pass (Chidsey, 1978). Furthermore, in contrast to the Fish Springs Range, the main bounding fault zone of the House Range is on the western side, and the rocks in the range dip east. Like the main bounding fault zone of the Fish Springs Range, the main fault zone of the House Range is a fault zone of large displacement that includes Holocene and late Pleistocene movement (Black et al., 2003); the scarp on the western side of the House Range is as imposing as that on the eastern side of the Fish Springs Range.

4.2.2 Gravity Data for Snake Valley

This subsection presents the interpretation of gravity data, not available when the Baseline Report (SNWA, 2008a) was published, collected from new stations in Snake Valley in east-central Nevada and west-central Utah (Mankinen and McKee, 2009). Analyzing gravity data helps delineate anomalies that can then be used to identify the overall shape of the basins, to provide estimates of the depth to pre-Cenozoic basement rocks, and to locate buried structures beneath the sedimentary cover.

Gravity data from the new stations were combined with previously available data and were reduced using standard gravity corrections (Blakely, 1995). The derived Bouguer gravity anomaly was adjusted by subtracting the regional isostatic field. This adjustment removed long-wavelength

variations in the gravity field that are inversely related to topography. Therefore, the resulting isostatic residual gravity anomaly (Figure 4-1) is a reflection of local density distributions within middle to upper crustal levels.

The isostatic gravity field (Figure 4-1) indicates several gravity anomalies, two of which are located along the eastern boundary of Snake Valley. The largest of these two gravity anomalies occurs along most of the Confusion Range. The second one occurs along the Fish Springs Range to the north. Mankinen and McKee (2009) used the gravity inversion method derived by Jachens and Moring (1990) to estimate the thickness of Cenozoic volcanic rock and sedimentary basin fill.

Among other findings, Mankinen and McKee's (2009) analysis reflected that the maximum basin depth in Snake Valley is about 3,000 m and occurs at Snake Valley's northern end. Also, the maximum basin-fill thicknesses in Pine and Wah Wah valleys and in the Sevier Lake area are about 3,000, 2,000, and 1,000 to 1,500 m, respectively. In contrast, the Tule Valley basin is shallow with a maximum depth of about 1,000 m.

4.2.3 Reinterpretation of Structural Features in Southern Basins

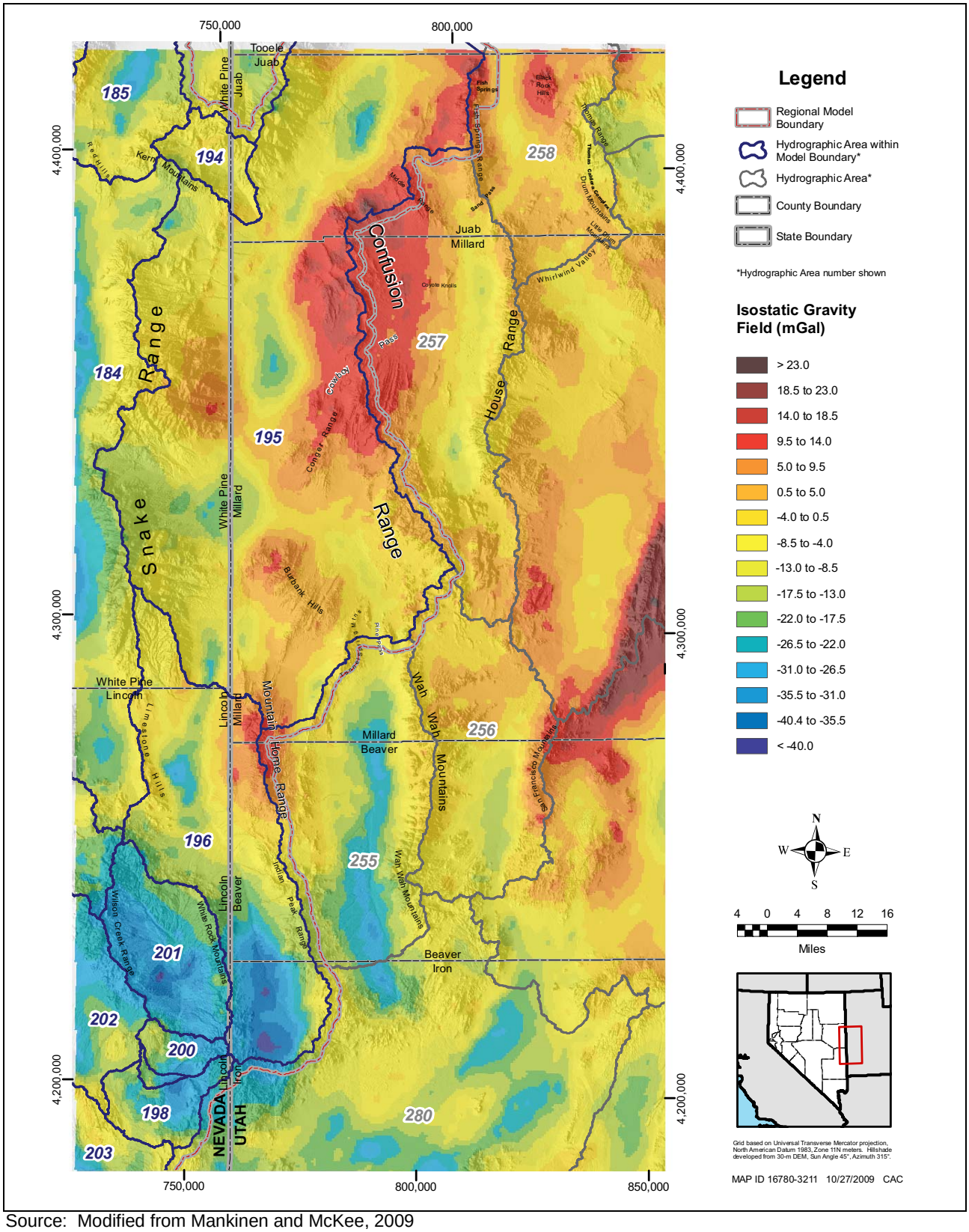
Recent photogeologic interpretations and limited field work (Page et al., 2005; Scheirer et al., 2006; Scheirer and Andreasen, 2008) have provided insight into the hydrogeology of the southern part of the area. Based on this work, selected structural features were reinterpreted as significant to groundwater flow in the southern part of the study area. These features consist of middle Miocene to Holocene basin-range faults of north, east, and northwest trends. These faults are interpreted to be connected and to form a path for groundwater flow from southern Coyote Spring Valley to the Muddy River Springs Area and eventually to Lake Mead. These faults are also interpreted to have hydraulic conductivities large enough to move groundwater through this area as evidenced by the spring and stream flow in the Muddy River Springs Area. These faults constitute a structural zone from Coyote Spring Valley to Lake Mead (Scheirer and Andreasen, 2008). These faults were directly added to the simplified hydrogeologic model that is discussed in Sections 4.3 and 4.4.

4.3 Construction of Simplified Hydrogeologic Framework Model

The simplified hydrogeologic framework consists of simplified hydrogeologic units, also called RMUs, and a set of major structural features that are interpreted to directly affect groundwater flow. The simplification process consisted of grouping HGUs into RMUs based on their hydraulic properties and structural positions. The unit grouping was then applied to the surficial maps, the unit extent maps, and the cross sections. A closer evaluation and simplification of the structural features that may play a role in groundwater flow were also made.

The construction of the simplified RMU framework consisted of the following steps:

1. Simplification of HGUs into RMUs. The RMUs are the Upper Valley Fill (UVF), Lower Valley Fill (LVF), Cretaceous Plateau Sediments (Kps), Upper Aquitard (UA), Upper Carbonate (UC) and Lower Carbonate (LC), Basement Rocks (BASE), and Intrusive Rocks (PLUT). RMUs and HGUs, and their relationships to each other, are described in Table 4-1.



Source: Modified from Mankinen and McKee, 2009

Figure 4-1
Isostatic Gravity Field in Snake Valley and Vicinity

Table 4-1
Description of Hydrogeologic Units and Regional Modeling Units

RMU	RMU Description	HGU	HGU Description
UVF	Upper Valley Fill	QTb	Quaternary and Tertiary basalt - Quaternary and late Tertiary mafic volcanic rocks. Generally permeable but not hydrologically significant regionally because typically thin.
		QTs	Quaternary and Tertiary sediments - Includes sediments younger than the volcanic section but may include older sediments where volcanic rocks are minor or nonexistent. Also includes playa deposits. Generally moderate permeability but may be high where fractured, commonly a significant aquifer.
LVF	Lower Valley Fill	Tv	Tertiary volcanic rocks - Miocene to Eocene volcanic rocks. Good to moderate permeability, commonly a significant aquifer.
		Tos	Older Tertiary sediments - Primarily created for the cross sections; includes the older Tertiary alluvial and lacustrine section below the volcanic section. Of moderate permeability where fractured.
Kps	Cretaceous Plateau Sediments	KTRs	Cretaceous to Triassic siliciclastic rocks - Thicker where near the Colorado Plateau and generally of low permeability. More abundant in the southern part of the geologic study area. A confining unit of limited extent.
UC	Upper Carbonate Rocks	PIPc	Permian and Pennsylvanian carbonate rocks - Includes Ely Limestone, Bird Spring Formation, Park City Group, and other units. May include thin Triassic carbonate rocks in the Butte Mountains. Also includes Permian red beds, undifferentiated. A highly permeable aquifer.
UA	Upper Aquitard	Ms	Mississippian siliciclastic rocks - Includes Chainman Shale, Scotty Wash Quartzite, Diamond Peak Formation, and Eleana Formation. The Chainman Shale and Scotty Wash Quartzite are not differentiated in Lincoln County, except in the Egan and Schell Creek ranges. Where mapped, is considered a confining unit of low permeability.
LC	Lower Carbonate Rocks	MOc	Mississippian to Ordovician carbonate rocks - Joana Limestone (Monte Cristo Formation) to Pogonip Group, also includes thin Chainman Shale in most of Lincoln and Clark counties. The Pilot Shale, Eureka Quartzite, Guilmette Formation, Simonson Dolomite, Sevy Dolomite, and Laketown Dolomite are also included. A highly permeable aquifer.
		Ꞓc	Cambrian carbonate rocks - Includes the Bonanza King, Highland Peak, Lincoln Peak, and Pole Canyon formations. A highly permeable aquifer.
BASE	Basement	ꞒpꞒs	Cambrian and Precambrian siliciclastic rocks - Includes the Wood Canyon Formation, Prospect Mountain and Stirling quartzites, Chisholm Shale, Lyndon Limestone, and Pioche Shale. Generally impermeable except where fractured.
		pꞒm	Precambrian metamorphic rocks - Precambrian X, Y, and Z high-grade metamorphic rocks, generally Early Proterozoic. Also includes the Johnnie Formation in the south and the McCoy Creek and Trout Creek groups in the Schell Creek, Deep Creek, and Snake ranges. Impermeable except where fractured.
PLUT	Plutons	TJi	Tertiary to Jurassic intrusive rocks - Includes all plutons. Generally impermeable except where fractured.

Source: SNWA (2008a, Vol. 1)

The LC was further subdivided into three RMUs based on location and structural positioning within the framework. Those resulting RMUs are the LC1, LC2, and LC3. To account for the overthrown Kps unit bounding the LC at the Summit/Willow Tank Thrust fault, the Kps was subdivided into two RMUs, Kps1 and Kps2.

2. Simplification of a surficial hydrogeologic map into an RMU map (Plate 2).

3. Simplification of hydrogeologic cross sections into RMU cross sections (Plate 3).

4. Preparation of digital unit extent maps for each RMU using the surficial RMU map and the RMU cross sections. The interpretation of the unit extents were limited to a minimum thickness of 500 ft. The RMU extents were then digitized as polygons and inspected for errors. Corrections were made as necessary.

5. Development of structural contour maps for each RMU in which the contours represent the elevation of the top of the RMU. The contours were digitized as polylines and inspected for errors. With two exceptions, the structure contour maps for all RMUs were derived directly from the HGU framework. The two exceptions were the interpretations of the UVF and the surface elevations for the Kps1 (i.e., the upper unit of the Kps). The entire extent of the UVF and Kps1 units are exposed at the land surface. To ensure consistency with the land surface, the 30-m digital elevation model (DEM) was used in place of an interpretation of the land-surface elevations.

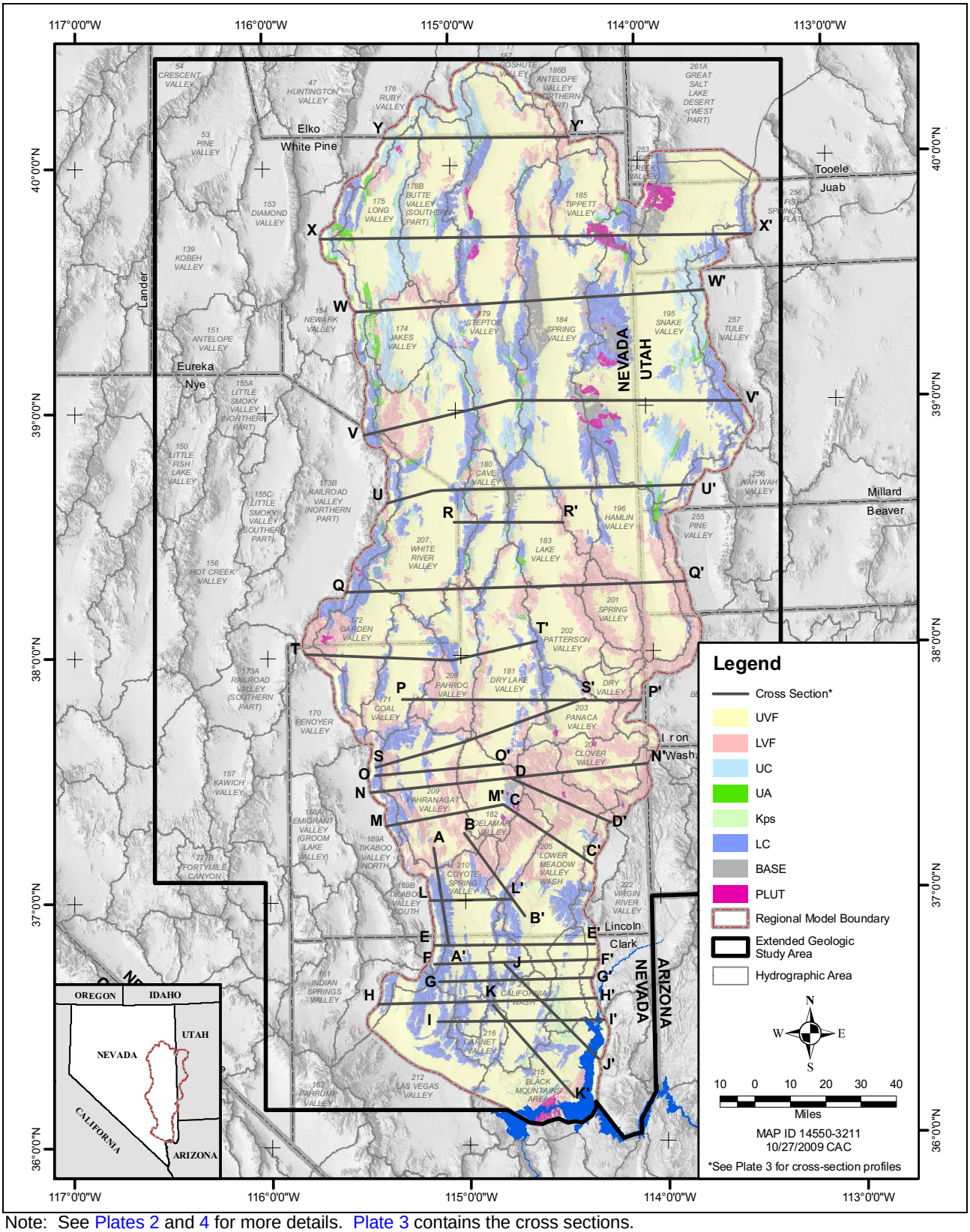
Major structural features included in the RMU model are those described in detail in the HGU model (SNWA, 2008b). They were not subjected to further simplification as were the HGUs. The only change is the addition of the structural features reinterpreted to form a conduit for groundwater flow from southern Coyote Spring Valley to the Muddy River Springs Area to Lake Mead (Section 4.2.3). A summary description is provided later in this section.

4.4 Description of Simplified Hydrogeologic Units (RMUs)

The resulting simplified hydrogeologic units, or RMUs, are described in this section. The descriptions are supported by a series of maps and cross sections. A surficial map of the RMUs showing the locations of the RMU cross sections is presented on Figure 4-2 and Plate 2. The RMU cross sections are presented in Plate 3. Maps of the extent and topography of all RMUs are presented on Figures B-1 through B-12 (Appendix B).

4.4.1 Upper Valley Fill (UVF)

The UVF RMU (Figure B-1) consists of basin-fill sediments and volcanic rocks of Miocene to Holocene age. The basin-fill sediments accumulated in down-faulted basins through erosion of the surrounding mountain ranges. Some of the minor sections of volcanic rocks deposited at the same time as the basin-fill sediments were combined with thick, interbedded, basin-fill sediments. Local thicknesses of the UVF can be more than 10,000 ft (SNWA, 2008a). The basin fill consists of boulders, gravels, cobbles, sands, silts, and clays. The UVF is considered a significant aquifer where



Note: See Plates 2 and 4 for more details. Plate 3 contains the cross sections.

Figure 4-2
Surficial RMU Map and Locations of Cross Sections

present in the region. Generally, the sediments forming this unit are unconsolidated near the surface but become both increasingly compressed at depth as the overburden pressure increases and semi-consolidated (partially indurated). The compression of the basin-fill sediments causes their horizontal hydraulic conductivity to decrease with depth (see Section 4.6). In addition, finer-grained sediments where present within this RMU may act as confining units or aquitards (SNWA, 2008a).

4.4.2 Lower Valley Fill (LVF)

The LVF RMU (Figure B-2) consists of discontinuous Tertiary and Cretaceous sediments as well as middle Tertiary volcanic rocks. These rocks are composed of conglomerates, sandstones, siltstones, nonwelded to densely welded ash-flow tuffs, ash-fall tuffs, and lava flows. The LVF RMU occurs throughout the study area in a discontinuous manner (Figure B-2) and may behave as an aquifer or an aquitard depending on the specific types of rocks present at that location.

4.4.3 Intrusive Rocks (PLUT)

The PLUT RMU consists entirely of intrusive rocks, including granodiorites, quartz monzonites, and granites. Throughout the study area, the PLUT RMU is found sporadically, with several large irregularly shaped bodies along the eastern edge of the area. The PLUT RMU is considered an aquitard where present, although water may be transmitted through fractures (Figure B-12).

4.4.4 Cretaceous Plateau Sediments (Kps)

The Kps RMU consists of Cretaceous to Triassic siliciclastic rocks, including sandstones, siltstones, shales, and limestones of the Aztec, Chinle, Moenkopi, and Kaibab Formations, and is primarily located on the Colorado Plateau. The Kps is present in the southern portion of the study area (Figures B-3 and B-4).

The Summit/Willow Tank thrust fault causes the Kps to be split by carbonate rocks along the trace of the fault (Figures B-3 and B-4). To accommodate this geometry in the numerical groundwater flow model, the Kps was divided into an upper unit—Kps1—and a lower unit—Kps2. The Kps1 is a small-unit extent that represents the hanging wall of the Summit/Willow Tank thrust. The extent was derived by outlining where the Kps was present at the surface of the North Muddy Mountains. In addition to the Kps2's representing the footwall of the Summit/Willow Tank thrust, it also depicts the remaining regional representation of the Kps outside of the Kps1 extent. The southern portion of the Kps1 extent is bounded by the Glendale thrust fault to the west and a concealed lateral fault at the west end of the Black Mountains to the east. The remaining edges of the extent were truncated by the margins of the study-area boundary. The northern portion of the Kps2 extent is a long narrow band stretching from the southeast end of the Meadow Valley Mountains to the south edge of the Caliente Caldera Complex. A considerably smaller third piece of the Kps2 extent covers the minor Kps south of the Mormon Mountains.

4.4.5 Upper Aquitard (UA)

The UA RMU (Figure B-5) consists of Mississippian siliciclastic rocks, including quartzites and shales of the Chainman Shale, Scotty Wash Quartzite, Diamond Peak Formation, Eleana Formation, and others. The UA is predominantly found in the northern portion of the study area (Figure B-5) and is considered an aquitard where present, as indicated by its name.

4.4.6 Upper Carbonate (UC) and Lower Carbonate (LC)

The LC and UC RMUs (Figures B-6 through B-9) consist of Cambrian to Pennsylvanian carbonate rocks, including limestones and dolomites with lesser amounts of shale, siltstone, sandstone, and quartzites. The LC is present throughout the study area, while the UC is predominantly present in the northern areas.

Overthrown blocks caused by major thrust faults disrupt the LC's regional continuity. Therefore, the LC was divided into three layers: LC1, LC2, and LC3. The LC1 primarily depicts the LC affected by thrust faulting bounded by the Kps1 and Kps2 RMUs. Two components make up the LC1: a southern portion, generally affected by the Glendale Thrust fault, and a northern portion, mostly affected by the Tule Springs thrust fault that eases the LC transition between the Delamar Mountain calderas and the Caliente Caldera Complex (Plate 3). The LC2 represents the LC present at the hanging wall of the Gass Peak thrust fault. For simplicity, the entire area west of the Gass Peak thrust fault was included as LC2. Moving north along the Gass Peak thrust fault, the LC discontinuity was reduced. This allowed for the northern margin of the LC2 extent to be stopped at the Pahranagat Shear Zone (Plate 3). The LC3 is the largest piece of LC that represents the footwalls of both the LC1 and the LC2 RMUs as well as the remaining lower carbonate not affected by thrust faults.

4.4.7 Basement Rocks (BASE)

The BASE RMU consists of Precambrian metamorphic and Precambrian and early Cambrian clastic rocks. This unit is considered a major aquitard throughout the study area. It is buried deeply in most areas and constitutes the basement of the flow system in those areas (Figures B-10 and B-11).

Much like the LC, overthrown blocks of basement rock are present at the Gass Peak thrust fault. The BASE unit was separated into a Base1 unit and a Base2 unit to account for the repeating units caused by the thrusting fault (Plate 2). Base1 represents the basement rock present at the hanging wall of the Gass Peak thrust fault. The extent of Base1 is very similar to the LC1 extent with the exception of an outcrop band of basement rock in the Las Vegas Range (Plate 2). Base2 predominantly represents the regional extent of the basement rock. However, it also represents the basement rock of the footwall at the Gass Peak thrust fault. The Base2 extent covers the entire model area with the exception of areas where intrusive rocks (PLUT) exist.

4.5 Identification of Significant Structural Features

Major structural features that play a significant role in groundwater flow are summarized here essentially as described for the HGU model in SNWA (2008a). The only exception is the reinterpretation of the faults in the southern part of the study area.

Major structural features in the study area were defined by identifying the fault structures and classifying them as "structurally significant" or "less structurally significant." Structurally significant faults include faults that are clearly basin-bounding faults, faults that cause large juxtaposition of geologic units (range-front faults), faults that exhibit a large disturbance due to HGUs, and structures that have large cross-fault impedance. Less structurally-significant faults include normal faults with only minor displacements, low-angle detachment faults, and faults not necessarily defined as basin-bounding faults. Major structural features of interest are shown in Plate 2.

Among the structurally-significant features in the study area are those faults that act as conduits or barriers and control movement of groundwater flow. Examples of major structurally-significant faults in the study area are normal basin and range faults bounding or defining range fronts; strike-slip lateral faults, such as the Pahranagat Shear Zone and the Kane Springs fault zone; caldera-bounding structures, such as the Caliente caldera complex, Indian Peak caldera, and the Fortification Range caldera; and thrust faults such as the Gass Peak and Glendale/Muddy Mountains thrust faults.

Strike-slip faults are defined as faults on which the movement is parallel to fault strike. These faults can act as either conduits or barriers to flow depending on the orientation of the fault with respect to hydraulic gradients. The Pahranagat Shear Zone (Plate 2) is an example of a left-lateral strike-slip fault zone. This fault defines the southern extent of Pahranagat Valley and probably serves as a transverse barrier to southward-moving groundwater flow through the valley. This fault zone, in part, may impede southward flow (barrier) but may also divert flow laterally (conduit) to the west-southwest along the northern side of the fault zone (Rowley and Dixon, 2004).

Calderas are the result of volcanic activity throughout much of the Tertiary period. Calderas are the source of thick sequences of ash-flow tuffs and lavas with variable permeabilities. The volcanic rocks, when densely welded, are moderately to highly permeable; bedded and nonwelded tuffs display low permeabilities. These low-permeability volcanic rocks act like dams to groundwater flow. Groundwater moves through the calderas by faults that post-date the calderas' conception. Six calderas are present in the study area: the White River Caldera; the Indian Peak Caldera Complex; the Caliente Caldera; the Narrow Canyon Caldera; the Boulder Canyon Caldera; and the Kane Springs Wash Caldera (Plate 2). The Indian Peak Caldera Complex is the largest caldera of the group and has at least four structurally-significant faults that run entirely through or just short of the caldera margin. These normal faults could provide conduits for north-south groundwater flow through the caldera (Dixon et al., 2007).

Compressive deformation events, primarily in the southern part of the study area, were a result of major thrust faulting. Blocks of older units faulted over younger units created large zones of disruption (gouge zones), and other fracture fillings formed along the thrust faults. These gouge zones may act as barriers to groundwater flow. However, with the inception of basin and range extensional faulting overprinting the thrust faults, many of the thrust faults' influences on

groundwater flow are diminished (Dixon et al., 2007). Structural stacking of part of the stratigraphic sequence by motion along the Gass Peak and Glendale/Muddy Mountains thrust faults required designation of separate hydrostratigraphic units for the formations present above and below these thrust faults as described by SNWA (2008a).

4.6 Description of Hydraulic Properties

Information on the hydraulic properties of the components of the framework model was used to support the development of the numerical groundwater flow model. Relevant information included delineation of natural zones with similar hydraulic properties, hydraulic property estimates, and hydraulic properties of major structures.

4.6.1 Natural Zonation Features

As described in SNWA (2008a, Volume 1), the hydrogeology of the study area and surrounding region is the result of three tectonic episodes and an intervening episode of extensive volcanism. Major aspects of the hydrogeology of the study area were incorporated into the hydrogeologic framework model. These included the spatial configuration of the hydrogeologic units and major structures as described in SNWA (2008a, Volume 1) and earlier in this section as part of the RMU model. However, other more detailed aspects of the hydrogeology of the study area were used to delineate natural zones of similar hydraulic properties in the numerical model, if needed during model calibration. These aspects consisted of alluvial deposition patterns in the UVF RMU and distinctive features created by the Basin-and-Range extensional-deformation episode and the volcanism episode, not accounted for in the RMU framework model.

4.6.1.1 Alluvial Deposition Patterns

The valley-fill sediments were mostly deposited by streams in closed basins with coarse-grained materials generally accumulating on the alluvial aprons and the finer materials accumulating near the center of the basins (SNWA, 2008a). Although the stratigraphy of the basin-fill sediments consists of intertonguing beds of all lithologies, the sediment deposition process created four areas of similar lithologies: playas, stream channels, alluvial fans, and valley bottoms. The boundaries of these natural zones were delineated using the following information:

- County geologic maps (Longwell et al., 1965; Tschanz and Pampeyan, 1970; Hose and Blake, 1976; Ekren et al., 1977; Kleinhampl and Ziony, 1985; Coats, 1987; Hintze and Davis, 2002a and b)
- A map of pluvial lakes (Mifflin and Wheat, 1979)
- Topography represented in the USGS DEM
- Landsat imagery

Playa deposits were identified primarily using the county geologic maps (Longwell et al., 1965; Tschanz and Pampeyan, 1970; Hose and Blake, 1976; Ekren et al., 1977; Kleinhampl and Ziony, 1985; Coats, 1987; Hintze and Davis, 2002a and b). Some of the county geologic maps, however, did not delineate playa deposits (e.g., White Pine County). As a result, a map of pluvial lakes (Mifflin and Wheat, 1979) and satellite imagery were used to supplement the county geologic maps to identify the playa deposits. The satellite maps were also used to delineate stream channel zones within the valley-fill sediments.

The boundaries of major stream channel deposits within the UVF were delineated using a combination of the groundwater ET extent map (based on satellite imagery) and the county geologic maps (Longwell et al., 1965; Tschanz and Pampeyan, 1970; Hose and Blake, 1976; Ekren et al., 1977; Kleinhampl and Ziony, 1985; Coats, 1987; Hintze and Davis, 2002a and b). A map of the National Hydrography Dataset was used to verify the locations of the identified stream channels (Simley and Carswell, 2009).

The lower boundaries of the alluvial fans were delineated from an analysis of the slope of the topography from the USGS DEM. The valley bottoms were defined as the UVF extent less the extents of the other three zones.

The delineated UVF zones are shown in Figure 4-3. The alluvial fans and stream deposits constitute the most permeable zones, and the playa deposits are the least permeable zones. The permeability of the valley bottoms is in between these two extremes. The delineated zones support the zonation of the UVF into more refined parameter zones used in the numerical model. The refined parameter zones can be used as necessary.

4.6.1.2 Basin-and-Range Extensional Deformation

The aspects of the Basin-and-Range extensional-deformation episode that can be used to delineate natural zones of hydraulic properties include the extension of the terrains that existed prior to this episode and the deep basins and mountain ranges produced during the episode.

Extensional Terrains

SNWA (2008a) described the Basin-and-Range extensional-deformation episode and explicitly incorporated the major hydrogeologic features it generated in the RMU model. These features consist of the RMU spatial distribution (extent and thickness) and major structural features, including significant faults. Other effects of this extensional episode, including smaller faults and numerous fractures, particularly in the carbonate aquifer, could not be explicitly incorporated in the framework model. However, these effects could be incorporated in the numerical model through the creation of zones of different hydraulic conductivities.

Dettinger and Schaefer (1996) have suggested that various areas of the carbonate-rock province have gone through lesser or greater degrees of extension. They describe these areas as follows:

> Regionally, in areas of extreme extension, carbonate rocks that elsewhere serve to connect and integrate flow in basin-fill and volcanic-rock aquifers have been

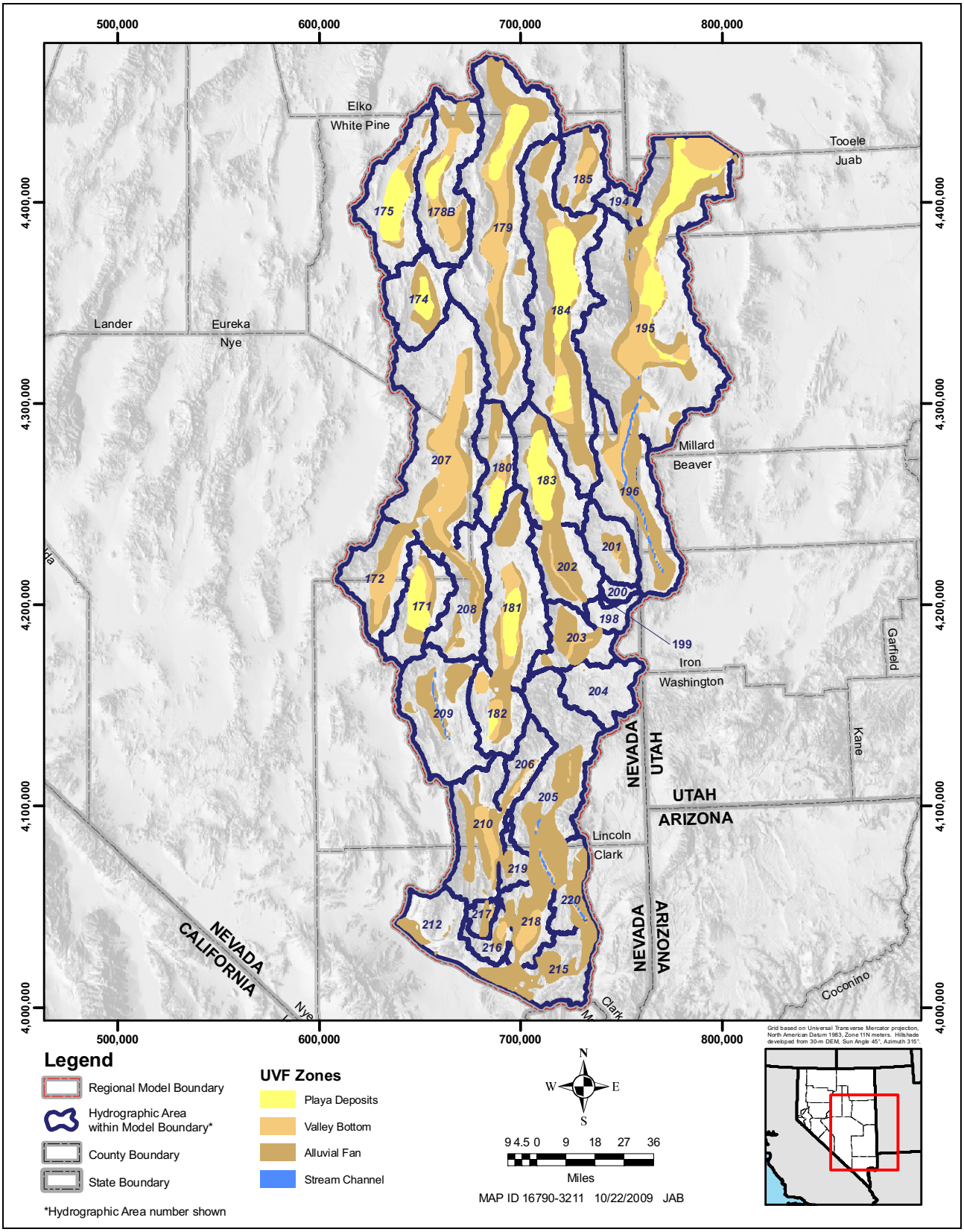


Figure 4-3
Main Alluvial Deposition in UVF Zones in Model Area

> themselves extended and removed. In areas of slight extension, carbonate rocks are thick, continuous aquifers that allow for broadly integrated flow.

Figure 4-4 shows areas of slight extension and extreme extension as interpreted by Dettinger and Schaefer (1996) within the study area. These authors further described the extended areas as follows:

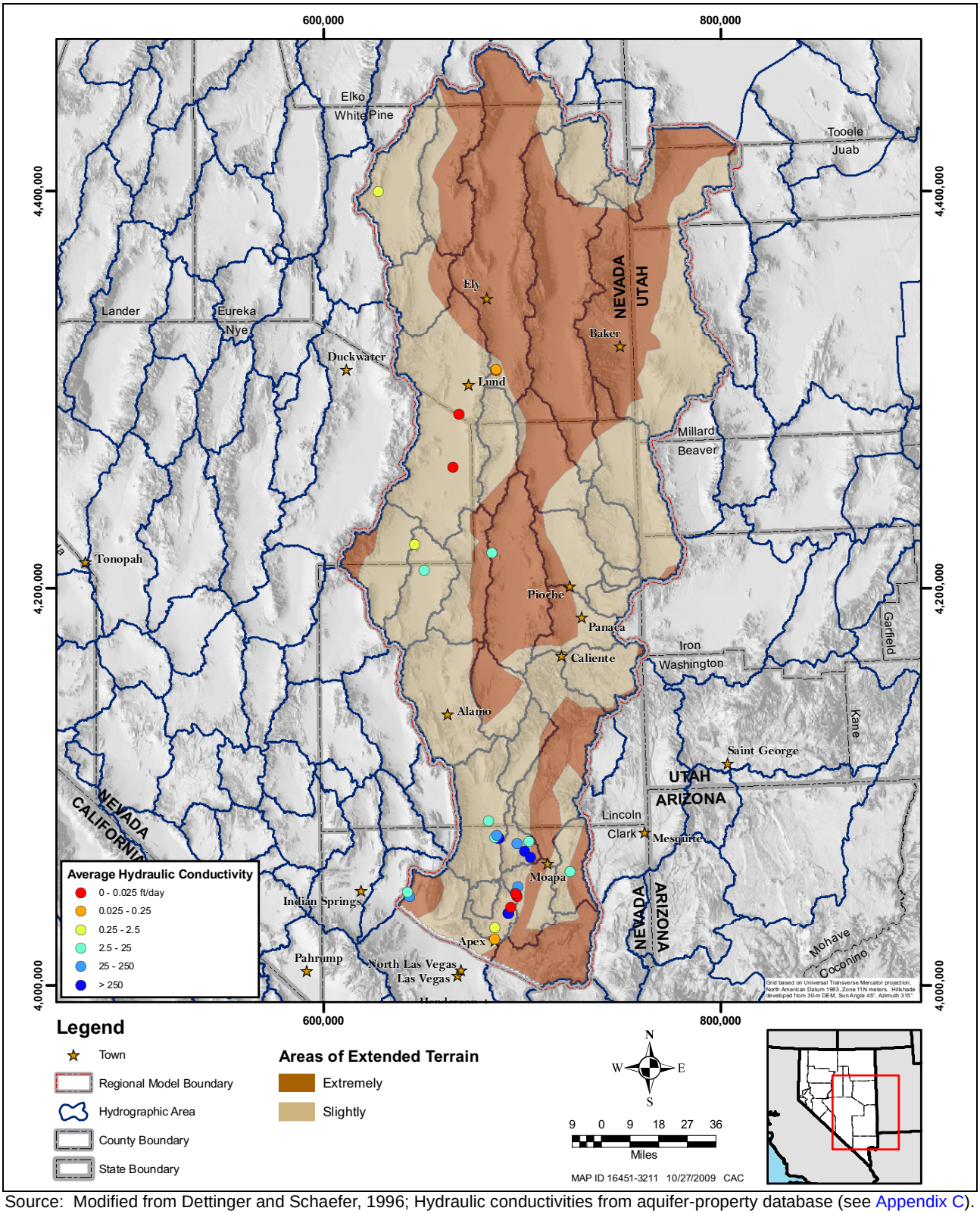
> Geologic descriptions of extensional remnants in the eastern Great Basin show numerous geographic parallels between structurally extended terrain and regional ground-water flow systems. In particular, some large areas of slight extension underlie major ground-water flow systems and may connect the upgradient, recharge-rich parts of the systems with their distal, discharge areas. Other areas of slight extension are not connected to recharge areas and contain only minor or local ground-water flow systems. Areas of extreme extension generally underlie single-basin flow systems that discharge from broad areas of basin fill.

Terrain extension stretches geologic units, thereby reducing their thicknesses and causing faults and fractures to form (hammer on glass effect [SNWA, 2008a]). Brittle geologic units, particularly carbonate rocks, are more susceptible to the effects of extension. Slight extension does not significantly reduce the thickness of the geologic units but enhances hydraulic conductivities by creating faults and fractures. This means that slightly extended carbonate rocks mostly retain their original thickness but have enhanced permeability. In areas of extreme extension, the carbonate aquifer is thin and perhaps absent. Volcanics rocks and valley fill may also be thin or absent in these areas, exposing the basement rocks. It is in these areas of extreme extension that detachment faulting occurs. Thus, areas of slight and extreme extension may be translated into corresponding zones of hydraulic conductivities as follows:

- Areas of slight extension correspond to sections of thick carbonate units with generally moderate large-scale hydraulic conductivities but large transmissivities due to the relatively unaltered original thicknesses of the carbonate aquifer. Note that hydraulic conductivities may still be very large along the strike of major faults.

- Areas of extreme extension correspond to sections of thin or absent carbonates units. Where carbonate units may still be present despite the stretching, they would be thin and highly fractured and therefore have large hydraulic conductivities but low transmissivities. In areas where they are absent, the basement rocks (BASE RMU) would have been exposed by the extreme extension of the carbonate aquifer.

The extended terrains delineated by Dettinger and Schaefer (1996) for the study area are shown in Figure 4-4. The available hydraulic-conductivity values derived from aquifer tests conducted in the carbonate aquifer are posted on this map in an attempt to support the zonation of the carbonate aquifer. Unfortunately, the available data are insufficient to draw a definite conclusion. Nonetheless, it was decided to incorporate these zones into the numerical model and use them during model calibration only if necessary. Incorporating these zones into the numerical model also allowed testing of the underlying assumption that hydraulic conductivities may be different depending on the degree of terrain extension.



Source: Modified from Dettinger and Schaefer, 1996; Hydraulic conductivities from aquifer-property database (see Appendix C).

Figure 4-4
Extended Terrain Areas in the Region and Available Conductivity Data for the LC and UC RMUs

The study area was subdivided into three separate zones of extensional terrain: two areas of slight extension and one area of extreme extension. The resulting three zones are as follows (Figure 4-4):

- Centralized area of extreme extension
- Eastern area of slight extension
- Western area of slight extension

Structural Basins, Mountain Blocks, and Normal Faults

Mountain blocks, structural basins, moderate-displacement faults, and large-displacement normal faults are delineated in Figure 4-5. The faults not only serve as delineating lines but also constitute separate zones of hydraulic properties.

In general, the least disturbed materials are the mountain blocks. The structural basin materials in which alluvial fill accumulated are more disturbed than the mountain blocks. The moderate- and large-displacement faults (normal faults) are the most disturbed materials and generally form conduits to groundwater flow north or south along the hydraulic gradient. High-angle oblique-slip and local strike-slip faults that formed as accommodation zones during the same extensional deformation episode are also important. Normal faults are interpreted to be zones of increased hydraulic conductivity along the strike of the normal faults if the fault is parallel to the direction of flow. In areas where the fault zones are perpendicular to the direction of groundwater flow, the amount of flow across the fault zone may be limited but not completely inhibited by gouge (SNWA, 2008a). Some faults may act as conduits in the north-south direction but may also act as barriers to east or west groundwater flow. In some cases, a series of faults may be linked together to form a pathway for groundwater flow. Such is the case for a series of faults located in the southern part of the study area discussed in Section 4.2.3.

Sufficient hydraulic-property data are not available to prove or disprove the variability of hydraulic conductivity of the bedrock units from mountain blocks to structural basins. Data documenting the hydraulic conductivities along and across the major faults are also practically nonexistent. The zones delineated based on mountain blocks, structural basins, moderate-displacement faults, and large-displacement normal faults were incorporated into the numerical model. The zones' hydraulic properties were varied during calibration, if needed, based on the logic described above.

4.6.1.3 Hydrothermally and Thermally Altered Areas

As described by SNWA (2008a), plutonic rocks (PLUT RMU) are exposed throughout the study area. During their emplacement, the plutons were hot bodies of material that may have both thermally and hydrothermally altered surrounding rocks (SNWA, 2008a), creating metamorphic rocks. These contact-metamorphic rocks constitute regions of decreased hydraulic conductivity. These alteration aureoles (or halos) could extend to significant distances around the plutons. The size of the aureole depends primarily on the size of the pluton and probably increases with its size. This alteration is expected to affect all the RMUs except the UVF. Figure 4-6 illustrates the hydrothermally and thermally altered areas assumed to extend 1.2 mi (1.9 km) laterally around plutonic intrusions that are more than 3,281 ft (1 km) thick.

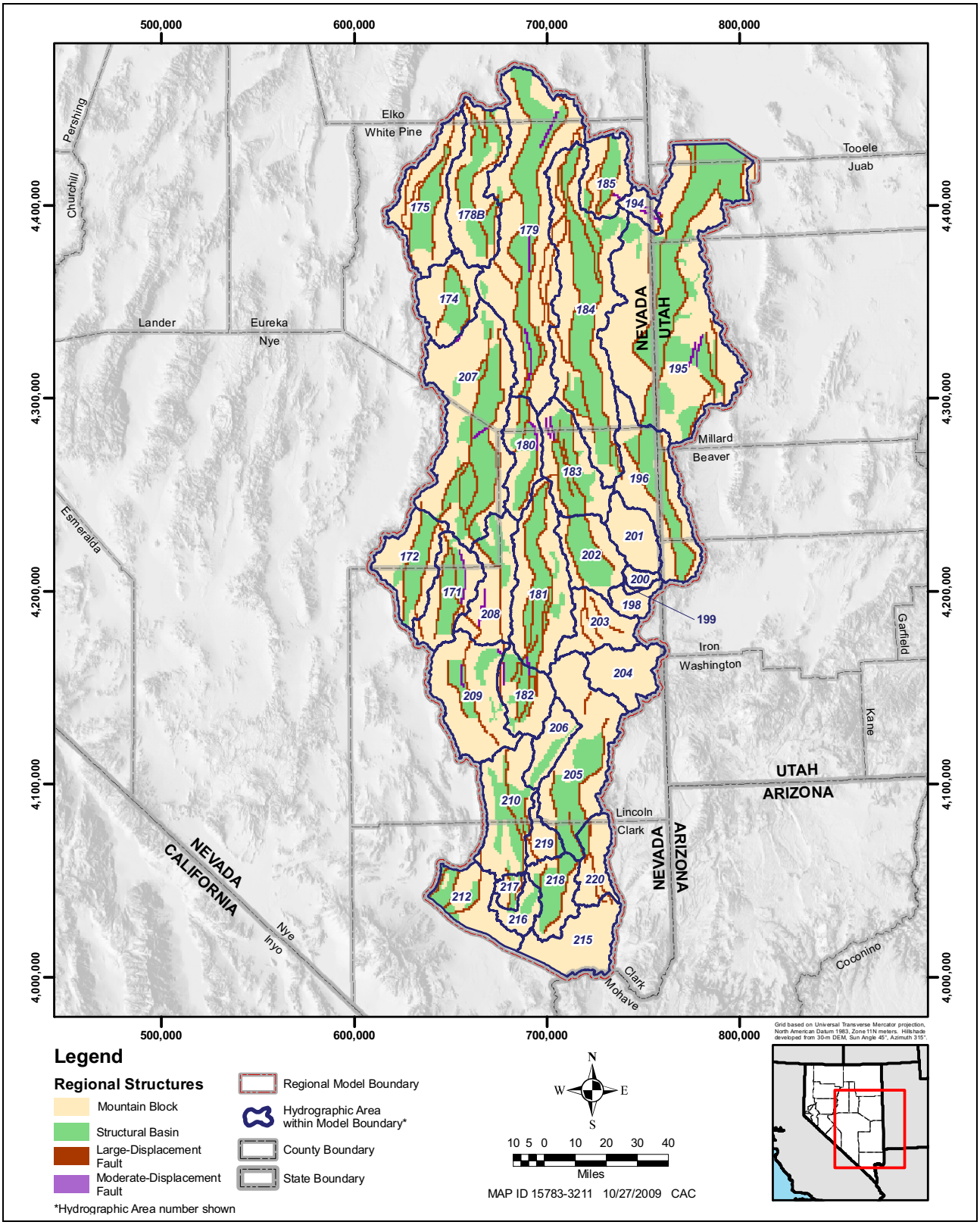


Figure 4-5
Mountain Blocks, Structural Basins, and Large- and Moderate-Displacement Normal Faults in the Study Area

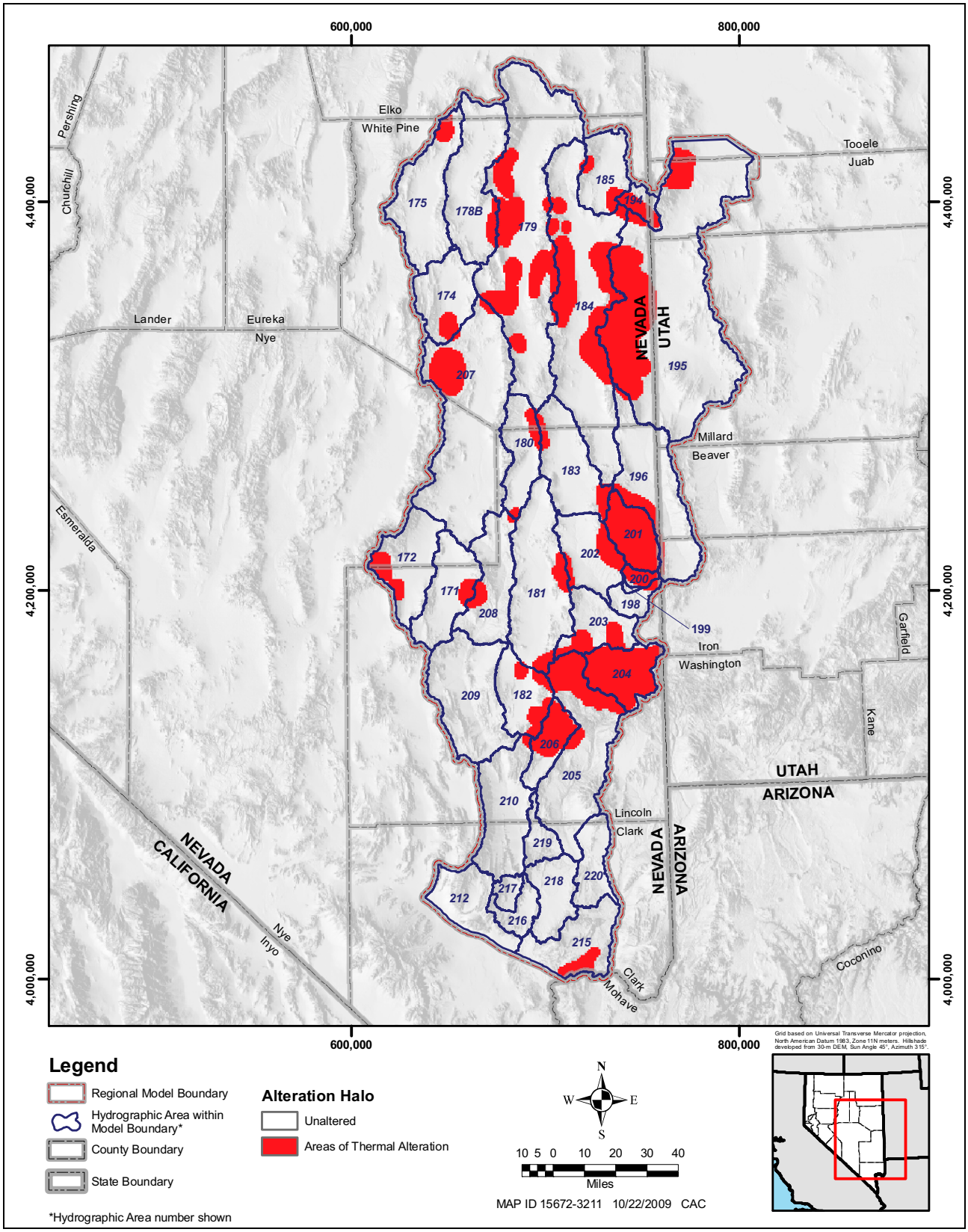


Figure 4-6
Thermally Altered PLUT RMU Areas in Study Area

4.6.2 Hydraulic Properties of RMUs

Hydraulic properties are important characteristics of an RMU, as they describe an RMU's ability to conduct and store water. Quantitative estimates of these properties are particularly important when a conceptual flow model is developed to form the basis of a numerical model. In numerical models, mean values derived from the statistical analysis of data serve as initial estimates of hydraulic-property parameters. The ranges derived from the data are used to gage the reasonableness of the simulated aquifer-property values. Estimates of hydraulic-property estimates were derived from the available aquifer-property data for the CCRP model. The data and the analysis are described in detail in Appendix C. A summary is presented in this section.

Except for preliminary data derived from the aquifer tests conducted by SNWA, reported data derived from aquifer testing were compiled from many sources and combined into a single aquifer-property database. The database was then queried to extract data for the eight RMUs listed in Table 4-1. The data set was reduced to a first subset of records, each representing a single tested interval. This was accomplished by sorting the data set by well and by interval. If an interval of a well had multiple records, the records were reduced to a single record as described in Section C.1.3.6.2 (Appendix C). The reduced data set was then statistically analyzed by RMU and by test type to derive geometric means and 95 percent confidence intervals for hydraulic conductivity. The range in values provides a measure of the uncertainty associated with the mean values. The results for all test types are provided in Section C.1.3.6.2. Statistics of the Log_{10} hydraulic conductivity derived from the constant-rate aquifer tests for most RMUs are presented in Table 4-2. The corresponding geometric means and associated 95 percent confidence intervals are also presented in Table 4-2. Constant-rate aquifer tests provide the most representative estimates of hydraulic properties for the scale of the CCRP model. For some RMUs, the estimates were derived from other test types or the literature because of a lack of constant-rate test data.

Table 4-2
Summary of Horizontal Hydraulic Conductivities for Regional Modeling Units

RMU	Log_{10} Hydraulic Conductivity (ft/day)				Hydraulic Conductivity (ft/day)				Source
	Mean	STD	95 percent CI[a]		Geometric Mean	STD	95 percent CI		
			Lower	Upper			Lower	Upper	
UVF	1.07	1.15	-1.18	3.32	11.75	14.13	0.066	2,089	Constant-rate test data in Table C-1.
LVF	0.29	1.04	-1.75	2.33	1.95	10.96	0.018	214	Constant-rate test data in Table C-1.
PLUT	-1.5	1.39	-4.22	1.22	0.032	24.55	6.03E-05	17	All test data in Table C-1.
Kps	-2.2	0.85	-3.87	-0.53	0.006	7.079	1.35E-04	0.30	Drill-Stem test data in Table C-1.
UC	0.73	1.24	-1.7	3.16	5.37	17.38	0.020	1,445	Constant-rate test data in Table C-1.
UA	-1.24	1.52	-4.22	1.74	0.058	33.11	6.03E-05	55	Constant-rate test data in Table C-1.
LC	0.73	1.24	-1.7	3.16	5.37	17.38	0.020	1,445	Constant-rate test data in Table C-1.
BASE	---	---	-7.2	0.11	---	---	6.6E-08	1.3	Reported by Belcher et al. (2001).

[a]CI = Confidence interval estimated as mean ± 1.96 x STD

Hydraulic conductivity is known to decrease with depth as a result of overburden pressures that compress sediments, fractures, and faults. The reduced data set described in the previous paragraph was used to investigate the relationship of hydraulic conductivity with depth for the UVF, LVF, and LC RMUs. The base-10 logarithmic values of hydraulic conductivity were plotted against the midpoint of the open interval of a given well for each aquifer RMU. The graphs were then visually examined for trends. Data from the constant-rate aquifer tests displayed the most consistent trends and were used to derive estimates of depth-decay constants through linear regressions (Figures C-9, C-10, and C-11). The reduced, first subset of records was also used to extract and summarize the few values of vertical anisotropy that are available. Depth-decay coefficients and vertical anisotropy factors derived from the available data are provided in Table 4-3. Because the available data on the vertical anisotropy of hydraulic conductivity are few, the BLM Hydrology Technical Group recommended that a vertical anisotropy ratio within the range of 10 to 100 be used in the numerical model. This range is within the range vertical anisotropy of 2 to 100 reported by Walton (1988).

Table 4-3
Summary of Depth Decay Coefficients and Vertical Anisotropy Ratios for Aquifer RMUs

RMU	Depth Decay Coefficients[a] (1/ft)	Vertical Anisotropy Ratio[b]
UVF	0.0019	3–333
LVF	0.0005	0.5–40
UC/LC	0.0004	2–137

[a]Based on Figures C-9, C-10, and C-11
[b]Ratio of horizontal-to-vertical hydraulic conductivity

Estimates of storage properties were only needed for the aquifer RMUs, i.e., the UVF, LVF, and UC/LC RMUs. Representative estimates of these aquifer properties can only be obtained from time-drawdown data collected from observation wells in multiple-well, constant-rate aquifer tests. Such tests also provide estimates of transmissivity values at the largest scale obtainable from all aquifer test types included in the database. Thus, a second subset of records was derived from the first one by extracting records corresponding to multiple-well, constant-rate aquifer tests for only the three aquifer RMUs. Aquifer-storage data were then statistically reduced. Estimates of transmissivities were also statistically reduced from this data set. The results are summarized in Table 4-4. The transmissivity range derived for the carbonate aquifer is on the larger side because the few available aquifer tests were conducted in fault zones.

The preliminary estimates of hydraulic properties derived from the aquifer tests conducted by SNWA, as provided in Section C.1.4 as supplemental information, helped guide the numerical model calibration in the basins where these tests were performed. These estimates were, however, used with caution, as they are preliminary and may represent localized rocks or features. The available data are not sufficient to estimate hydraulic-property ranges for the natural zones described in Section 4.6.1.

Table 4-4
Ranges of Transmissivity, Specific Yield, and Specific Storage Values for Aquifer RMUs

RMU	Transmissivity (ft^2/d)	Specific Yield (1/ft)	Specific Storage
UVF	39–72,719	0.0004–0.2870	1.72E-07–3.38E-03
LVF	43–34,432	0.0020–0.0030	1.03E-07–3.44E-05
UC/LC	963–1,000,000	0.0012–0.0309	4.67E-07–1.24E-05

4.6.2.1 Data Scaling

The hydraulic conductivity of geologic formations is highly variable as evident from Table 4-2. A substantial range in hydraulic conductivity with significant standard deviations is observed within each RMU. The tables also show that there is a difference in estimates based upon the method of analysis. This difference may be related to the scale of the test or to spatial differences in the tested medium.

Hydraulic properties, such as hydraulic conductivity and transmissivity, are thought to be functions of the scale at which they are determined (Neuman, 1990). The scaling concept stems from the idea that increasing the volume of material tested increases the amount of heterogeneity of the aquifer system encountered. For example, a laboratory measurement from a core sample may not contain the fractures that may be present and observable with a multi-well aquifer test (Belcher et al., 2001). In contrast, Zlotnik et al. (2000) have concluded that the apparent difference in hydraulic-conductivity values from laboratory to field-scale tests may be the result of sampling bias instead of scale dependence. They point out that there are very few data where the different methods were applied to the same spatial domain and that aquifer properties are highly spatially variable.

Most, if not all, of the data in the aquifer-property database have different spatial domains. This difference in domains would make the determination of any scaling factor problematic. The issue of scaling of hydrologic properties is difficult and even more difficult when developing models of fractured media (National Academy of Sciences, 1996). However, modeling is, by its nature, an iterative process whereby a conceptual model is developed and tested within a numerical flow model. As additional data are acquired, the assumptions that were made in the conceptual model are evaluated, and revisions to both the conceptual and numerical models are made, if necessary (National Academy of Sciences, 1996). This iterative process may also influence subsequent decisions on the types and locations of data to be collected to improve the overall understanding of the flow systems.

4.6.3 Hydraulic Properties of Major Structural Features

Faults play an important role in hydrogeology in that they provide pathways for fluid flow (National Academy of Sciences, 1996). Faults and fractures are a major target for many economically-significant petroleum, geothermal, and water supply reservoirs as a result of their transmissive abilities. For groundwater research, perhaps the most useful studies specific to fracture flow were

those of Caine et al. (1996) and Sibson (1996) because they dealt primarily with the geology of fracture flow. For purposes of groundwater flow, Caine et al. (1996) broke faults into (1) a central core zone, which was generally of low permeability across it because of gouge and foliation in clay minerals formed along the axis of fault deformation, and (2) outer damage zones on each side of the core, which were likely to be of high permeability across and along them because they consist largely of joints and small faults that are generally parallel to the core zone. Both studies pointed out that the central core zones were in many places cut by synchronous or later faults and joints, so local flow was common across them. This heterogeneity in the composition of faults leads to heterogeneous hydraulic properties with faults that tend to retard flow across (perpendicular to) them and provide conduits to flow laterally along (parallel to) them. This heterogeneity has been described for Snake Valley by Kirby and Hurlow (2005).

Early hydrologic and geologic research, primarily by the USGS, on the role of faults with respect to groundwater flow resulted from Department of Energy (DOE)-funded studies on the NTS in order to trace movement of contaminated groundwater resulting from hundreds of above- and below-ground nuclear tests (Winograd and Thordarson, 1975; Laczniak et al., 1996; Leahy and Lyttle, 1998; Rowley and Dixon, 2006). These studies, which began in the 1950s, resulted in practical as opposed to academic research findings, and many were buried from the scientific community because they were published as limited-distribution USGS Open-File Reports, owing to the tight (yearly) deadlines required by DOE. The research led to the recognition of the Death Valley regional groundwater flow system (Harrill et al., 1988; Laczniak et al., 1996; Harrill and Prudic, 1998; D'Agnese et al., 2002; Belcher, 2004). In this flow system, recharge originated in the broad, high mountains of central Nevada, and the flow terminated at springs in Death Valley.

Among the early reports issued on the Death Valley Flow System (DVFS) was the early summary by Winograd and Thordarson (1975), who noted what had become general knowledge, that some major faults in the DVFS act as hydraulic barriers (groundwater dams) that compartmentalize the lower carbonate aquifer (LCA). One such barrier identified early is the east-northeast-trending Maynard Lake fault of the Pahranagat shear zone, at the southern end of Pahranagat Valley, where southward flow is dammed and deflected west-southwest along the fault (Eakin, 1966; Winograd and Thordarson, 1975; Ekren et al., 1977; Rowley, 1998; Rowley and Dixon, 2004; Johnson, 2007). Another example is the west-northwest-trending LVVSZ, which dammed southward flow sufficiently to create a water-level difference of 600 ft between two wells that are only 3 mi apart (Winograd and Thordarson, 1975; Prudic et al., 1995).

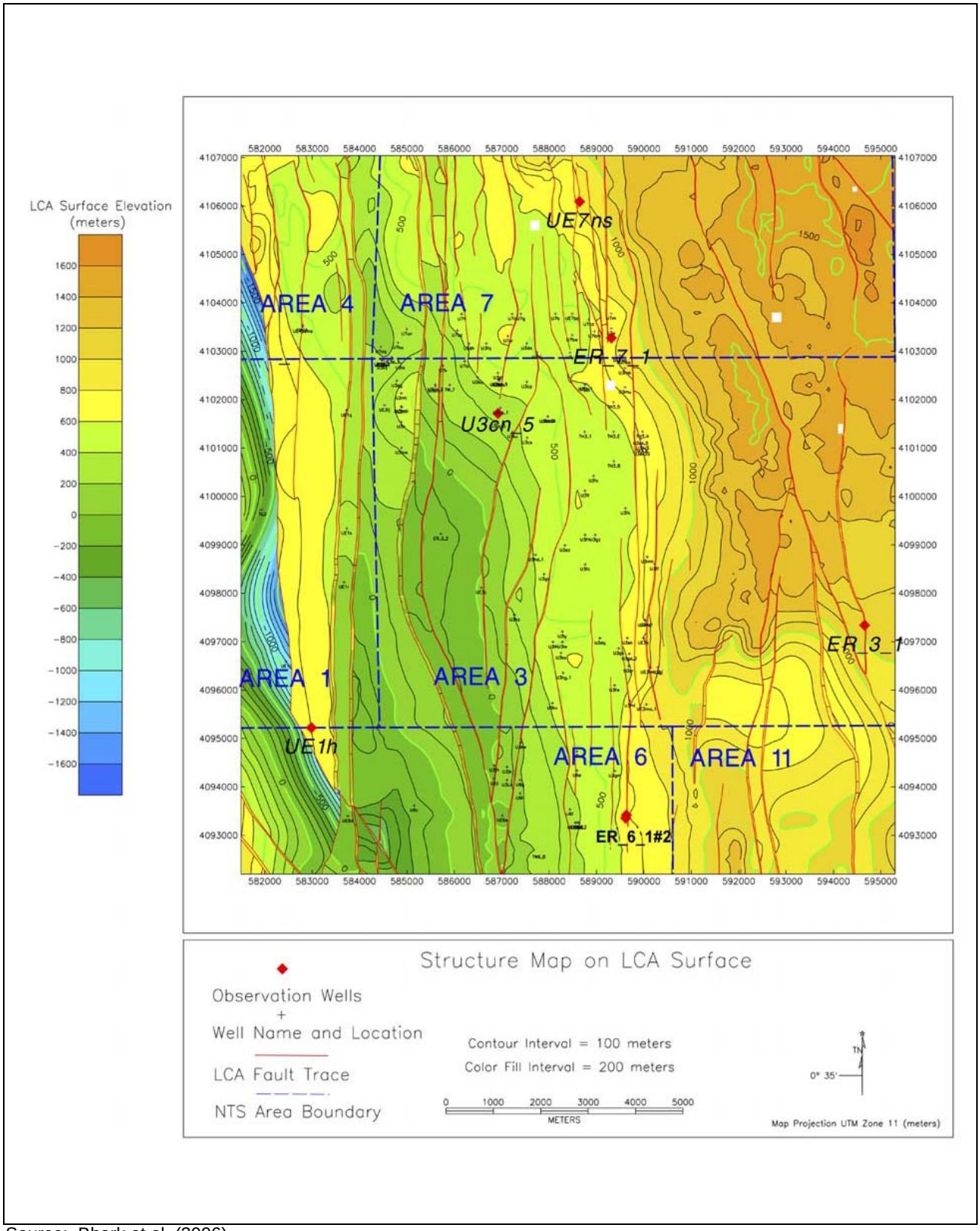
Research at the NTS also addressed lateral (horizontal) permeability along faults, in other words, conduit flow. Winograd and Thordarson (1975, p. C29) concluded from evidence from high yields in pump tests at the NTS and in the Eureka mining district of Nevada (Stuart, 1955) that "fault zones…are locally the principal water-bearing fractures in the lower carbonate aquifer." Highly permeable fracture zones in the NTS area were discussed in greater detail by Winograd and Thordarson (1975). Winograd and Thordarson (1975) and Dudley and Larson (1976) described pathways and springs that are along buried faults in the Ash Meadows area of the Amargosa Desert. Dettinger et al. (1995) suggested that some faults may act as conduits in the carbonate aquifer. Laczniak et al. (1996) summarized the literature of work at and near the NTS, including the role that high-angle faults had in directing the flow through, then south and southwest of the NTS. They detailed high groundwater yields in wells and high hydraulic conductivity along the Carpetbag-Yucca

fault zone in the early nuclear-test areas of Yucca Flat and Frenchman Flat in the eastern part of the NTS. Winograd and Pearson (1976) discussed "megachannels" along faults in the lower carbonate aquifer in Frenchman Flat. Winograd and Thordarson (1975, Table 15) proposed flow rates between 600 and 60,000 ft/yr between Frenchman Flat and Ash Meadows, the former rate presumably by porous-media flow and the latter rate presumably by fracture-dominated flow. Laczniak et al. (1996) summarized these data on the topics of barriers versus conduits along faults in the Yucca and Frenchman Flat areas. They also described more complex, more deeply buried, and more poorly known flow directed toward Oasis Valley from the later areas of underground nuclear tests at Pahute Mesa, in the northwestern NTS, that are assumed to be also along faults and fractures formed along north-trending faults.

Faunt (1997), in studying the DVFS, noted that faults in that region may be conduits or barriers to flow and that large interbasin groundwater movements must be a result of regional structures. In Faunt (1997), faults were categorized as being either preferential conduits or barriers to flow, depending on their stress field, with faults in relative tension being more likely conduits to flow while those in shear or compression are more likely to be barriers to flow. Winograd and Thordarson (1975) stated that flow through the matrix is much less than flow through the secondary openings in carbonate aquifers, with secondary openings such as fractures, faults, and solution channels or cavities. Dettinger et al. (1995) found that hydraulic tests conducted in the carbonate aquifers of southeastern Nevada indicate much larger transmissivities (25 times or more) when faults are present. In areas where the carbonate rocks have been subjected to different types of secondary processes, the transmissivities may be even larger.

Dettinger et al. (1995) indicate that the most open faults found on carbonate rock outcrops are high-angle normal faults (range-front and basin-and-range faults). These faults tend to be the most permeable because they contain somewhat less gouge than flat-lying normal faults or compressional faults. Range-bounding faults also constitute large structures in the carbonate rocks of the study area. Other types of faults have been observed to have a tendency to contain more gouge and are, therefore, most likely not as permeable. Such faults include thrust faults and strike-slip faults (Dettinger et al., 1995).

A local example of the effects faults have on fluid flow was demonstrated during the ER-6-1 multiple well aquifer test-tracer test conducted on the NTS in Yucca Flat. This test was performed to investigate groundwater flow through the LCA (Bhark et al., 2006). The aquifer test in well ER-6-1#2 began on April 24, 2004, and ran for 90 days at an average pumping rate of 523.8 gpm. Several wells, principally those completed in the lower carbonate aquifer, were used as observation wells during the test. The observation wells were located anywhere from a couple hundred feet to as much as 8 mi away from the production well and were located both along and across the north-south-trending faults within the region (Figure 4-7). Responses to pumping varied with each observation well, including a lack of response at the UE-1h well located west of the ER-6-1 site and across the Yucca and Topgallant Fault systems, a 10-day lag in response at the ER-3-1 well located northeast of the production well and across at least three major faults, and an almost immediate response at the ER-7-1 well located approximately 6 mi north of the production well (Figure 4-7). The results of the test showed that the north-south faults impact flow through the aquifer by acting as east-west barriers to flow and north-south high-permeability conduits (Bhark et al., 2006).



Source: Bhark et al. (2006)

Figure 4-7
Structural Features Impacting Groundwater Flow at the Nevada Test Site

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5.0 OCCURRENCE AND MOVEMENT OF GROUNDWATER

In addition to the hydrogeologic framework, potentiometric data and locations of the major recharge and discharge areas are necessary to identify the occurrence and movement of groundwater within the flow systems of the study area. The compilation and analysis of potentiometric data are documented in Volume 4 of SNWA (2008a). The processes used to delineate the recharge and discharge areas and estimate the associated volumes are described in Sections 7.0 and 9.0, respectively. Relevant features are shown in Plate 1.

5.1 Groundwater Occurrence

Groundwater is known to occur within all the defined RMUs depending on their locations and volumes within the hydrogeologic framework model. However, only the saturated portions of the most expansive RMUs are considered to form major aquifers and to be relevant at the scale of this regional study. These RMUs include the UVF, LVF, UC, and LC. Groundwater occurring in both the UVF and LVF is termed the "basin-fill" aquifer, and groundwater occurring in the UC and LC is termed the "carbonate" or "regional" aquifer.

Although the basin-fill aquifer is discontinuous through the study area, it constitutes a major source of groundwater. This aquifer generally occurs within the valleys, between the mountain ranges, forming a series of aquifers. These basin-fill aquifers may be locally confined or semiconfined, but overall they are considered to form a major unconfined aquifer over most of the study area. Observed depth-to-water levels in the basin-fill aquifers are included in SNWA (2008a). Depth-to-water varies from above the ground surface in the discharge areas of some valleys to hundreds of feet beneath the floors of other valleys.

The carbonate aquifer is present everywhere in the study area, except where interrupted by calderas, and occurs under both confined and unconfined conditions. It is unconfined in areas where carbonate rocks crop out to the surface. The carbonate aquifer is confined in areas where a confining unit separates it from the basin-fill aquifer, as it is in the southern part of the study area where the Kps is present. In the northern part of the study area, the UC is separated from the LC by a confining unit, the UA. The LC is, therefore, under confined conditions in this area. Mean observed depth-to-water measurements in the carbonate aquifer are reported in SNWA (2008a).

5.2 Groundwater Movement

Although the general flow patterns in flow systems of the Great Basin region are understood, the flow patterns within the flow systems of the study area are subject to interpretation because of sparse data.

5.2.1 General Groundwater Flow Patterns

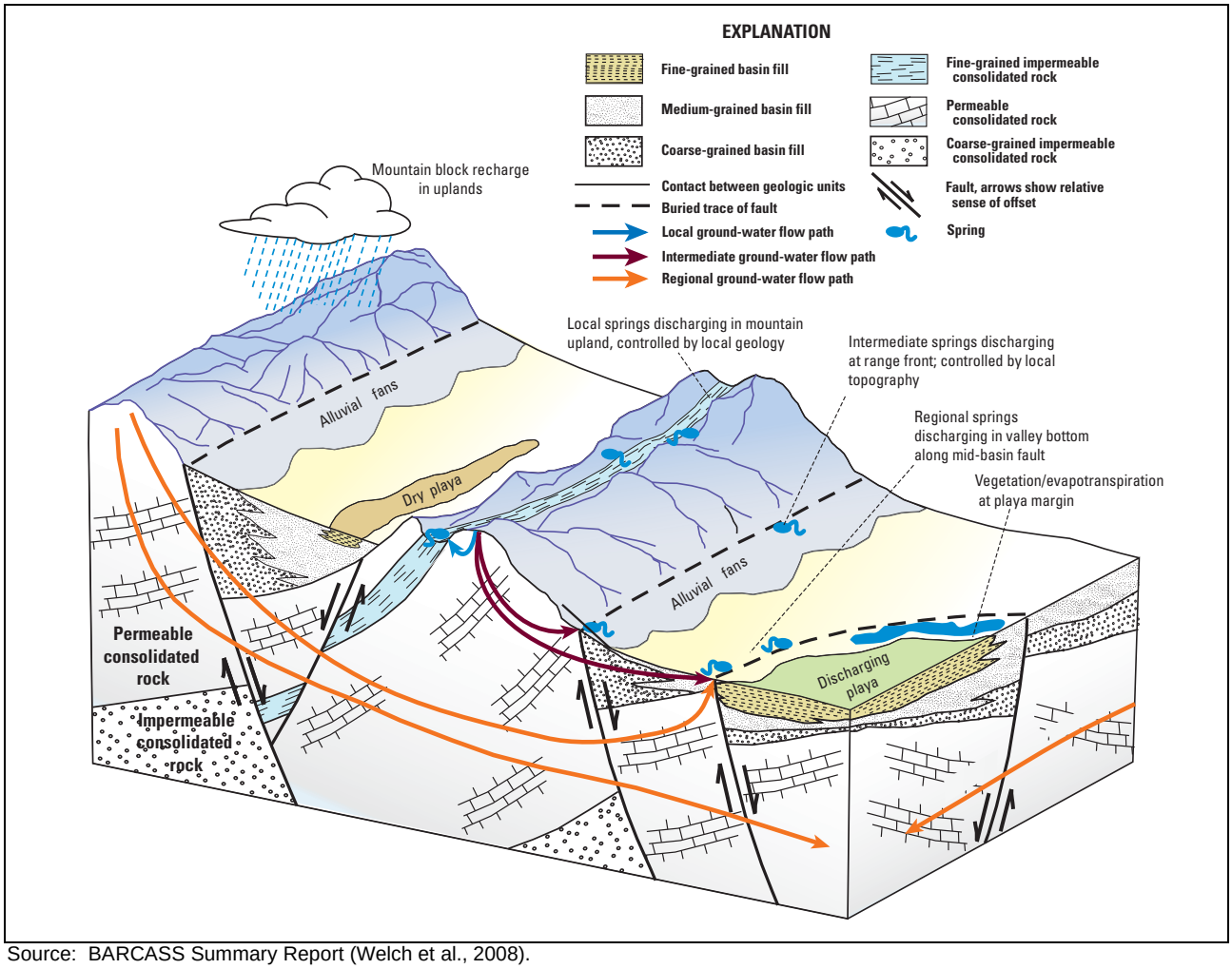
In general, a flow system can be subdivided into three subsystems as a function of their depth and the lengths of their flow paths. These are the so-called regional, intermediate, and local flow systems (Tóth, 1963; Freeze and Cherry, 1979) shown on Figure 5-1, as depicted by Welch et al. (2008). Welch et al. (2008, p. 38) describe the general flow patterns as follows:

> Local flow systems are characterized by relatively shallow and localized flow paths that terminate at upland springs. Local springs are low volume, tend to have temperatures similar to annual average ambient atmospheric conditions and have discharge that fluctuates according to the local precipitation. Intermediate flow systems include flow from upland recharge areas to discharge areas along the floor of the intermontane valley. Within intermediate-flow systems, springs typically discharge near the intersection of the alluvial fan and the valley floor near the range front. Intermediate-flow system springs often are of moderate volume and tend to have less-variable flow relative to local springs. Regional ground-water flow follows large-scale (tens to hundreds of miles) topographic gradients as water moves toward low altitudes in the region. Discharge from these regional flow systems manifests as large springs and, in some areas, extensive wetlands.

The maximum extent of a given regional flow system is defined by the longest flow paths between the most up-gradient recharge area and the most down-gradient discharge area. The flow system is usually named after this discharge area. The flow-system boundaries are usually selected to coincide with the hydrographic-area boundaries of the outer basins of the flow systems. The hydrographic-area boundaries coincide with the crests of the mountains, which provide most of the recharge to the flow system and typically form groundwater divides. A portion of the recharge from precipitation occurs in place on the mountain block. The remainder infiltrates through the beds of perennial and ephemeral streams located on the alluvial aprons from mountain-front runoff (Eakin, 1966; Frick, 1985). A portion of the recharge infiltrates in place within the mountain blocks, then moves through the subsurface to areas of lower groundwater potential located within the same basins (local and intermediate flow system) or other basins located down-gradient (regional flow systems). In some basins, this groundwater is forced to the surface by structural features in the form of large groundwater-discharge areas, which may include regional springs. Some of the recharge flows past the discharge areas and exits the basins via the subsurface. Water discharged from the regional springs exits the flow system through the process of ET in most basins. In some areas, however, spring discharge flows on the surface, and a portion of it exits the basins as stream discharge.

5.2.2 Groundwater Flow in Model Area

This section describes groundwater flow within the flow systems in the model area, including flow directions, flow system boundaries, and groundwater movement within each flow system.



Source: BARCASS Summary Report (Welch et al., 2008).

Figure 5-1
General Conceptual Model of Groundwater Flow

5.2.2.1 Regional Groundwater Flow Directions

The northern part of the study area is higher in topography and precipitation than the southern area (Plate 1). Thus, wet valleys are found in the northern area, and dry valleys in the southern area. The study area is located in the central part of the Basin and Range Province where the extensional block faulting has produced the characteristic linear, northward-trending ranges and the intervening closed basins. The tectonic history has imprinted the rock mass with joints, faults, and fractures. Rock masses comprising such features are generally more permeable to groundwater than the rock matrix. The general direction of groundwater in the study area is from areas of both high precipitation and high topography to areas of low precipitation and topography.

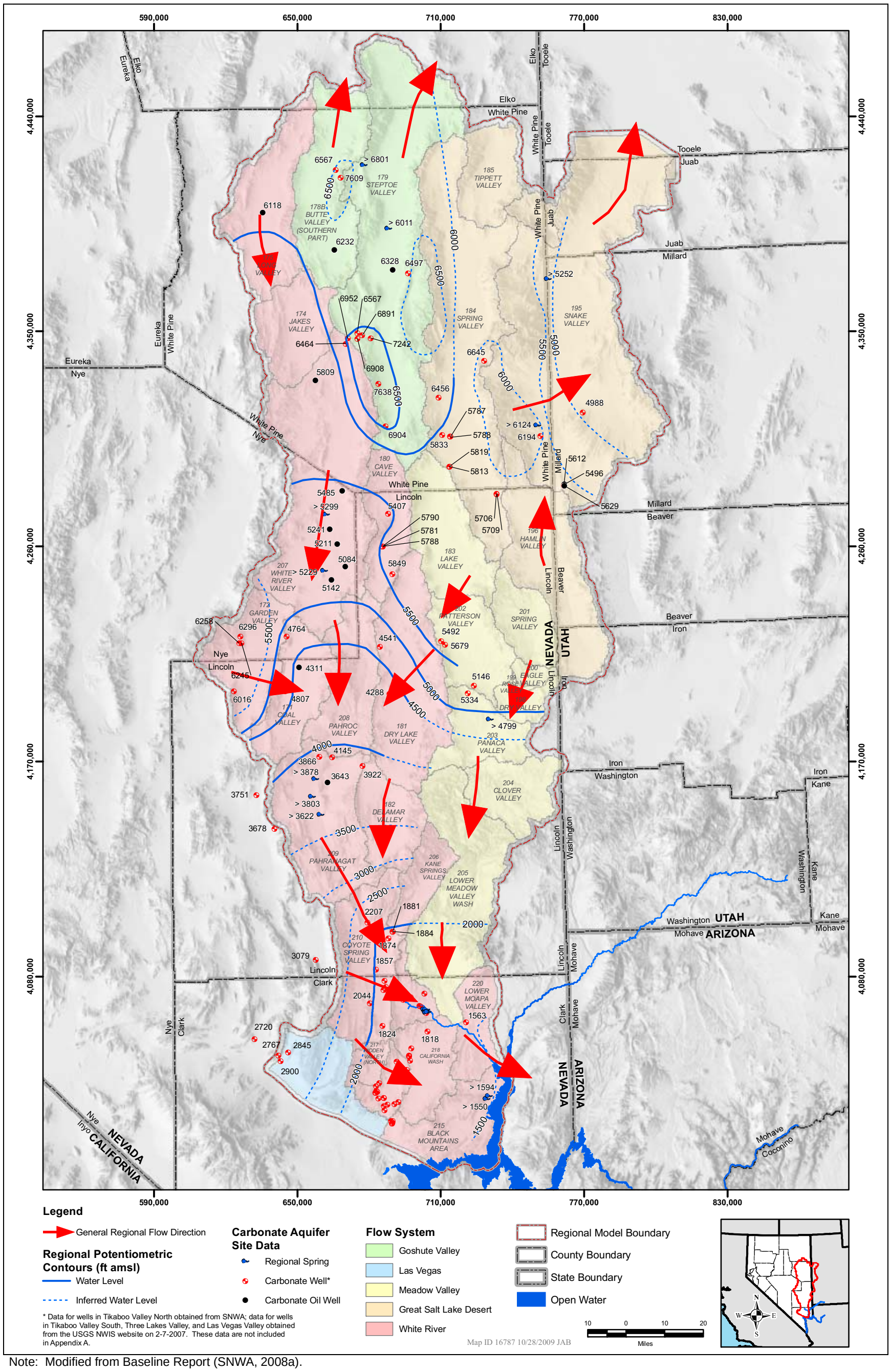
Although data are available from a large number of wells in the study area, most wells are shallow and clustered in the central parts of the valleys where the water table is generally closest to the land surface. The current understanding of flow directions and quantities is constrained by the limited spatial distribution of the wells within the flow domain. The groundwater flow directions within the

intermediate flow systems in the model area are interpreted to be from the mountains (zones of higher potential) to the bottoms of the valleys (zones of lower potential). Groundwater flow directions within the basin-fill aquifers were contoured from the water-level data available for wells completed in these aquifers. These maps may be found in Volume 4 of the Baseline Report (SNWA, 2008a). Groundwater flow directions within the deeper regional aquifer system are less obvious and subject to interpretation.

The available potentiometric data are insufficient to create detailed contour maps and identify definite regional flow directions. However, a simplified map of the potentiometric surface of the regional flow system was previously developed using a combination of the scarce available data, factors known to influence the potentiometric surface, and previous interpretations. This map was first presented in the Baseline Report (Figure E.1-1 in SNWA, 2008a). A modified version of that potentiometric map is presented in Figure 5-2. The available data used to develop this map (Figure 5-2) consisted of water-level elevations from 109 wells and 19 regional spring elevations. Factors influencing the potentiometric surface consist of geologic structures, topography, locations of recharge and discharge areas, and the extent of the carbonate-rock aquifer. Previous interpretations used to guide the construction of this map are those of Thomas et al. (1986), Prudic et al. (1995), Bedinger and Harrill (2004), and Wilson (2007). Due to the sparsity of the available point data, contour lines were hand-drawn at 500-ft intervals and were represented by dashed lines where uncertain or inferred. General regional flow directions have been depicted on this map by approximate arrows. Given the uncertainty associated with the regional potentiometric surface, the regional flow patterns cannot be identified with confidence in large portions of the model area (Figure 5-2). As a result, the boundaries of the flow systems are also uncertain and subject to interpretation.

5.2.2.2 Flow System Boundaries

The discussion of groundwater movement between and within the flow systems of the study area is supported by Plate 1, which depicts the five flow systems, their basins, and major groundwater features. Major features shown in Plate 1 consist of potential recharge areas (see Section 9.0), regional discharge areas including relevant springs and streams (see Section 7.0), and interbasin flow locations and directions (Section 8.0). Because of the sparsity of the available information, regional groundwater flow directions, and therefore, flow system boundaries, and interbasin flow are subject to interpretation. Thus, the initial configuration of interbasin flow used for this study (Section 8.0) was supplemented with previous interpretations. Major interpretations of interbasin flow locations and directions are shown on Plate 1 with arrows of different colors. These interpretations include those of Harrill et al. (1988) and Prudic et al. (1995) for the Great Basin; Belcher (2004) and San Juan et al. (2004) for the DVFS; SNWA (2007) for the WRFS; and Welch et al. (2008) for the BARCASS area (Plate 1). The interpretations contained in the Reconnaissance Series and those reported by Scott et al. (1971) are similar and have been incorporated and updated by Harrill et al. (1988) and were, therefore, not explicitly considered. More details about interpreted interbasin flow in the model area are provided in Section 5.2.2.2.2.



Note: Modified from Baseline Report (SNWA, 2008a).

Figure 5-2
Regional Potentiometric Map and General Regional Flow Directions

5.2.2.2.1 Interpretations of Flow System Extents

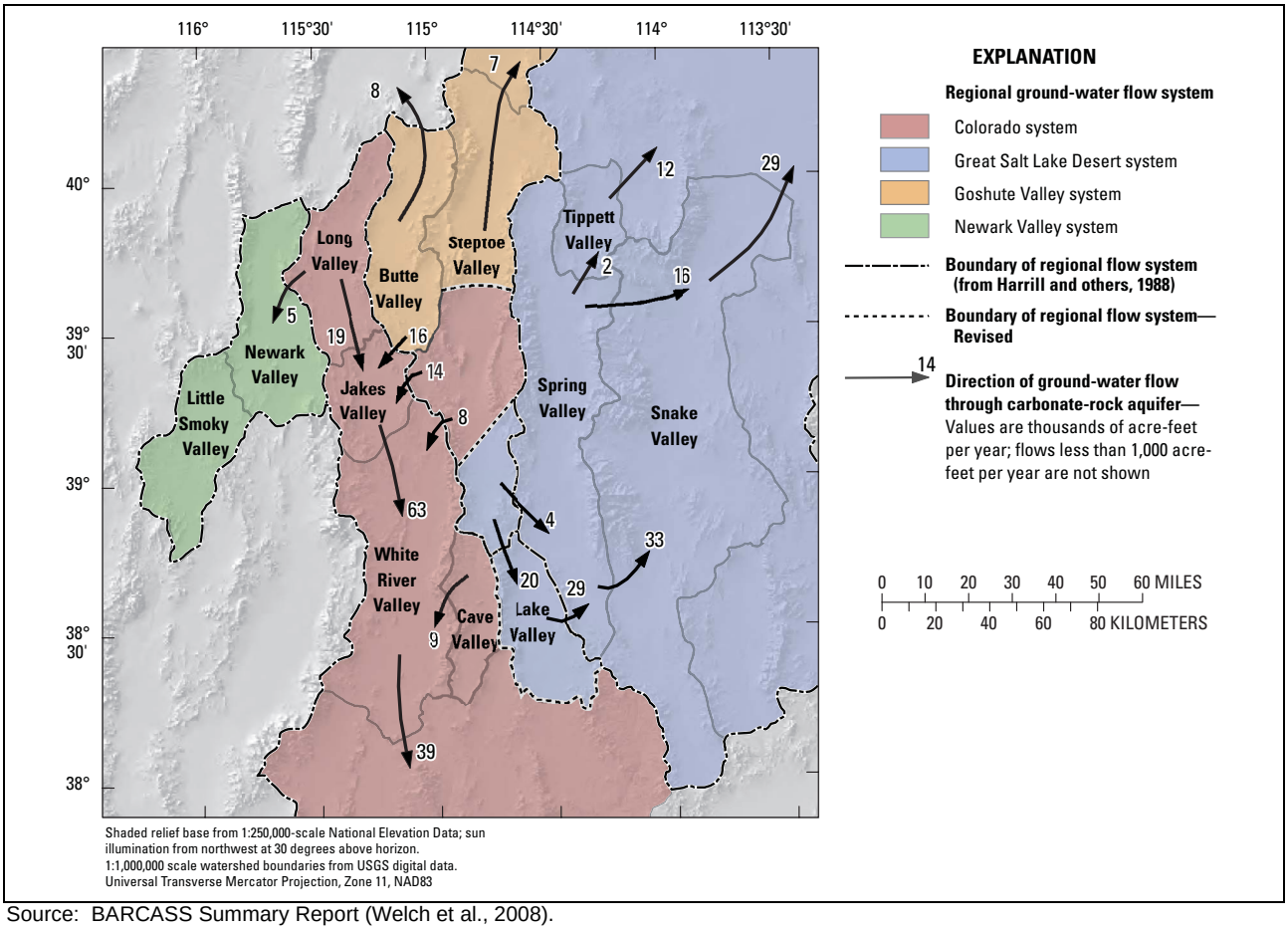
As stated in Section 2.5, several flow systems have been delineated within the study area and vicinity. The primary flow systems of interest to this Project are the Meadow Valley and White River flow systems and portions of the Goshute Valley, Great Salt Lake Desert, and Las Vegas flow systems as generally depicted by Harrill et al. (1988) (Figure 2-2). A few major interpretations exist for the entire study area or substantial portions of it (Harrill et al., 1988; Prudic et al., 1995; Welch et al., 2008). The available data do not prove or disprove any of these interpretations. Summaries of the three main interpretations are presented in this section.

Harrill et al. (1988) developed an atlas of the major groundwater flow systems of the Great Basin region as part of the RASA program. The purpose of their atlas was to synthesize the information available at that time into a map report to include a discussion of regional groundwater flow and the delineation and description of major flow systems. Harrill et al. (1988) used general concepts of groundwater flow at the regional scale and the available information as of 1984. Such information included reported hydraulic heads and estimates of water budgets and interbasin flow. Their interpretations, therefore, incorporate the findings and estimates reported in the Reconnaissance Series and summarized by Eakin (1966) for the WRFS and by Scott et al. (1971) for Nevada. They combined the WRFS and MVFS into a single flow system referred to as the Colorado System. Harrill et al. state that "the Colorado and Virgin rivers act as drains at terminus of system, but most discharge occurs upgradient at discharge points of major regional subsystems" (1988, Table 1, Sheet 1). The interbasin flow directions posted on their map are shown in Plate 1 of this report.

Prudic et al. (1995) developed a conceptualization of groundwater flow within the flow system of the Central Carbonate-Rock Province of the Great Basin region, using a numerical flow model based on the USGS code MODFLOW (McDonald and Harbaugh, 1988). The model is focused on Nevada and Utah and has two layers representing the deep regional aquifer and the shallow aquifers, using equivalent porous-media aquifer properties. Based on the potentiometric levels simulated by their numerical flow model, they identified the groundwater flow directions in the two model layers (Plate 1). They also subdivided the Central Carbonate-Rock Province into several regions, which were further subdivided into subregions. The subregions approximately correspond to flow systems as defined by previous investigators. Their boundaries do not correspond everywhere. For example, the White River subregion does not include Long and Jakes valleys, ends at the Muddy River Springs Area, and extends into the classic DVFS to the west and into the MVFS to the east. Prudic et al. (1995) stress that their interpretation is conceptual in nature. They state that "although a fairly detailed analysis of ground-water will be discussed, it does not intend to indicate that the study results presented here are adequate…"(Prudic et al., 1995, p. D-15). The concept of the WRFS has been a classic example of regional flow systems.

Another interpretation of the flow systems within the study area was the one put forth during BARCASS. The volume of recharge estimated for Steptoe Valley by Welch et al. (2008) as part of BARCASS was first estimated at 168,600 afy for the period of 1971 to 2004. It was then adjusted to 154,068 afy for the period of 1898 to 2006 to represent long-term mean conditions (Flint and Flint, 2007). This adjusted estimate was used in the groundwater-budget estimates. The difference between recharge and groundwater ET, about 53,000 afy, was routed to neighboring valleys through the subsurface (Figure 5-3). About 22,000 afy of groundwater was routed from Steptoe Valley to the

WRFS (Jakes and White River valleys). About 24,000 afy of groundwater was routed from Steptoe Valley to the GSLDFS (Lake and Spring valleys) (Figure 5-3). This led to a redefinition of the boundaries of the three flow systems by placing portions of Steptoe Valley in the WRFS and the GSLDFS. This interpretation was incorporated into the current analysis through the uncertainty analysis.



Source: BARCASS Summary Report (Welch et al., 2008).

Figure 5-3
BARCASS Interpretation of Flow Routing and System Boundaries

The flow systems delineated in the model area are approximately consistent with the interpretations of Harrill et al. (1988) (Figure 2-2). This interpretation of the flow systems is used here for illustration purposes and in Section 9.0 for purposes of deriving an initial estimate of the recharge distribution. However, because of the uncertainties associated with the available information, other interpretations of regional flow patterns, and therefore flow-system boundaries, are possible and were not dismissed in this study. They constitute alternate interpretations that were considered during the calibration of the numerical model.

5.2.2.2.2 Groundwater Movement by Flow System

Each of the flow systems in the study area is described with an emphasis on the available interpretations of interbasin flow. The discussion is supported by four maps showing the reported

ranges of interbasin flow (Figures 5-4 through 5-7) and a table summarizing and providing the sources of the flow ranges (Table 5-1). Arrows of opposite directions are shown on Plate 1 and in the four figures in cases where the interpretations conflict. The detailed list of reported interbasin flow annual volumes is provided in Appendix H. Findings of selected major studies are discussed in the subsections.

Goshute Valley Flow System

Most previous investigators, such as Harrill et al. (1988), define the GVFS to include Southern Butte, Goshute, and Steptoe valleys. A portion of this flow system, as defined by Harrill et al. (1988), consisting of Southern Butte and Steptoe valleys is included within the study area (Plate 1 and Figure 5-4). Even though SNWA does not have groundwater applications in the GVFS, baseline conditions have been established to evaluate potential future changes in the groundwater system.

To the northwest, the GVFS is bounded by the Butte Mountains along the western side of Southern Butte Valley. To the southwest, the GVFS is bounded by the Egan Range along the western side of Steptoe Valley. The Schell Creek Range forms most of the eastern boundary of the flow system along the eastern side of Steptoe Valley (Plate 1). A small portion of this boundary coincides with the Antelope Range and is shared with Antelope Valley located outside of the study area. The Egan and Schell Creek ranges meet at the southern end of Steptoe Valley and form the southern boundary of this flow system. To the north, Southern Butte Valley is open to Northern Butte Valley, and Steptoe Valley is open to Goshute Valley.

The Egan and Schell Creek ranges constitute important recharge areas and are interpreted to coincide with groundwater divides along their crests (Plate 1). The available water-level data (SNWA, 2008a, Volume 4) indicate the presence of groundwater at a high altitude on the Egan Range between Steptoe Valley and Jakes and White River valleys. The data may represent perched conditions but are indicative of recharge occurrence.

Groundwater discharge by the ET process occurs in the central part of Steptoe Valley (Plate 1). Groundwater ET in this area is primarily by phreatophytes. No surface-water outflow of groundwater origin occurs from this flow system. Groundwater discharge may also occur through the subsurface. Given that the largest mountain ranges are located in the southern part of this flow system, a large amount of recharge creates a groundwater divide separating the GVFS from the other flow systems.

Regional flow directions are generally depicted from south to north (Eakin et al., 1967; Frick, 1985; Harrill et al., 1988; and Nichols, 2000) (Figure 5-2). However, significant amounts of groundwater have also been interpreted to flow to the south (Welch et al., 2008) for example. The available potentiometric data are insufficient in this area to identify definite regional flow directions. Given the uncertainty associated with the potentiometric surface, the regional flow patterns cannot be identified with certainty, and the interbasin flow for this flow system is uncertain as well. Several interpretations exist (Plate 1) and are discussed in the following text.

In a report describing a numerical flow model of the valley-fill aquifer of Steptoe Valley, Frick (1985) identified the potential locations of groundwater flow out of Steptoe Valley. They are a narrow canyon north of Currie, Connors Pass, McGill, an area 7 mi north of Gallagher Gap, Smith Valley,

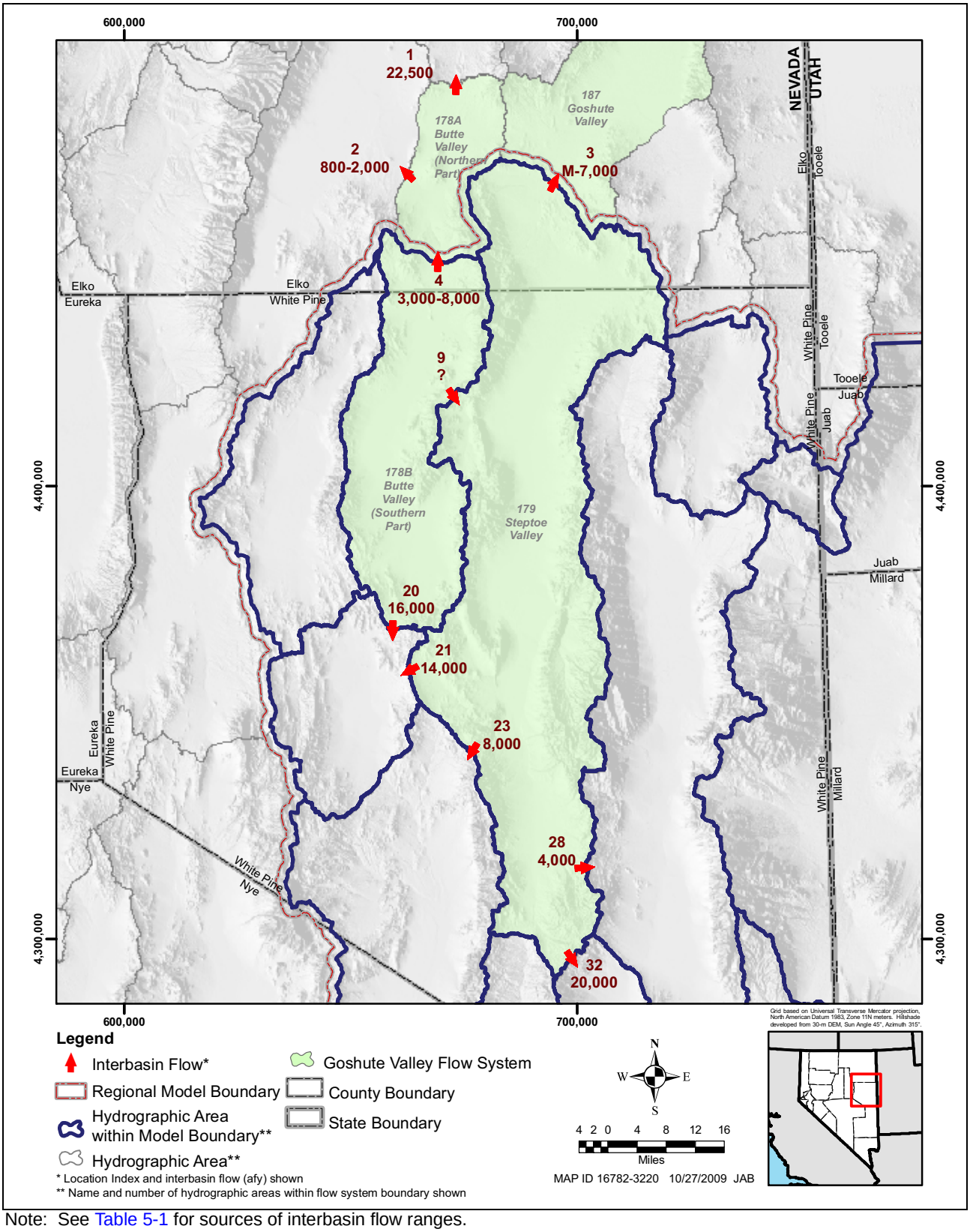
Table 5-1
Ranges of Reported Interbasin Flow Volumes
(Page 1 of 2)

Location Index[a]	Interbasin Flow (afy)[b]	Sources of Extreme Values
1	22,500	Nichols (2000)
2	800 to 2,000	Scott et al. (1971); Nichols (2000)
3	M to 7,000	Harrill et al. (1988); Welch et al. (2008)
4	3,000 to 8,000	Glancy (1968); Welch et al. (2008)
5	3,000	Harrill et al. (1988)
6	2,000 to 12,000	Harrill et al. (1988); Welch et al. (2008)
7	3,500 to 29,000	Carlton (1985); Welch et al. (2008)
8	1,000 to 8,500	Harrill et al. (1988); Carlton (1985)
9	?	Harrill et al. (1988)
10	? to 18,500	Harrill et al. (1988); Carlton (1985)
11	? to 12,700	Harrill et al. (1988); Prudic et al. (1995)
12	3,600	Nichols (2000)
13	3,000	Scott et al. (1971)
14	-2,000 to 2,000	Welch et al. (2008); Harrill (1971); Harrill et al. (1988)
15	6,000	Carlton (1985)
16	25,500 to 27,000	Carlton (1985); Harrill et al. (1988)
17	4,000 to 16,000	Nichols (2000); Welch et al. (2008)
18	?	Harrill et al. (1988)
19	8,000 to 19,000	Eakin (1961); Welch et al. (2008)
20	16,000	Welch et al. (2008)
21	14,000	Welch et al. (2008)
22	5,500 to 9,000	Carlton (1985); Harrill et al. (1988)
23	8,000	Welch et al. (2008)
24	? to 700	Harrill et al. (1988); Nichols (2000)
25	15,000 to 42,000	Hood and Rush (1965); Harrill et al. (1988)
26	16,527 to 63,000	Kirk and Campana (1990); Welch et al. (2008)
27	30,000	Scott et al. (1971)
28	4,000	Welch et al. (2008)
29	-4,250 to 4,000	Harrill et al. (1988); Carlton (1985)
30	4,250 to 26,500	Harrill et al. (1988); Carlton (1985)
31	-5,500 to 16,500	Harrill et al. (1988); Carlton (1985)
32	20,000	Welch et al. (2008)
33	5,500 to 30,000	Harrill et al. (1988); Carlton (1985)
34	4,000 to 11,180	Thomas and Mihevc (2007); Kirk and Campana (1990)
35	4,000 to 33,000	Rusk and Kazmi (1965); Welch et al. (2008)
36	29,000	Welch et al. (2008)
37	10,000	Scott et al. (1971)
38	14,000 to 15,000	Eakin (1966); LVVWD (2001)
39	3,000 to 17,000	Rusk and Eakin (1963); Thomas et al. (2001)
40	9,400 to 15,000	Thomas and Mihevc (2007); Thomas et al. (2001)
41	6,400 to 40,000	Thomas and Mihevc (2007); Scott et al. (1971)
42	1,500	Carlton (1985)
43	2,000	Thomas and Mihevc (2007)
44	M to 15,000	Scott et al. (1971); Thomas et al. (2001)

Table 5-1
Ranges of Reported Interbasin Flow Volumes
(Page 2 of 2)

Location Index[a]	Interbasin Flow (afy)[b]	Sources of Extreme Values
45	20,000 to 27,000	LVVWD (2001); Thomas and Mihevc (2007)
46	8,000 to 23,100	Eakin (1966); Thomas and Mihevc (2007)
47	0 to 16,000	Scott et al. (1971); Thomas et al. (2001)
48	9,000 to 28,000	Harrill et al. (1988); Thomas et al. (2001)
49	0 to 16,000	Scott et al. (1971); Thomas et al. (2001)
50	7,400 to 16,000	Thomas and Mihevc (2007); Thomas et al. (2001)
51	1,216 to 3,758	San Juan et al. (2004); Faunt et al. (2004)
52	10,000 to 20,000	Eakin (1963b); Thomas et al. (2001)
53	1,330 to 59,000	Kirk and Campana (1990); LVVWD (2001)
54	M to 36,000	Harrill et al. (1988); Thomas et al. (2001)
55	M to 9,000	Scott et al. (1971); Thomas et al. (2001)
56	5,000 to 17,700	Eakin (1966); Thomas and Mihevc (2007)
57	9,000 to 9,700	LVVWD (2001); Thomas and Mihevc (2007)
58	6,000	Eakin (1966)
59	811 to 11,307	San Juan et al. (2004); Faunt et al. (2004)
60	16,000 to 24,100	Thomas et al. (2001); Thomas and Mihevc (2007)
61	22,300 to 35,000	Thomas and Mihevc (2007); Eakin (1966)
62	S	Scott et al. (1971)
63	M to 6,000	Scott et al. (1971); Thomas et al. (2001)
64	? to 14,023	Harrill et al. (1988); Faunt et al. (2004)
65	2,400 to 13,000	Buqo (2002); Prudic et al. (1995)
66	28,000 to 37,700	Thomas et al. (1996); Eakin (1966); Thomas and Mihevc (2007)
67	32,000	LVVWD (2001); Thomas et al. (2001)
68	M to 41,804	Rush (1968b); Kirk and Campana (1990)
69	5,300 to 7,000	Thomas and Mihevc (2007); Rush (1968b)
70	M to 41,000	Rush (1968b); LVVWD (2001)
71, 73, 74	15,000 to 16,000	Thomas and Mihevc (2007); Thomas et al. (2001)
72	?	Harrill et al. (1988)
75	5,000	Harrill et al. (1988)
76	1,100 to 49,000[c]	Scott et al. (1971); LVVWD (2001)
77	?,M to 15,000	LVVWD (2001); Harrill et al. (1988); Thomas and Mihevc (2007)
78	? to 17,000	LVVWD (2001); Thomas et al. (2001)
79	M to 4,000	Scott et al. (1971); Thomas et al. (2001)
80	1,378	San Juan et al. (2004)
81	600 to 1,000	Thomas and Mihevc (2007); LVVWD (2001)
82	400 to 1,200	Rush (1968b); Harrill et al. (1988)
83	M to 2,000	Scott et al. (1971); Thomas et al. (2001)
84	4,000	Kirk and Campana (1990)

[a]Location of interbasin flow is shown on Figures 5-4 through 5-7 and Figure H-1.
[b]A positive value signifies flow in same direction as arrow, and a negative value signifies flow in the opposite direction.
[c]This value includes 1,000 afy outflow from Black Mountains Area to Lake Mead.
? = Flow volume not specified.
M = Minor quantity. An amount which is either less than 500 afy, or small in comparison to other quantities in the particular hydrologic area (Scott et al., 1971).
S = Some quantity. Sufficient information is not available to make an estimate (Scott et al., 1971).



Note: See Table 5-1 for sources of interbasin flow ranges.

Figure 5-4
Locations and Ranges of Interbasin Flow in Goshute Valley Flow System

and the southernmost boundary of Steptoe Valley. The canyon north of Currie is the only location on the boundary of Steptoe Valley where a topographic divide is not present (Plate 1). According to Spengler et al. (1979), plutons occur in the subsurface at this location. Spengler et al. (1979, p. 184) state that "the Currie pluton and Dolly Varden stock may be connected at depth despite observed contrasts of mineralogic and petrologic composition." This interpretation implies that groundwater outflow from Steptoe Valley through this location is probably restricted. Outflow simulated by the calibrated model through this location is 2,510 afy or 2.5 percent of the total simulated inflow to the valley-fill groundwater (Frick, 1985).

A positive hydraulic gradient to valleys adjacent to Steptoe Valley exists across the other potential locations of interbasin flow (Plate 1). However, the hydrogeological characteristics, especially the structural and stratigraphic orientations at these locations, are not favorable to interbasin flow (Frick, 1985). Specifically, dips of hydrostratigraphic units are in opposite directions to hydraulic gradients between Steptoe Valley and White River Valley, Connors Pass of Spring Valley, and the Duck Creek Valley area of Spring Valley (Frick, 1985). Frick (1985) explains this concept:

> Altitude of hydrostratigraphic units is important where the original stratigraphic units remain roughly parallel. If the hydrostratigraphic units dip in the same direction as the groundwater gradient, then the more transmissive layers, such as limestone and dolomite, may act as conduits for flow. However, if the hydrostratigraphic units dip in the opposite direction to the gradient, then the interbedded layers with low transmissivities are more likely to act as aquicludes or aquitards. Dips of hydrostratigraphic units are in opposite directions of groundwater gradients between Steptoe Valley and the following valleys: White River Valley, Connors Pass area of Spring Valley, Duck Creek Valley area of Spring Valley, and the northern part of Southern Butte Valley.

Thus, interbasin groundwater flow through these locations, if any, is probably insignificant. In addition, north-south-trending stratigraphic units and/or faults may impede or prevent interbasin flow between Steptoe Valley and White River, northern Spring, Northern Butte and the northern end of Southern Butte and Jakes valleys (Frick, 1985).

Prudic et al. (1995) included Steptoe Valley and Butte Valley South into their Spring-Steptoe subregion of the Bonneville Region and simulated 3,000 afy of outflow into the White River subregion of the Colorado River Region (Plate 1). In southern Steptoe Valley, simulated flow is westward from the Schell Creek Range and eastward from the Egan and Cherry Creek ranges (Plate 1) (Prudic et al., 1995). Simulated flow in Butte Valley is westward from the Egan and Cherry Creek ranges and eastward from Butte Mountains (Plate 1) (Prudic et al., 1995). Potential deeper groundwater flow from Butte Valley to Steptoe Valley was simulated beneath the Egan Range (Prudic et al., 1995). This potential interbasin flow is supported by limited geochemical evidence (Prudic et al., 1995).

Based on his independent estimates of groundwater recharge and ET, Nichols (2000) calculated an annual outflow volume of 4,000 afy from Steptoe Valley to Goshute Valley (Plate 1). He estimated a total of 24,500 afy of subsurface outflow from Butte Valley (Butte Valley North and South). This total outflow consists of 22,500 afy to Clover Valley and 2,000 afy to Ruby Valley (Plate 1).

In BARCASS, however, a significant amount of underflow is interpreted to flow from the GVFS to the WRFS and the GSLDFS (Welch et al., 2008). The three referenced flow systems are not as delineated by BARCASS; they are as delineated in Figure 2-2. Underflow to the WRFS is from Butte Valley South and the southern portion of Steptoe Valley to Jakes Valley and the northern portion of White River Valley (Plate 1). Underflow to the GSLDFS is from the southern portion of Steptoe Valley to Lake Valley to Spring Valley (Plate 1).

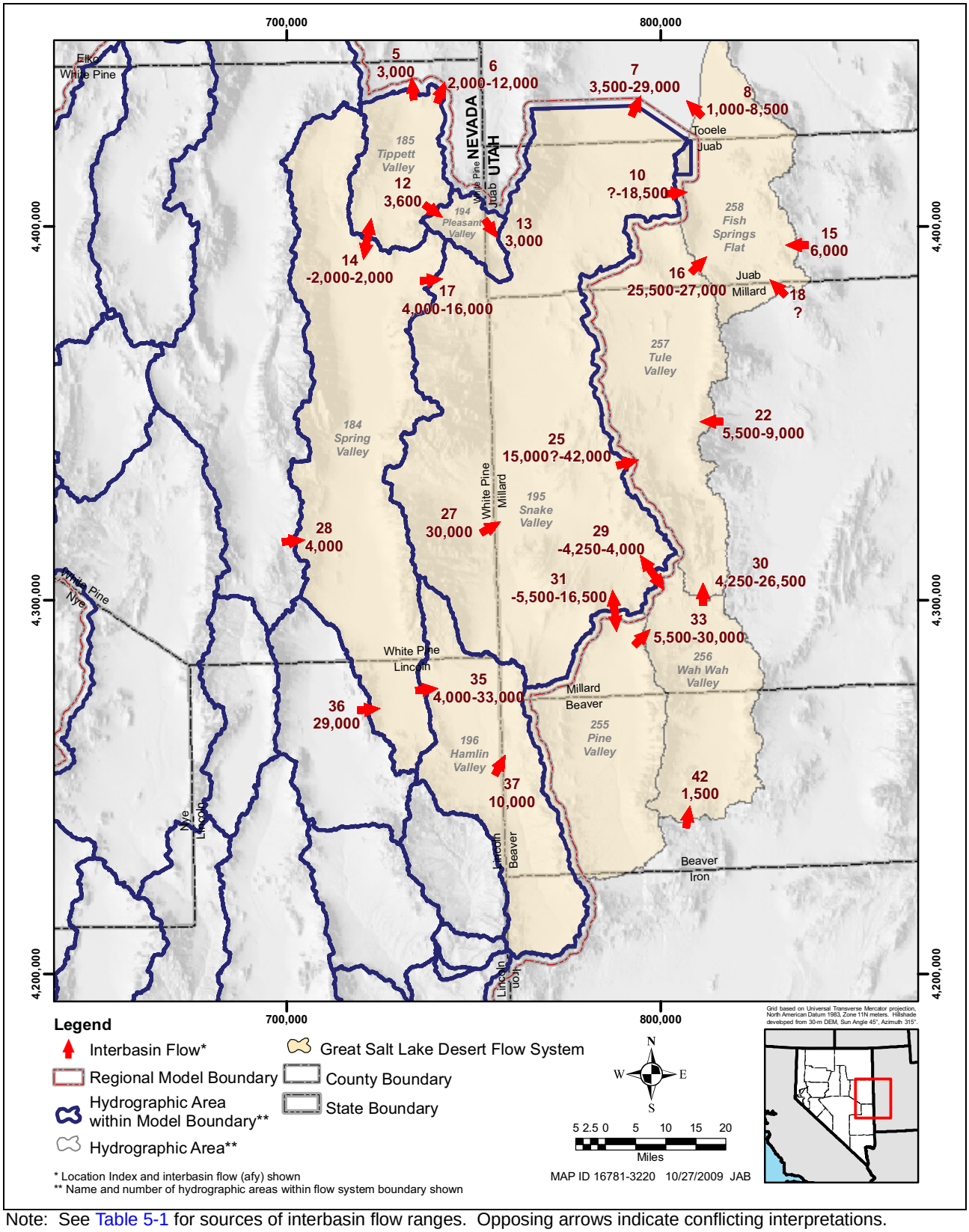
Great Salt Lake Desert Flow System

The part of the GSLDFS located in the study area includes Spring Valley, Tippett Valley, and Big Snake Valley (Pleasant, Snake, and Hamlin valleys), and a small portion of Fish Springs Flat comprising Fish Springs. Major features of the flow system, including interpretations of interbasin flow, are discussed (Plate 1 and Figure 5-5).

This part of the GSLDFS is bounded on the west by the Schell Creek and Fortification ranges; on the east by the Confusion Ranges, Middle Range, and Fish Springs Flat; and on the north by Deep Creek Range and a portion of the Antelope Range (Plate 1). Other major mountain ranges throughout the area are the Snake Range and Wilson Creek Range. No perennial streams connect any of the valleys, and the only interbasin ephemeral drainage is Hamlin Valley Wash that is tributary to Snake Valley. The small portion of Fish Springs Flat containing the springs is included in the study area. Fish Springs Flat encompasses about 590 mi^2 in Tooele, Juab, and Millard counties in Utah. The valley is bounded by the Fish Springs Range on the west, the Dugway and Thomas ranges and Drum Mountains on the east, the Little Drum Mountains on the southeast, and a low divide between Swasey Mountain and the Little Drum Mountains on the southern boundary. Fish Springs Flat opens to the Great Salt Lake Desert to the north (Bolke and Sumsion, 1978). Callao, Utah, is located approximately 25 mi to the west of Fish Springs, and Delta, Utah, is approximately 78 mi to the southeast. The Fish Springs NWR, which contains the springs of interest, was founded in 1959 and is located in the northwest corner of Fish Springs Flat (USFWS, 2004).

Groundwater recharge occurs in the mountains and discharges in two large ET areas primarily by phreatophytes on the valley floors in Spring and Snake valleys (Plate 1). No surface-water outflow of groundwater origin occurs from this flow system. Groundwater discharge may also occur through the subsurface primarily across the northern and the eastern boundary of the portion of the GSLDFS considered in this study. As will be discussed later in this section, groundwater discharge from Fish Springs is believed to originate from the portion of the GSLDFS east of the model area. Hamlin Valley is hydrologically connected to Snake Valley and is typically considered part of Snake Valley. A portion of this recharge flows through the subsurface to the east and northeast and exits the portion of the GSLDFS in the study area, most likely through the northern boundary of Snake Valley. A portion of the recharge to this flow system may exit the system from the eastern boundary of Snake Valley (Plate 1) towards Fish Springs Flat.

General regional flow directions are south to north (Figure 5-2). However, because of sparse information, the detailed configuration of groundwater flow and therefore interbasin flow within the flow system is not well understood and is subject to interpretation. Various interpretations exist and are summarized in the following text.



Note: See Table 5-1 for sources of interbasin flow ranges. Opposing arrows indicate conflicting interpretations.

Figure 5-5
Locations and Ranges of Interbasin Flow in Great Salt Lake Desert Flow System

Rush and Kazmi (1965) estimated that 4,000 afy of subsurface outflow occurs from Spring Valley to Hamlin Valley through the Snake Range. Scott et al. (1971) estimated that 2,000 afy of inflow to Spring Valley originates in Tippett Valley. This inflow was accepted and used by Scott et al. (1971) and by Harrill et al. (1988). This interpretation of flow routing was also used by SNWA in the Spring Valley water-rights hearing (SNWA, 2006).

In the RASA model, Prudic et al. (1995) included the GSLDFS, as delineated in this study, in the Bonneville region. Prudic et al. (1995) state that simulated flow in the basins of this flow system is primarily in the upper layer, from recharge areas in the mountains to discharge areas on the adjacent valley floors. About 78 percent of the total inflow is simulated through the upper layer (Prudic et al., 1995). Simulated flow in northern Spring Valley is eastward from the Schell Creek Range and westward from the Snake Range to the valley floor. In southern Spring Valley, groundwater is simulated to flow into Hamlin Valley through the Limestone Hills. In Snake Valley, most of the simulated flow is toward the Great Salt Lake Desert.

Nichols (2000) estimated recharge in excess of groundwater ET in Tippett and Spring valleys. He routed the excess water (9,600 afy) in Tippett Valley as outflow toward the north (Plate 1). Recharge from precipitation in Spring Valley was estimated to be about 104,000 afy, whereas groundwater ET was estimated at 90,000 afy. The difference of 14,000 afy may be the result of an underestimation of groundwater ET, an overestimation of recharge, or a combination of both. However, much of the excess recharge is believed to leave the valley as interbasin flow to the east. Nichols (2000) routed 4,000 afy through the southern end of Spring Valley to Hamlin Valley and the remaining 10,000 afy to Snake Valley through a topographic low between the northern end of the Snake Range and the Kern Mountains.

As part of BARCASS, Welch et al. (2008) derived a new flow-routing configuration for the GSLDFS (Plate 1 and Figure 5-3). They routed groundwater from Steptoe Valley and Lake Valley to Spring Valley. The total volume of this interbasin flow is 33,000 afy, which accounts for more than one-third of the recharge of Spring Valley. All outflow from Snake Valley was routed through the northern boundary of Snake Valley, even though a high-potential interbasin flow segment was placed on their geological map along the eastern boundary of the valley (Figure 5-3). Welch et al. (2008) also estimated 2,000 afy of groundwater to flow from Spring Valley to Tippett Valley. This interbasin flow volume is the same as the volume estimated by Scott et al. (1971). However, the flow direction is reversed (i.e., flow is from Tippett Valley to Spring Valley).

As part of BARCASS, Hershey et al. (2007) evaluated data on dissolved gases, stable isotopes, and tritium from 15 wells and springs located in the BARCASS area. Using these data, they derived estimates of recharge ages, recharge altitudes, and flowpath directions. Hershey et al. (2007) also identified the major flow paths using water-rock reaction models. The paths they identified are as follows: (1) from north to south in White River Valley; (2) from south to north in Steptoe Valley; (3) from the central part of Spring Valley northward and then to northern Snake Valley; (4) from the central part of the valley southward and then to southern Snake Valley; and (5) from south to north in Snake Valley. Groundwater ages were calculated using dissolved organic ^{14}C and dissolved inorganic ^{14}C for groundwater flowing across the following basin boundaries: between Lake and Spring valleys, between Steptoe and Spring valleys, and between Spring and Snake valleys. The calculated groundwater ages ranged from less than 1,000 years to 16,000 years.

Lundmark (2007) developed a steady-state, mass-balance groundwater-accounting model, using the discrete-state compartment code and the Monte Carlo method, to evaluate basin and regional water budgets for the BARCASS area. The model was used to calculate annual interbasin flow volumes based on the fluxes of a conservative tracer (deuterium), using the independent estimates of recharge and groundwater ET reported by Welch et al. (2008). The model results consist of deterministic estimates and a limited analysis (Monte Carlo) of the uncertainty in the predicted interbasin flow volumes resulting from the uncertainty in recharge characteristics.

Gillespie (2008) conducted an analysis of flow paths in the GSLDFS using water chemistry, stable isotopes, measurable tritium, ^{14}C activities, and geochemical models. He concluded that (1) interbasin flow from southern Spring Valley to southern Snake Valley cannot be confirmed or rejected and (2) interbasin flow from northern Spring Valley to northern Snake Valley is unlikely.

The Utah Geological Survey (UGS) (2008) published a provisional project map on its website (http://geology.utah.gov/esp/snake_valley_project/pdf/projectmap.pdf). In that map, the UGS posted the volume of interbasin flow reported by Welch et al. (2008). The location of that interbasin flow is, however, different from that used in BARCASS. The UGS used a location of interbasin flow similar to that depicted by Harrill et al. (1988).

Of particular interest in this portion of the GSLDFS are the springs located in Fish Springs Flat (Plate 1). Although the total discharge from Fish Springs is known (described above), the source of the spring flow is much larger than the estimated recharge within Fish Springs Flat. Most groundwater in Fish Springs Flat is in the eastern parts of the north-flowing GSLDFS. Some groundwater is derived from the Sevier Desert area (Wilberg, 1991), moving northward along basin-range fault zones into Fish Springs Flat (Bolke and Sumsion, 1978; Harrill et al., 1988) (Figure 5-5). Most groundwater discharging from Fish Springs is probably derived from Tule Valley. Some of the Tule Valley groundwater is probably derived from local precipitation, but most of the groundwater in Tule Valley is probably derived from the ranges to the south and passes northward along basin-range faults through Wah Wah Valley, Pine Valley, and the southeastern Snake Valley (Figure 5-5) (Harrill et al., 1988). A portion of this northward-moving groundwater may be deflected eastward (Stephens, 1977; Bolke and Sumsion, 1978; Gates and Kruer, 1981; Harrill et al., 1988), from Tule Valley to Fish Springs Flat. Findings of the major existing interpretations are summarized in the following text.

Bolke and Sumsion (1978) estimated a recharge from precipitation of 4,000 afy, a discharge by ET of 8,000 afy, a total spring discharge of 27,000 afy, and subsurface inflow to Fish Springs Flat of about 31,000 afy. Groundwater discharge by subsurface outflow is negligible. Bolke and Sumsion (1978) argued that the high local relief of the eastern Fish Springs Range may contribute some recharge from surface water to the area around Fish Springs, but most of the spring discharge is groundwater. They state that this groundwater is from subsurface inflow from other basins, such as Tule Valley, and imply that the other contributing basins may be Snake, Wah Wah, and Pine valleys located to the south and west of Fish Springs Flat. However, no allocated volumes of underflow were provided in their report.

Gates and Kruer (1981) presented a theory to explain the source of spring flow to Fish Springs. They used the various types of data available at the time to conclude that:

> Although available evidence indicates that interbasin flows occurs to and within west-central Utah and that it likely occurs through solution-enhanced fracture openings in carbonate rocks of Paleozoic age, the exact source area of all this water is not known. Water budgets of Fish Springs Flat, Tule Valley, and the southern Great Salt Lake Desert require that large quantities of water move to these basins by subsurface flow; and water levels in west-central Utah (pl. 2) show that ground water potentially could move eastward from Snake Valley and northward from Pine and Wah Wah Valleys to Tule Valley and Fish Springs Flat. (p. 34)

Carlton (1985) developed a numerical groundwater flow model for the flow system comprising Fish Springs Flat. The flow system comprises Fish Springs Flat, Pine, Tule, Snake, and Wah Wah valleys. He constructed the model using the data available at the time. The model simulated subsurface inflow from external sources as follows: 25,500 afy from Tule Valley; 6,000 afy from the Sevier Desert; and 18,500 afy from Snake Valley. Simulated subsurface outflow was 8,500 afy to the southern Great Salt Lake Desert. The simulated discharge from Fish Springs was 28,000 afy. As indicated by Carlton (1985), about 50 percent of the water discharged by Fish Springs originates in Snake Valley. These modeling results are uncertain as the model was based on limited data and reconnaissance studies.

In Sheet 2 of 2 of HA-694-C, Harrill et al. (1988) presented estimates of recharge by precipitation and underflow to Fish Springs Flat as follows: (1) recharge from precipitation of 4,000 afy; (2) subsurface outflow of less than 1,000 afy; (3) 27,000 afy of subsurface inflow from Tule Valley; and (4) unknown amounts from Snake Valley (through the Fish Springs Range) and Wah Wah Valley. An unknown portion of the underflow from Tule Valley originates from Snake Valley by underflow through the Confusion Range. The uncertainty in the flow routing within these basins is most probably the reason why Harrill et al. (1988) reported three potential values for the subsurface outflow from Snake Valley to Tule Valley through the Confusion Range: 22,000, 33,000, and 42,000 afy.

Bedinger et al. (1990) pointed out that hydraulic gradients in the carbonate rocks are very low, creating relatively long groundwater travel times from potential host rocks to natural discharge points, such as springs. They estimated these travel times to be on the order of 10,000 to 100,000 years, not including movement in the unsaturated zone of the host rock (Bedinger et al., 1990). The age reported for water from Fish Springs ranges between 9,000 to 21,000 years (Gates and Kruer, 1981; Carlton, 1985).

Based on the results of the RASA model, Prudic et al. (1995, p. D-84) state that "at least half of the simulated flow to Fish Springs Flat from Tule Valley originates in the Snake Valley drainage basin. Of the 23,000 afy simulated as entering Tule Valley in the lower Interbasin Flow layer, 14,000 is underflow from Snake Valley through the Confusion Range and 9,000 is from Wah Wah Valley."

In summary, although Harrill et al. (1988) queried possible eastward movement of groundwater through the northern Fish Springs Range, presumably along the east-striking faults or basal parts of the lower carbonate aquifer (Plates 2 and 4), no evidence exists to support such flow. The hills and ranges, including the Confusion Range, that form the western side of Tule Valley are, like the Fish Springs Range, underlain by the basement-confining zone, so it appears unlikely that substantial

groundwater is derived from west of Tule Valley. Furthermore, through-going easterly trending faults do not cut the Confusion Range (Plates 2 and 3). Thus, the source of groundwater flow to the springs must be from neighboring basins through the carbonate aquifer.

Meadow Valley Flow System

The MVFS is roughly parallel to the WRFS, starting in Lake Valley and ending as the Lower Meadow Valley Wash joins the Muddy River in Upper Moapa Valley. The MVFS (Plate 1 and Figure 5-6) is hydraulically connected to the WRFS in the south and is part of the Colorado River Region. A portion of the Muddy Springs discharge is believed to originate from the MVFS along Meadow Valley Wash.

The MVFS is bounded by the Schell Creek Range to the north; by the Fairview, Bristol, Highland, Chief, Burnt Spring ranges, and the Delamar and Meadow Valley mountains to the west; and by the Fortification and Wilson Creek ranges and the Clover and Mormon mountains to the east (Plate 1).

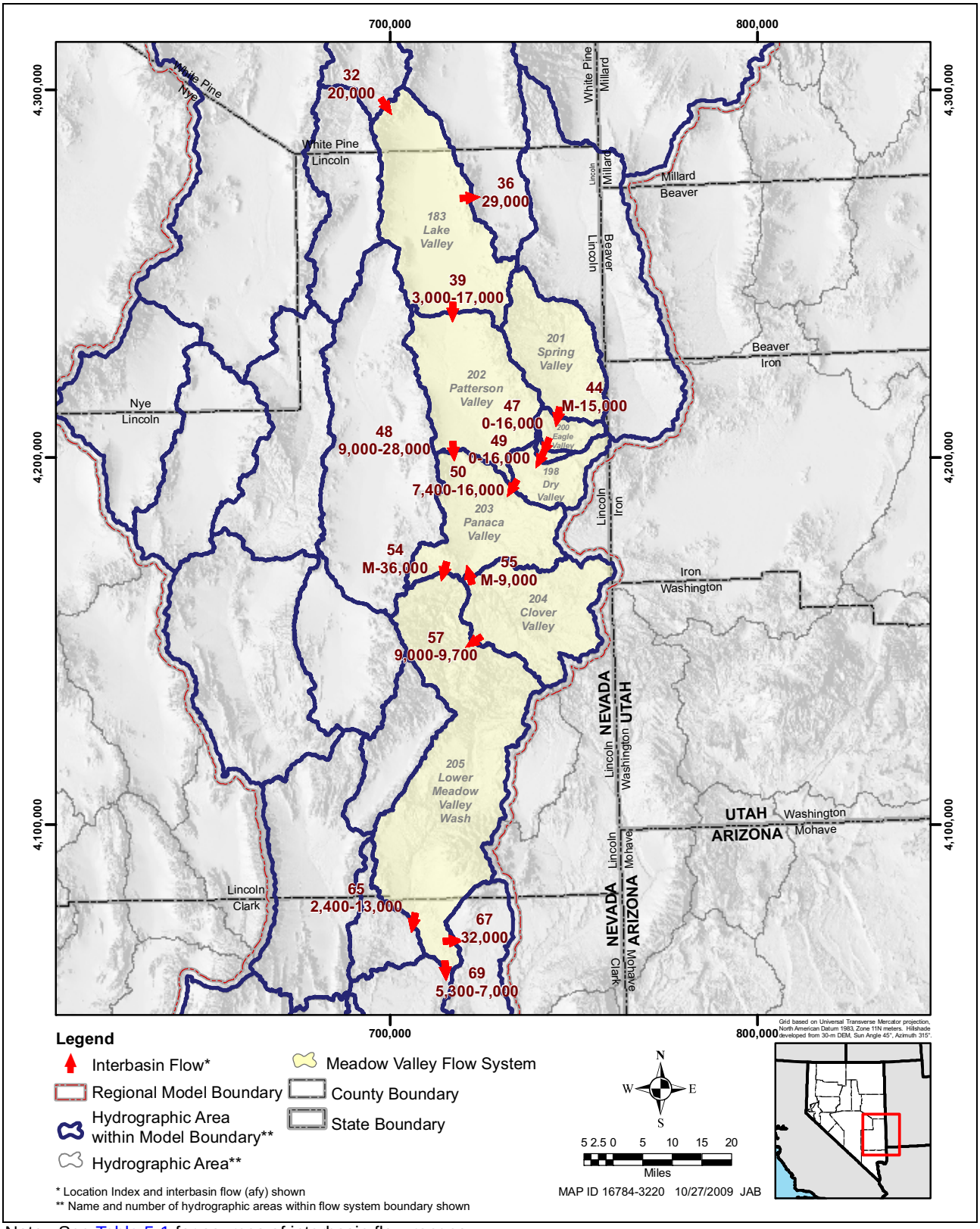
Recharge from precipitation occurs mostly on the mountains located in the northern and northwestern parts of this flow system (Plate 1). Groundwater discharges by the process of ET along the banks of Meadow Valley Wash, which has its headwaters in the Wilson Creek Range. The Meadow Valley Wash is perennial for much of its length with intermittent stream reaches occurring within the Lower Meadow Valley Wash. Clover Creek is a stream with an intermittent upper reach and perennial lower reach that headwaters in the Clover Mountains and is tributary to Meadow Valley Wash.

Regional flow directions are north to south, and flow out of this flow system is to the Muddy River Springs area and California Wash in the WRFS. The general regional flow directions are shown in Figure 5-2. The existing interpretations of interbasin flow are shown on Plate 1 and summarized in the following text.

The earliest and most detailed study of groundwater conditions for MVFS was conducted by Phoenix (1948). The basins included in MVFS, as defined by Phoenix (1948), are the same as in this study. Physiographic evidence indicates that the Meadow Valley Wash drainage pattern, with headwater starting from Spring Valley, possibly dates back well into the Pleistocene period (Phoenix, 1948).

Rush and Eakin (1963) constructed a cross section of the general topography and water table for Lake Valley. The cross section indicates that the general groundwater flow direction in Lake Valley is southward toward Patterson Wash (Patterson Valley in this study). Rush and Eakin (1963) estimated the annual volume of interbasin flow through this location at 3,000 afy.

Rush (1964) discussed groundwater conditions in basins of the MVFS that are connected by perennial or intermediate streams. This includes all basins of this flow system, except Lake Valley. During periods of spring snowmelt or flash floods, water of these streams flows to the mouth of Meadow Valley Wash and discharges into the Muddy River. However, most of the base flow in Meadow Valley Wash is from groundwater sources. Groundwater outflow from MVFS to the Muddy River Springs area occurs in two forms: underflow through the alluvium of lower Meadow Valley Wash and leakage through bedrock (Rush, 1964). The volume of this outflow was estimated as 7,000 afy based on the balance of recharge and discharge in the system.



Note: See Table 5-1 for sources of interbasin flow ranges.

Figure 5-6
Locations and Ranges of Interbasin Flow in Meadow Valley Flow System

Based on a mass-balance model of deuterium, Kirk and Campana (1990) and Thomas et al. (1996) estimated that 5,500 to 9,000 afy and 8,000 afy of Muddy River Springs discharge is from the southern MVFS, respectively. The RASA model simulated the contribution of MVFS water to the Muddy River Springs area at 13,000 afy (Prudic et al., 1995).

LVVWD (2001) estimated a large flow rate of 32,000 afy from MVFS into Lower Moapa Valley based on the water balance of updated annual recharge and discharge volumes. Based on Darcy flux calculations, Buqo (2002) estimated an annual volume of flow from Lower Meadow Valley Wash to the Muddy River Springs area ranging from 2,400 to 7,200 afy.

Synoptic discharge measurements conducted by Beck and Wilson (2006) along the Muddy River indicate that a gain of about 4,200 afy occurs in the Muddy River flow from a gage near Moapa to the Muddy River below Anderson Wash near a Logandale gage. Based on these synoptic discharge measurements, Beck and Wilson (2006) and SNWA (2007) estimated an annual flow volume of 9,200 afy from the MVFS to the Muddy River Springs area.

The conceptual model of groundwater flow in MVFS had been about the same until 2008 when BARCASS was published (Welch et al., 2008). In BARCASS, Lake Valley is included in the GSLDFS. An annual volume of 20,000 afy of groundwater was routed from Steptoe Valley to Lake Valley, and an annual volume of 29,000 afy was routed from Lake Valley to Spring Valley.

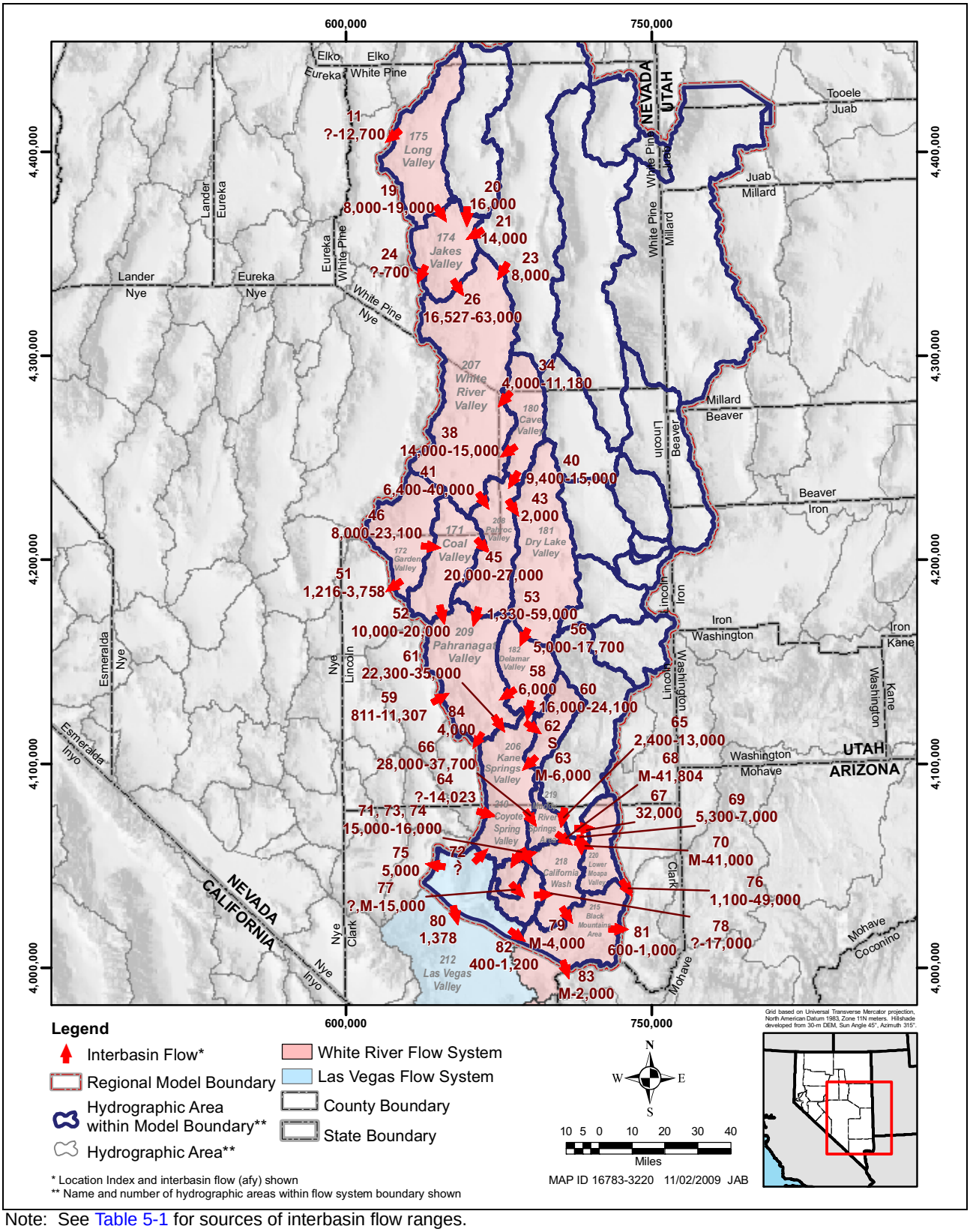
White River Flow System

The WRFS (Plate 1 and Figure 5-7) used in this study is approximately as defined by Eakin (1966) and Harrill et al. (1988). It is the longest flow system in Nevada. Prudic et al. (1995) consider this flow system to be part of the Colorado River Region. Their interpretation excludes Long and northern Jakes valleys from the WRFS. As part of BARCASS, the USGS (Welch et al., 2008) first extended the boundary to include a portion of southern Butte Valley South and south-central Steptoe Valley in the WRFS.

The WRFS is bounded by the Maverick Springs, White Pine, Grant, Quinn Canyon, Pahranagat, and Sheep Mountain ranges to the west, and by the Egan, Schell Creek, Bristol, Highland, and Chief ranges and the Clover, Delamar, and Muddy mountains to the east (Plate 1). The southern boundary of this flow system is Lake Mead.

Based on the interpretation of Eakin (1966), all groundwater recharge to the WRFS is from precipitation on the bordering mountains, especially in its northern basins. However, according to other interpretations such as that of Welch et al. (2008), some recharge may also occur by interbasin flow from Steptoe Valley.

Major groundwater discharge areas occur in the White River and Pahranagat valleys and the Muddy River Springs area. Other minor discharge areas include Long, Cave, and Garden valleys and the Black Mountains Area. Numerous regional springs located in areas from southern White River Valley to the Muddy River Springs area discharge important volumes of groundwater, which is lost to ET for the most part (Plate 1). Except for White River Valley and the Muddy River Springs area, spring discharge is assumed to be completely consumed by the phreatophytes within the groundwater



Note: See Table 5-1 for sources of interbasin flow ranges.

Figure 5-7
Locations and Ranges of Interbasin Flow in White River Flow System

ET areas. The discharge from the regional springs of southern White River is also mostly consumed by phreatophytes. However, a portion of the discharge contributes to the interbasin outflow to Pahroc Valley (Maxey and Eakin, 1949). The Muddy River Springs, which are the largest springs in the WRFS, are located in the central part of the Muddy River Springs area (Upper Moapa Valley). The Muddy River Springs form the headwaters of the Muddy River, a tributary to Lake Mead on the Colorado River (Plate 1). Water from the Muddy River Springs contributes to the riparian ET areas located along the Muddy River, down-gradient from the springs.

The general groundwater flow direction in the regional part of the flow system is from areas of major recharge (north) to major areas of discharge (south). Regional groundwater movement is through the carbonate aquifer, which occurs throughout the flow system. The regional flow through the carbonate aquifer of the WRFS is facilitated by north-south faults (Plate 2 and Figure 5-2). Although there is general agreement on the general direction of regional groundwater flow, interbasin flow locations and volumes are subject to interpretation.

Eakin (1966) proposed the first regional groundwater flow system and named it the White River System. The system is based on a regional gradient derived from elevation of springs, water levels of groundwater wells, playas, and water budgets of several basins in southeastern Nevada. The direction of the regional gradient was inferred from the elevation of water levels in adjacent basins; principal springs in White River, Pahranagat, and Upper Moapa valleys; and playas in Cave, Coal, Dry Lake, Delamar valleys. Eakin (1966) subtracted the annual discharge volume from the annual recharge volume and routed the residual to down-gradient basins. Because the water level of Jakes Valley is unknown, Eakin (1966) estimated it to be as much as 400 ft below the playa surface. The lowest known water-level elevation beneath the playa of Long Valley is about 6,000 ft. The elevation of the water level in a well in Jakes Wash of northern White River Valley is about 5,780 ft, whereas the elevation at Preston Springs, about 12 mi farther south, is about 5,680 ft. This indicates that a potential southward gradient apparently exists through the carbonate rocks toward White River Valley.

A synoptic view of regional groundwater potential based on inference of the regional head from the surface elevation of thermal springs was first offered by Mifflin (1968). Hydraulically forced thermal springs are expressions of movement of water from a depth heated by the natural geothermal gradient. The numerous thermal springs present in the Great Basin region indicate the inherent, permeable nature of a significant network of vertical faults associated with the extensional block faulting of this region.

Harrill et al. (1988) used previous estimates of basin-water budgets in their interpretation of groundwater flow in the Great Basin region. They also considered the topographic and shallow water-level differences between basins for interpreting the direction of interbasin flow and regional groundwater potential. Harrill et al. (1988) included an interbasin flow arrow on the western boundary of Long Valley, Jakes Valley and Pahranagat Valley, but without a flow volume. The western and southern boundary of Coyote Spring Valley was also marked with an interbasin flow arrow into the valley without a flow volume on the map prepared by Harrill et al. (1988). No volume of interbasin flow was estimated by Harrill et al. (1988) from the MVFS to WRFS. Rush (1964) interpreted an annual volume of 7,000 afy of interbasin flow from the MVFS into the Muddy River Springs area.

Nichols (2000) estimated about 10,000 afy and 13,000 afy of interbasin flow from Long Valley to Newark Valley and Long Valley to Railroad Valley, respectively. Nichols (2000) also estimated about 700 afy of interbasin flow from Jakes Valley to Newark Valley. In addition, he estimated a contribution of about 51,200 afy of interbasin flow from both Long and Jakes valleys to White River Valley.

The Muddy River Springs are the dominant hydrologic feature of the Muddy River Springs Area. Measurements of the discharge at a gaging station near Moapa have ranged from 43.5 cfs in 1930 to 49.6 cfs in 1958 (Eakin, 1964). Small variations in spring discharge exclude contributions of surface runoff that is highly variable and correlated to precipitation events. However, the exact sources of water discharging at the Muddy River Springs are not definitely known. Based on previous studies, the main source of water discharging from the Muddy River Springs is recharge occurring in the northern WRFS (Eakin, 1966; Harrill et al., 1988; Kirk and Campana, 1990; Thomas et al., 1996; and SNWA, 2007).

As part of a groundwater modeling study of the DVFS, which is located immediately to the west of the CCRP model area, estimated interbasin flow between the two flow systems was reported as (1) 811 afy to 11,307 afy from the DVFS into the WRFS at Pahranagat Valley; (2) 5,513 afy to 14,012 afy to Coyote Springs Valley from Tikaboo Valley South; and (3) 1,216 afy to 3,758 afy of interbasin flow from the WRFS to the DVFS at Garden Valley (San Juan et al., 2004; Faunt et al., 2004).

SNWA (2007) estimated the total outflow from the WRFS at 25,000 afy, which includes spring discharge from the Muddy Springs, Rogers Spring, and Blue Point Spring, and subsurface outflow from Lower Moapa Valley to the Colorado River.

In BARCASS, 16,000 afy of interbasin flow was routed into the WRFS from Butte Valley South and 22,000 afy was routed in from Steptoe Valley. About 5,000 afy interbasin flow was routed out of WRFS from Long Valley (Welch et al., 2008).

5.2.2.2.3 Las Vegas Flow System

The portion of Las Vegas Valley that includes the area located north of the LVVSZ is included in the model domain and is shown with the WRFS in Figure 5-7.

The LVVSZ is a west-northwest-striking fault with a traceable length of about 120 km. The western segment of the LVVSZ separates the highly extended Sheep Range detachment system to the north from the unextended Spring Mountain block to the south (Guth, 1981, 1990). The central segment of the LVVSZ forms the northern boundary of the Las Vegas Valley (Longwell, 1960; Campana and Levandowski, 1991). The eastern segment of the LVVSZ separates the highly extended Boulder Basin block to the south from the weakly extended Muddy Mountains block to the north (Duebendorfer and Black, 1992). The LVVSZ acts as not only a tectonic divide but also as a hydraulic barrier (SNWA, 2005).

The western hydrographic boundary of this portion of the Las Vegas Flow System consists of thick carbonate and alluvial deposits, so it is permeable. Harrill et al. (1988) routed 5,000 afy of

groundwater through this boundary out of Las Vegas Valley. Harrill et al. (1988) also routed 1,200 afy of groundwater out of this portion along the LVVSZ to Black Mountains Area and an unknown amount of groundwater to Coyote Spring Valley.

San Juan et al. (2004) did not depict any interbasin flow arrows into this portion of Las Vegas Valley. Thus, the actual groundwater flow direction in this portion of the flow system is not known.

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6.0 PRECIPITATION

Precipitation is the main source of groundwater recharge to the flow systems of the study area. An estimate of the spatial distribution of precipitation is needed to estimate groundwater ET and the spatial distribution of recharge. The precipitation distribution needed for these estimates should represent long-term mean annual conditions, which are assumed to approximate predevelopment conditions. A brief review of the available methods and a description of the method selected for this analysis follow.

6.1 Available Methods

The available methods of deriving spatial distributions for precipitation are explained in this section, and previously reported volumes of precipitation are described.

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 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 Nevada State Engineer (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 Natural Resources Conservation Service (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. 10) 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 DEM. PRISM incorporates rain shadows, coastal effects, and temperature inversions. 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; SNWA, 2006). 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 can be 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.

6.2 Selected Method

The main criterion for the selection of a precipitation map for use in the groundwater-budget estimate is an accurate spatial distribution of precipitation. The magnitude of the precipitation volume does not have a direct impact on the volume of recharge from precipitation. It does, however, affect it indirectly as will be explained in Section 6.3. 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 for determining the precipitation distribution of the study area. The precipitation maps developed 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, represent state-of-the art distributions at the basin and regional scales and 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). Precipitation distributions developed using the PRISM method use modern tools and incorporate 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 station precipitation data used to generate the PRISM maps are not available to the public. The most recent normal grid (800-m 1971 to 2000 precipitation normals, Version 2, May 3, 2007) is considered to be the best-quality product to date and was deemed appropriate for the purposes of the conceptual model. One potential limitation of the use of this grid in the groundwater flow model is the limited period of record it represents, as this 30-year period may not exactly represent the desired long-term mean conditions that will be described in the next subsection. However, the historical precipitation record indicates that the overall variability of precipitation within the region is limited as discussed in the following paragraph.

The Climate Diagnostics Center/National Oceanic and Atmospheric Administration calculates historical precipitation indexes for the U.S. Climate Divisions. Climate Divisions intersecting the model area consist of Utah division 1 and Nevada divisions 2, 3, and 4 (Figure 6-1). The historical precipitation indexes were obtained for these four divisions and graphed (Figure 6-2). All four divisions exhibit an apparent slight increase starting in 1970. However, the difference between the

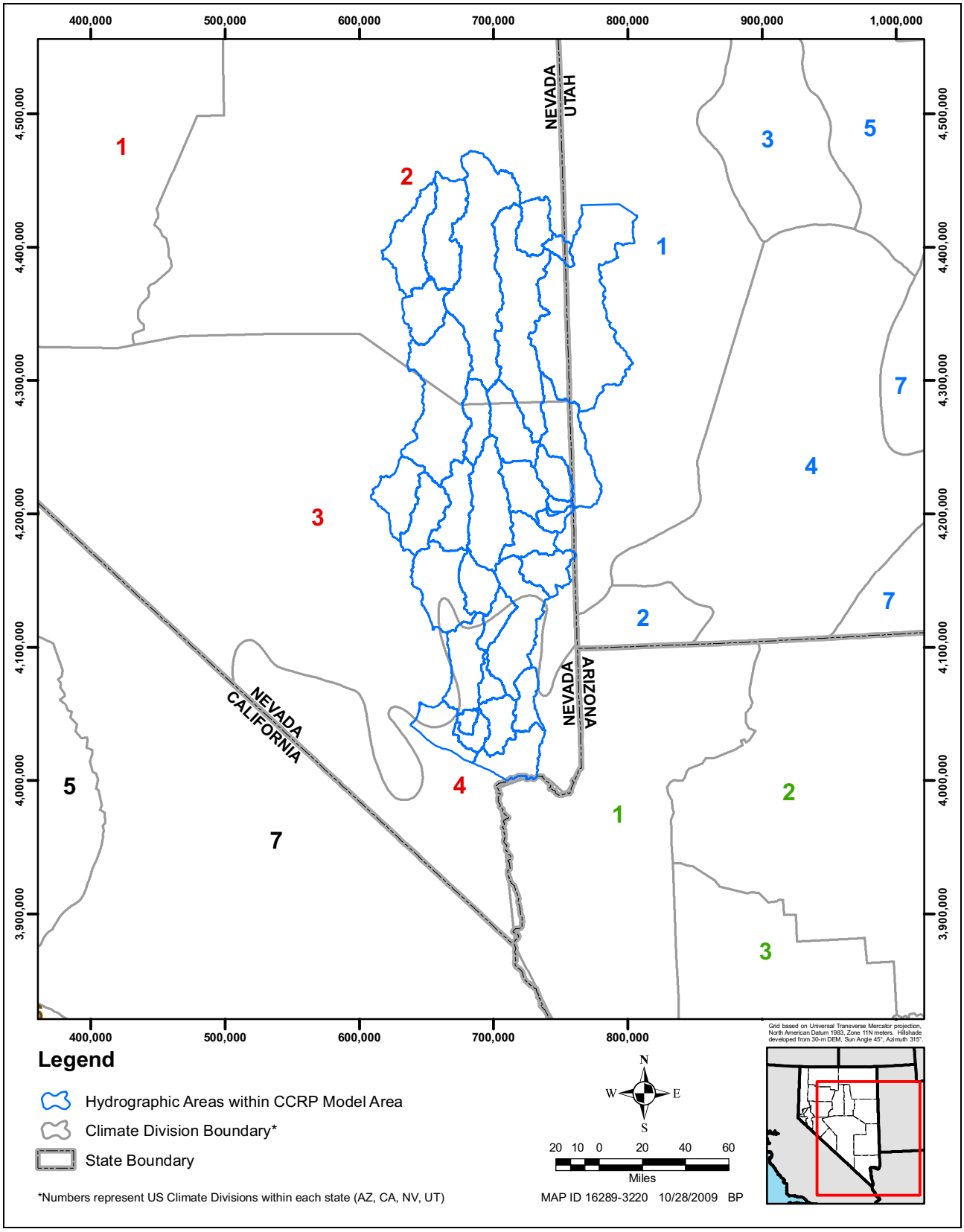
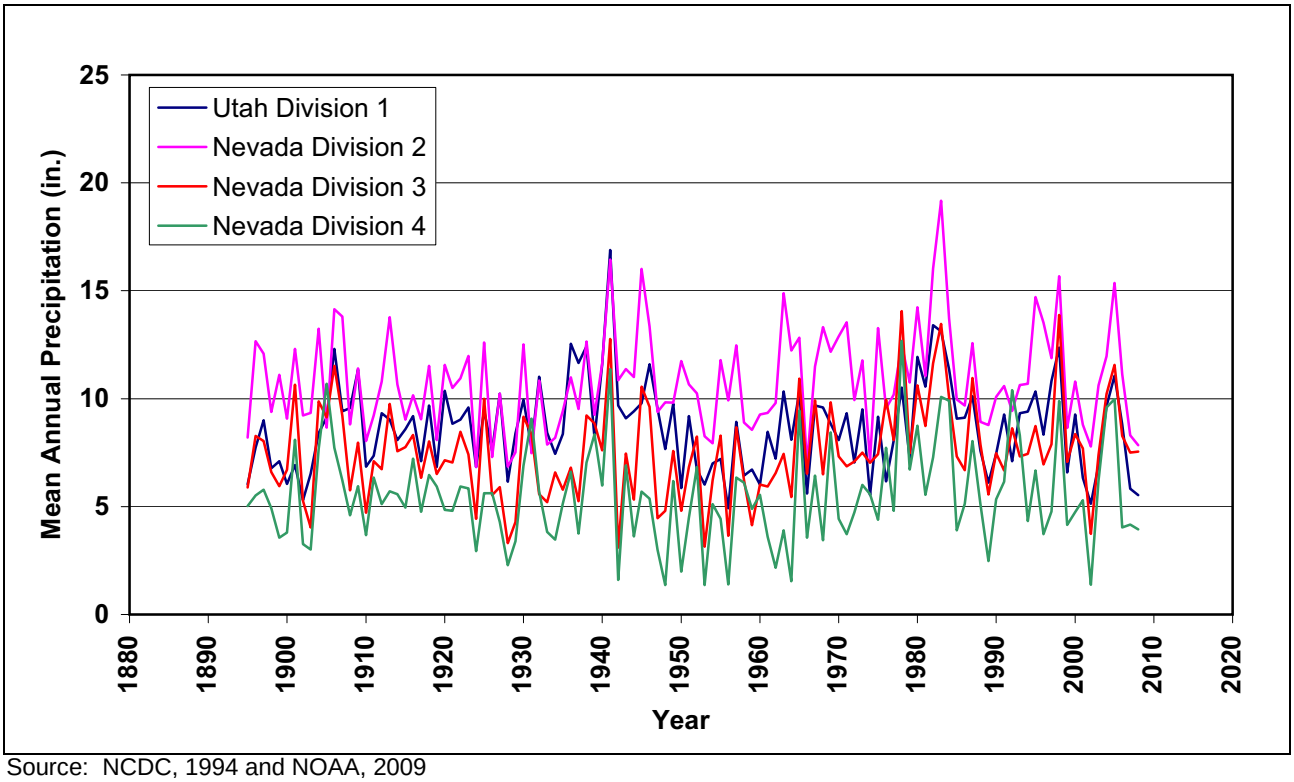


Figure 6-1
Location of U.S. Climate Divisions in Study Area and Vicinity



Source: NCDC, 1994 and NOAA, 2009

Figure 6-2
Historical Precipitation Variability in the Study Area and Vicinity

means for all four divisions for the periods of 1895 to 1970 and 1971 to 2008 is only 0.85 in. or about 10 percent of the overall mean. This uncertainty in the precipitation due to using the normal PRISM grid is negligible compared to the uncertainties associated with other components of the model.

In addition, precipitation is only used as a guide to estimate recharge in the groundwater-budget method used in this study, the volume of recharge is dictated by the estimated volume of discharge from the flow system. Thus, the magnitude of the precipitation is not important in estimating the total volume of recharge for a given flow system. The spatial distribution of precipitation, however, does affect the spatial distribution of recharge and therefore the individual basin's volume of recharge. This issue was addressed in the numerical model using additional constraints (water levels, spring flows, and other observations) to adjust the recharge volumes of the individual basins if necessary.

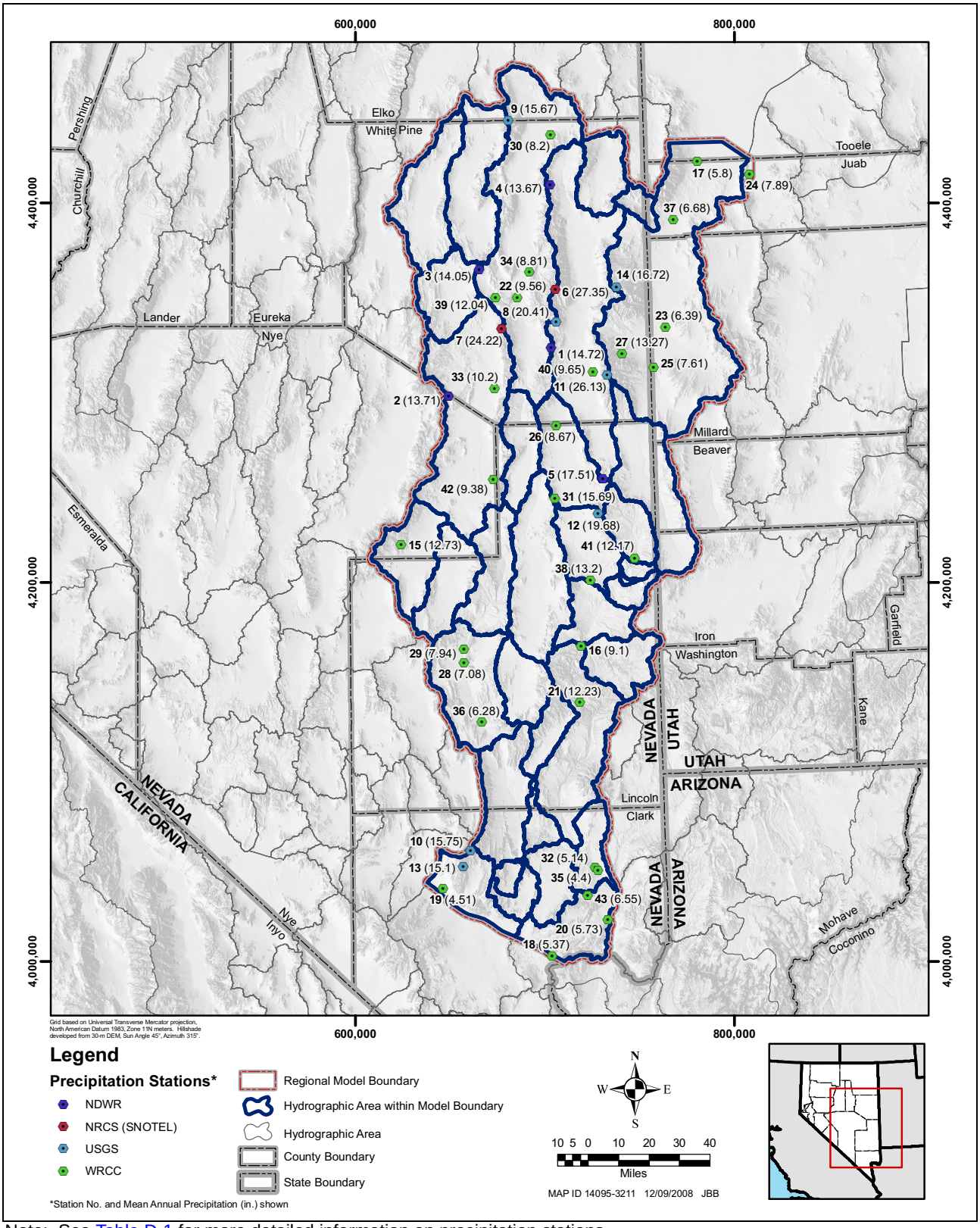
6.3 Estimated Precipitation Distribution and Comparison to Previous Estimates

The precipitation distribution over the study area was extracted from the 800-m PRISM grid, and the quality of this distribution was evaluated. The distribution was then integrated by hydrographic area to obtain yearly precipitation volumes for all basins in the study area. The resulting volumes were compared to previous estimates.

To ensure the selected PRISM precipitation grid approximated long-term mean conditions, it was compared to the period-of-record mean annual precipitation values of precipitation stations within the study area and vicinity. Precipitation station data were compiled, and the mean annual value for the

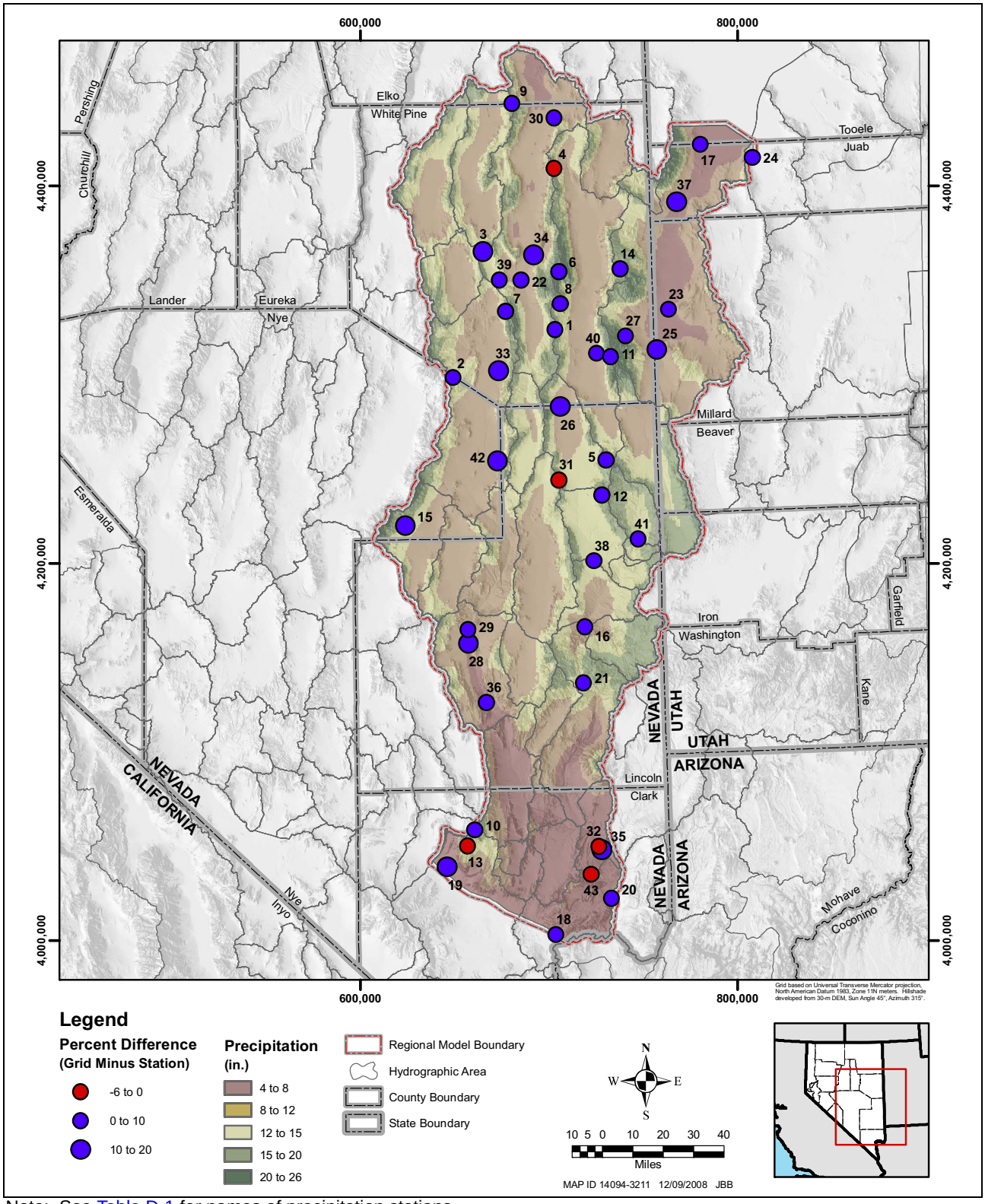
period of record was derived for each station. Summary data for the stations located within and near the study area are listed in Appendix D and shown on Figure 6-3. Figure 6-4 depicts the PRISM precipitation distribution within the study area and a relative comparison of the model fit at the precipitation station locations. The comparison shows that the PRISM distribution slightly overestimated the period-of-record mean precipitation values for most stations. As precipitation is subtracted from ET to obtain groundwater ET, the larger estimates of precipitation derived from the PRISM grid will lead to smaller estimates of groundwater ET and, therefore, smaller recharge estimates. This demonstrates that the use of the PRISM precipitation distribution leads to conservative estimates of recharge and is appropriate in this study.

The derived precipitation volumes for all basins in the study area are listed in Table 6-1. Estimates derived for other studies (Scott et al., 1971; Nichols, 2000; LVVWD, 2001; Flint and Flint, 2007) are also listed in this table for comparison. The estimates reported by Scott et al. (1971) are those derived during the NDWR/USGS Reconnaissance investigations and are based on the Hardman (1936) map or subsequent updates. The estimates derived by Nichols (2000) are based on the 4-km PRISM grid for the normal period of 1961 to 1990. The estimates derived by LVVWD (2001) are based on linear relationships between the precipitation station data available at the time and land-surface elevation. The estimates derived by this study are generally larger than those estimated during the Reconnaissance investigations (Scott et al., 1971) but are very similar to the estimates derived for BARCASS (Flint and Flint, 2007).



Note: See Table D-1 for more detailed information on precipitation stations.

Figure 6-3
Location of Precipitation Stations and Mean Annual Precipitation within Study Area



Note: See Table D-1 for names of precipitation stations.

Figure 6-4
PRISM Precipitation Distribution within Study Area and Percent Difference between PRISM and Precipitation Station Data

Table 6-1
Precipitation Volumes in afy for Basins in Study Area

HA Number	HA Name	800-m PRISM (This Study)	Scott et al. (1971)	Nichols (2000)	LVVWD (2001)	Flint and Flint (2007)
Goshute Valley Flow System						
178B	Butte Valley South	502,000	420,000	NE	NE	470,000
179	Steptoe Valley	1,271,000	1,200,000	1,344,191	NE	1,303,000
	Total	**1,773,000**	**1,620,000**	**NE**	**NE**	**1,773,000**
Great Salt Lake Desert Flow System						
184	Spring Valley	1,116,000	960,000	1,141,444	NE	1,131,000
185	Tippett Valley	213,000	160,000	211,905	NE	209,000
254	Big Snake	2,321,000	2,000,000[a]	NE	NE	2,159,000
	Total	**3,650,000**	**3,120,000**	**NE**	**NE**	**3,499,000**
Meadow Valley Flow System						
183	Lake Valley	401,000	290,000	NE	437,000	380,000
202	Patterson Valley	318,000	190,000	NE	275,000	NE
201	Spring Valley	243,000	180,000	NE	212,000	NE
200	Eagle Valley	46,000	28,000	NE	37,000	NE
199	Rose Valley	9,000	5,100	NE	7,000	NE
198	Dry Valley	92,000	50,000	NE	77,000	NE
203	Panaca Valley	234,000	180,000	NE	224,000	NE
204	Clover Valley	307,000	140,000	NE	205,000	NE
205	Lower Meadow Valley Wash	552,000	320,000	NE	523,000	NE
	Total	**2,201,000**	**1,383,100**	**NE**	**1,998,000**	**NE**
White River Flow System						
175	Long Valley	450,000	250,000	452,367	460,000	407,000
174	Jakes Valley	289,000	240,000	289,477	312,000	261,000
207	White River Valley	1,011,000	750,000	NE	1,032,000	892,000
180	Cave Valley	265,000	220,000	NE	258,000	245,000
172	Garden Valley	351,000	230,000	NE	320,000	NE
171	Coal Valley	267,000	170,000	NE	234,000	NE
208	Pahroc Valley	310,000	190,000	NE	260,000	NE
181	Dry Lake Valley	571,000	340,000	NE	455,000	NE
182	Delamar Valley	236,000	140,000	NE	176,000	NE
209	Pahranagat Valley	418,000	270,000	NE	344,000	NE
206	Kane Springs Valley	146,000	80,000	NE	140,000	NE
210	Coyote Spring Valley	272,000	220,000	NE	224,000	NE
219	Muddy River Springs Area	54,000	33,000	NE	38,000	NE
217	Hidden Valley	33,000	28,000	NE	28,000	NE
216	Garnet Valley	55,000	58,000	NE	45,000	NE
218	California Wash	106,000	100,000	NE	76,000	NE
215	Black Mountains Area	169,000	200,000	NE	132,000	NE
220	Lower Moapa Valley	95,000	76,000	NE	101,000	NE
	Total	**5,097,000**	**3,595,000**	**NE**	**4,638,000**	**NE**

NE = Not Estimated
[a] Reported in Hood and Rush (1965)

7.0 GROUNDWATER DISCHARGE TO THE SURFACE

Within the CCRP model area, groundwater discharges to the surface primarily through the process of ET and spring flow. Groundwater may also discharge to the surface directly into streams through the process of upward leakage. At the regional scale, discharge to streams is considered important only for a few of the streams located in the model area, including the Muddy River. Thus, this section includes descriptions of groundwater ET, discharge from major springs, and information supporting groundwater discharge into these streams.

7.1 Groundwater Discharge by ET

The objective of this work was to develop estimates of groundwater ET for relevant basins of the study area using the information available to date. Groundwater ET is a portion of the ET observed at the surface of a given basin. Other sources of water to the ET process include surface water and precipitation. Furthermore, the portion of groundwater ET of interest to this project is from the connected portion of the flow system. In the following discussion, the term "net ET" will refer to total ET less the contribution by precipitation. Depending on the assumption of a given ET study, the difference between ET and precipitation will be termed "net ET" and may represent ET from groundwater or ET from groundwater and surface water. The following items are described: (1) ET process, (2) methodology, (3) compilation of ET and PET rates, (4) deterministic groundwater ET estimates derived for this study, and (5) stochastic groundwater ET estimates.

7.1.1 Evapotranspiration Process

ET is the process whereby water is returned to the atmosphere through evaporation from soil, wet plant surfaces, and open water bodies and through transpiration from plants. The portion of ET that was of interest to this study is groundwater ET, more specifically, ET from plants, open water bodies, and wet playas that are linked to the main groundwater system (regional and intermediate). Groundwater ET is an important component of discharge when conducting basinwide water-resource budgeting in arid and semiarid areas. It is the only budget component that can be observed and estimated with some level of confidence. In general, estimates of groundwater ET may be derived using the basic simplifying assumption that the volume of groundwater ET discharging from a given ET area is equal to the volume of total ET reduced by the volume of precipitation on that area. When added to estimates of underflow for a given groundwater flow system, estimates of groundwater ET can be used with the groundwater-balance method to derive estimates of groundwater recharge.

7.1.1.1 Evapotranspiration by Plants

Evapotranspiration by plants consists of two basic processes: evaporation and transpiration. In the evaporation process, water on the plants and in the soils surrounding the plants is removed by

conversion from the liquid phase to the vapor phase. Transpiration is similar to evaporation, but the water is removed from the plant tissues, mostly through small openings on the plant leaves called stomata. The resulting vapor is lost to the surrounding atmosphere (Allen et al., 1998).

The type of plants that use groundwater as a source of water are called phreatophytes. Phreatophytes were first defined by Meinzer (1927, p. 1) as "plants that habitually grow where they can send their roots down to the water table or the capillary fringe immediately overlying the water table and are thus able to obtain a perennial and secure supply of water." Phreatophytes occur in many basins within the study area. However, phreatophytes tapping the water table occur mostly in the northern part of the study area. The phreatophytic plant assemblage present in the study area is composed primarily of greasewood (*Sarcobatus vermiculatus*), saltgrass (*Distichlis spicata*), rabbitbrush (*Chrysothamnus nauseosus*), saltbush (*Atriplex canescens*), spiny hopsage (*Grayia spinosa*), shadscale (*Atriplex confertifolia*), and big sagebrush (*Artemisia tridentata*).

A riparian plant assemblage also occurs within the study area and includes cottonwood (*Populus fremontii*), willow (*Chilopsis linearis*), saltcedar (*Tamarix ramosissima*), mesquite (*Prosopis glandulosa*), cattails (*Typha sp.*) and tules (*Scirpus sp.*). Most riparian vegetation occurs in basins located in the southern part of the study area.

7.1.1.2 Open-Water Evaporation

Evaporation from water bodies is a major component of the hydrologic cycle and a primary process of water loss from open water bodies. As such, it has important implications on water-resource management. Open-water evaporation takes place during energy transfer from an evaporating surface when the vapor pressure in the air is less than the saturated pressure (Rosenberry et al., 2007). Some of the meteorological factors that influence evaporation from water bodies are solar radiation, wind speed, air humidity, and air temperature (Allen et al., 1998). The quantity of evaporated water from open water bodies, such as lakes, reservoirs, and streams and springs, is dependent on the quantity of open water.

Evaporation from water surfaces is rarely measured directly. Rather, it is usually measured by proxy (Kirono and Jones, 2007). A widely used proxy method to calculate evaporation rates from open water bodies is the pan-evaporation method (measuring rates of evaporation from pans filled with water). The decrease in water depth in the pan during a given period equals the amount of water evaporated during that period, provided that no precipitation occurred. The measured evaporation rate implicitly incorporates the effects of radiation, wind, temperature, and humidity prevailing during that period (Allen et al., 1998). If precipitation occurs during that period and is measured nearby, the net amount of evaporated water is derived by subtracting the amount of precipitation from the measured amount of evaporated water. An empirical method is used to derive estimates of evaporation rates from pan-evaporation measurements, applying a coefficient that relates pan evaporation to open-water-body evaporation (Allen et al., 1998).

Basins having major open water bodies in the study area are Jakes Valley, Butte Valley (southern part), Steptoe Valley, Lake Valley, Spring Valley, Snake Valley, Hamlin Valley, Dry Valley, Lower Meadow Valley Wash, White River Valley, Pahranagat Valley, and Lower Moapa Valley. When estimating groundwater ET, it makes sense to include evaporation from open water bodies in the

estimate if the surface water is known to originate from groundwater. However, the main source of water to open water bodies is not always known with certainty.

7.1.1.3 Wet-Playa Evaporation

Wet playas are defined here as playas located above a water table shallow enough for groundwater evaporation to occur. Quantitative estimates of groundwater evaporation from wet playas is important to the estimation of a basin's ET volumes.

The process and magnitude of groundwater evaporation through wet playas yield essential information regarding the relationship of mass and energy fluxes between the ground and the atmosphere (Bittelli et al., 2008). The quantity of evaporated water is influenced by the hydrology and climatic factors of the area. The amount of evaporation depends on the local depth of the water table below the ground surface (Menking et al., 2000). The process is carried out through vapor pressure gradient between soil water and the atmosphere, and this phenomenon is directly related to groundwater depth (Deverel et al., 2005). When the water table is at or near the ground surface, the rate of water loss is equivalent to molecular diffusion of open water bodies driven by the vapor pressure gradient. As the water table gets deeper, the rate of water loss declines, and additional factors, such as the soil's physical and chemical properties and the meteorological conditions, play an important role in driving ET rates. Deverel et al. (2005) further explain that evaporation from playas with shallow groundwater is affected by the spatial and temporal patterns of physical and chemical properties of the soil. The salinity of wet-playa groundwater also has a great impact on the rate of evaporation (Kampf et al., 2005).

In this study, the largest wet playas occur in Steptoe, Snake, Cave, and White River valleys. Wet playas of lesser extent occur in Lake, Spring, and Tippett valleys.

7.1.2 Methodology

The general method for developing groundwater ET estimates for a given area is described, followed by a description of the methodology used in this study.

7.1.2.1 General Methodology

The general methodology of estimating groundwater ET is described followed by a brief mention of other methods.

In general, estimates of groundwater ET can be made using the simplifying assumption that the volume of groundwater ET discharging from a given ET area is equal to the volume of total ET reduced by the volume of precipitation on that area, expressed by:

$$ET_{gw} = ET_T - P \qquad \text{(Eq. 7-1)}$$

where,

ET_{gw} = Volume of groundwater ET from a given ET unit
ET_T = Volume of total ET from the same given ET unit
P = Volume of precipitation over the same given ET unit

All three terms of Equation 7-1 represent a rate multiplied by the same area (the potential groundwater area). Thus, information needed to derive estimates of groundwater ET volumes for a given period of time are:

- ET rates (total)
- Precipitation rates
- Areas of potential groundwater ET

ET rates can be derived from field measurements or from remote-sensing data. Field measurements of energy variations are made using eddy covariance towers (ET towers). ET rates from remote-sensing data may be derived using the Surface Energy Balance Algorithm for Land (SEBAL) remote-sensing model (Bastiaanssen et al., 2005). Precipitation rates may be obtained as described in the previous section. Areas of potential groundwater ET may be derived from field mapping or from a combination of satellite imagery and field data. To obtain more detailed and accurate groundwater ET volumes, the potential groundwater ET areas are subdivided into classes or units using vegetation type and density, and sometimes soil characteristics, depending on the classification method.

Another methodology of estimating groundwater ET is similar to the one expressed by Equation 7-1 but consists of removing only a portion of the precipitation volume, called effective precipitation. Effective precipitation represents the volume of precipitation residing in the root zone that is actually used by the plants. In this method, ET areas and ET and precipitation rates may be measured as described above. Note that this method generally yields larger estimates of groundwater ET, as less precipitation is assumed to be available to the plants.

Similar methods for estimating groundwater ET were applied by Nichols (1993, 1994) and Nichols et al. (1997). In these methods, groundwater ET rates are estimated separately and integrated over the period when plants transpire groundwater only. Furthermore, the groundwater ET rates are related to the leaf area index and the depth to water to derive estimates of annual groundwater ET volumes for areas covered by specific plants. Nichols (2000) used ET information collected by Nichols (1994), Nichols et al. (1997), and Duell (1990) to estimate groundwater ET for basins in Nevada. Nichols (2000) developed two equations, one relating groundwater ET to plant cover and the other one relating groundwater ET to depth to water. He found that the correlation between groundwater ET and plant density is much stronger and used it together with satellite imagery to derive estimates of annual groundwater ET volumes for the basins in the study area. This method of groundwater ET estimation generally yields larger estimates of groundwater ET volumes. The larger estimates may be because the groundwater ET rates derived by this method contain some precipitation or because other methods remove some of the groundwater contribution by assuming it is precipitation.

7.1.2.2 Methodology Used in this Study

The groundwater ET estimates for this study had to include ranges of uncertainty. Thus, deterministic and stochastic estimates were derived.

To derive one set of deterministic estimates, two methods were considered, compared, and combined. The first method (Method 1) was developed as part of this study for the whole study area. The second method (Method 2) is that used by Welch et al. (2008) in BARCASS and by DeMeo et al. (2008) in the southern part of the Colorado Regional Ground-Water Flow System. The combination of these two methods constitutes the deterministic method adopted for this study. The BARCASS estimates (Method 2) required simplification that will be explained in Section 7.1.8. Estimates made by DeMeo et al. (2008) (Method 2) were not fully incorporated in the analysis. Rather, estimates for selected basins were later incorporated in the deterministic estimates for the CCRP model.

In Method 1, potential areas of groundwater ET are delineated and classified, and published ET rates are compiled and evaluated. Appropriate rates are selected, adjusted to local PET conditions, and applied to the delineated potential groundwater ET areas in each basin. The 800-m PRISM precipitation grid is then used to remove the ET volume associated with precipitation as the source.

In Method 2, potential areas of groundwater ET are delineated and classified similarly to Method 1 but with more detail. Welch et al. (2008) and DeMeo et al. (2008) handled the ET rates differently. Welch et al. (2008) derived mean ET rates from the literature and adjusted them to local conditions using the Modified Soil Adjusted Vegetation Index (MSAVI) method (Qi et al., 1994). DeMeo et al. (2008) estimated annual ET rates from measurements or used published ET rates for similar environments. The ET rates were then multiplied by the corresponding potential groundwater ET areas and adjusted for precipitation. DeMeo et al. (2008) reported that their estimates of ET included ET from groundwater and surface water.

Stochastic estimates of mean annual groundwater ET volumes were derived using the information in the deterministic estimates and other available information as necessary. This stochastic analysis was implemented using the Monte Carlo method via Crystal Ball software.

The information needed to derive the groundwater ET estimates by the methods described above includes previous interpretations and historical data, as well as the most recent data, including ET rate measurements, remote-sensing data, and field verification. The overall process consists of the following steps: (1) compilation of ET rate data, (2) derivation of groundwater ET estimates by Method 1, (3) derivation of groundwater ET estimates by Method 2, (4) derivation of groundwater ET estimates for the groundwater flow model by combining Method 1 with a simplified Method 2, and (5) calculation of stochastic estimates of groundwater ET volumes. Each of these steps is described in the following text.

7.1.3 ET Rates and Related Information

The available measurements of total ET rates, groundwater ET rates, and related information were compiled from the literature and are presented in Appendix E. The ET process and the variables that affect it are discussed in this section.

ET rates vary greatly spatially and temporally and are affected by a number of factors including air temperature, relative humidity, wind, water availability, plant type and coverage, and soil type. The rates generally increase with temperature (during the growing season), wind, and water availability within limits and with plant density and leaf area. The rates generally decrease as the relative humidity of the air increases.

Phreatophytes extract water from both the unsaturated and saturated zones through the process of ET. Different phreatophytic species, however, use the available water at different rates. Groundwater ET emanating exclusively from the saturated zone is difficult, if not impossible, to measure separately. ET rates derived from field data (using ET towers) represent the total ET rates from the plants and the soils under and around the plants. The measured ET rates may include several sources of water: groundwater and soil moisture uptake by the plants, groundwater and soil moisture lost by evaporation, and water on the plant leaves lost by evaporation. The following simplifying assumption is usually made to derive mean annual groundwater ET rates: all sources of water, other than groundwater, can be attributed to the mean annual precipitation. Estimates of groundwater ET rates can then be obtained by subtracting the local mean annual precipitation rate from the measured annual ET rate.

ET rates are at their maximum when the water table is at the land surface and are approximated by measurements of PET. They decrease with increasing depth to water and reach zero at the extinction depth (Shah et al., 2007). The depth at which ET ceases is called the ET-extinction depth. This depth is important because it affects the magnitude of groundwater ET rates. Phreatophytes, in essence, pump groundwater from the water table to the atmosphere through their root systems. Thus, rooting depths of phreatophytes are good indicators of the extinction depths of groundwater ET.

Groundwater-ET-extinction depths are influenced by several physical characteristics. Soil characteristics, for example, can have an impact on the maximum rooting depth. For instance, a phreatophyte in a sandy clay soil can have a greater extinction depth than in sandy loam (Shah et al., 2007). Conventionally, it was believed that the relationship between depth and groundwater ET is linear, but as mentioned above, different soil characteristics with different phreatophytes could generate different relationships. For example, Shah et al. (2007) found an exponential decline of groundwater ET with increasing depth to water.

A literature survey for annual ET rates measured in the study area and vicinity was conducted and the rates were compiled into the data set presented in Table E-1 (Appendix E). Additionally, selected ET data derived from on-going SNWA studies were used. A description of the SNWA field ET sites is presented in Appendix A. Annual ET rates measured by DeMeo et al. (2008) are not included in Table E-1 because they did not become available until the data analysis was completed. They are, however, comparable to the rates listed in Table E-1 for similar vegetation types.

A literature survey was conducted to compile the available phreatophyte rooting depths for the phreatophytes present in the study area. Together with the depth-to-water data (see SNWA, 2008a), rooting depths help identify ET-extinction depths (Appendix E, Table E-2).

The PET rates were calculated using a regression equation derived from PET data compiled by McCurdy and Albright (2004). The PET calculation details are provided in Appendix E. The spatial distribution is provided on Figure E-1 (Appendix E).

7.1.4 Method 1 - Groundwater ET Estimates

The groundwater ET estimates were developed as follows: (1) delineation of groundwater ET areas, (2) identification of mean annual ET rates, and (3) calculation of groundwater ET volumes. Each of these steps is described in the following subsections.

7.1.4.1 Delineation of Groundwater ET Areas

The groundwater ET areas of interest were identified in three steps: (1) a "current-condition" map was developed using satellite imagery and other information; (2) this map was then converted to predevelopment conditions; and (3) groundwater ET areas delineated in the predevelopment map were evaluated to interpret the source of the water.

Method 1 - "Current-Condition" ET Map

SNWA defined the outer boundaries of the groundwater ET areas, subdivided them into classes, and assessed the accuracy of this classification through field investigations. This work is summarized in the following text.

The SNWA current-condition ET map (Figure 7-1) was derived using 2002 satellite imagery together with the USGS 1:100,000 scale topographic maps and phreatophytic areas mapped by previous studies. The 2002 image was used to confirm and/or refine the phreatophytic areas and define any additional areas where no previous remote-sensing analysis had been conducted. Phreatophytic communities are typically located on the relatively flat areas of a basin between mountain blocks. To ensure that all potential groundwater ET areas were identified, flat areas were defined as land expanses in the basin where the land-surface slope is less than or equal to 10 percent. These areas were initially defined by performing a slope analysis in ArcGIS®, using USGS 30-m National Elevation Dataset (NED) seamless DEMs and masking out any land-cover features that fell on slopes greater than 10 percent.

The groundwater ET areas were delineated based on a compilation of earlier work described in the Reconnaissance Series, LVVWD et al. (1994), LVVWD (2001), and Nichols (2000). Occasionally, the Southwest Regional Gap Analysis Project (SWReGAP) data (USGS, 2004) and the National Land Cover Data (NLCD, 1992) were used if there was great uncertainty over the location of a boundary. Boundaries of many, but not all, of the phreatophytic areas were checked in the field during the summer of 2004 by SNWA and modified as needed using high-resolution global positioning system equipment.

Areas of groundwater ET representing current conditions were then classified using Normalized Difference Vegetation Index (NDVI) and Landsat 7 Thematic Mapper 2002 satellite imagery. To represent current conditions, the areas of groundwater ET were classified into six categories: Open Water, Bare Soil/Low Vegetation, Phreatophyte/Medium Vegetation, Wetland/Meadow, Agriculture,

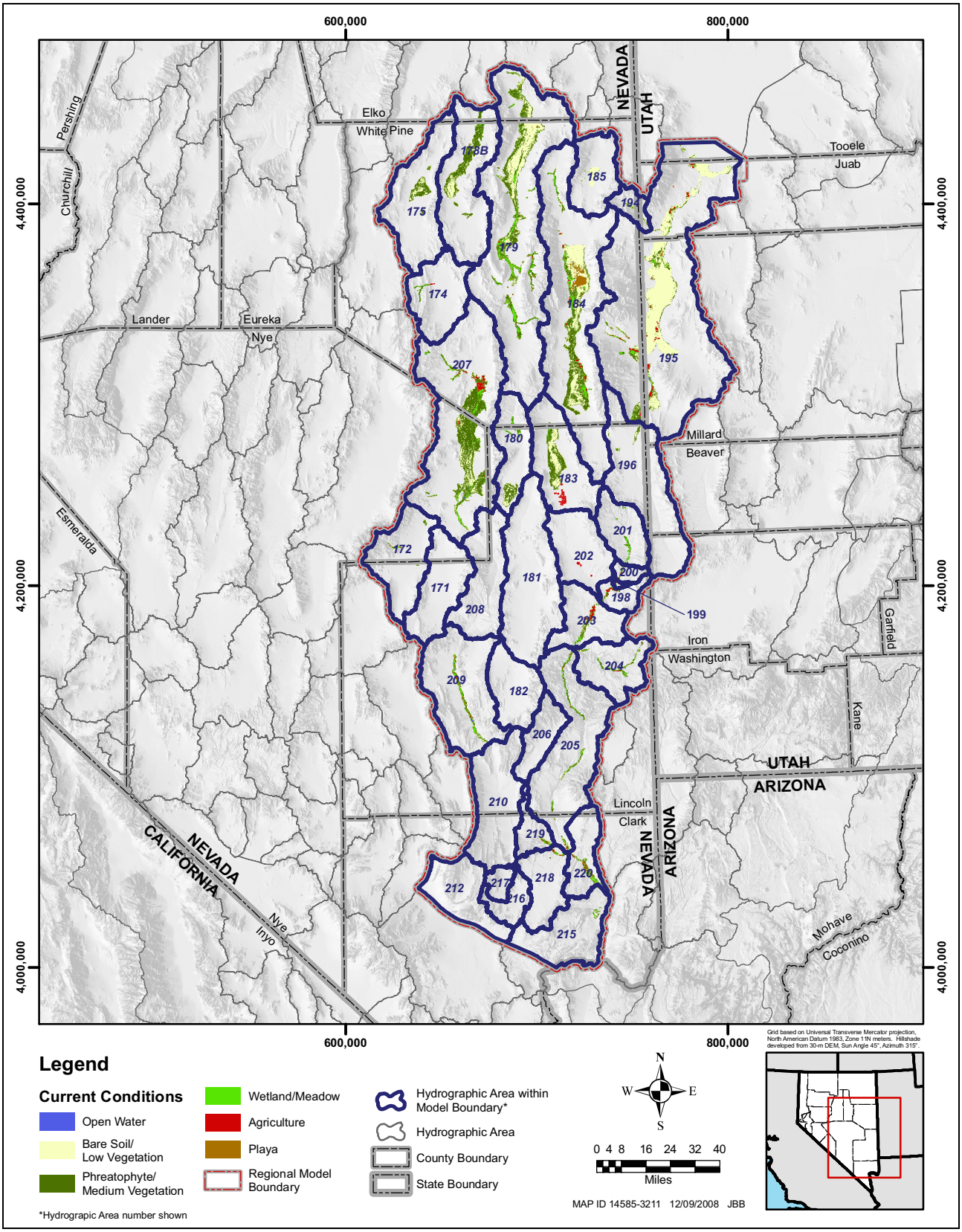


Figure 7-1
Method 1 - "Current-Condition" Groundwater ET Map

and Playa (Table 7-1). A number of transects were generated to supplement the remote-sensing techniques in defining phreatophytic-area boundaries across the landscape. Transects are strips of land across the groundwater ET areas along which estimates of the percent cover and density of the vegetation community were made and recorded. Percent cover was estimated as the fraction of the line that is covered by each species, and density estimates were calculated using strip transects as described in Barbour et al. (1987).

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 randomly selected points representing each classification were field checked. This assessment returned an overall accuracy of 88 percent. The detailed results are presented by ET class in Table F-4 (Appendix F). This value is above the generally accepted value of 85 percent as established by Anderson et al. (1976). These accuracies suggest that the error on the areas of the delineated classes is approximately 12 percent on average.

Table 7-1
Method 1 - Land-Cover Classification

ET Class	Classification	Description	Depth-to-Water Range (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 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 >30 ft bgs (Roots have been observed at depths up to 175 ft bgs)
3	Phreatophyte/ Medium 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	Agricultural lands identified from 2002 satellite image and field observations	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

Method 1 - Predevelopment Map

The SNWA current-condition groundwater ET map was converted to predevelopment conditions by removing the agricultural areas from the map. For agricultural areas located within phreatophytic areas, it was assumed that these areas had displaced what otherwise would have been phreatophytes prior to development. It was also assumed that the majority of water being used for agricultural purposes originated within the phreatophytic areas prior to development. This seems to be an appropriate assumption for the regional conceptual evaluation described in this report. These agricultural areas were reclassified to represent the phreatophytes they apparently displaced, which in most cases were Wetland/Meadow. Agricultural areas located outside of phreatophytic areas were simply deleted from the groundwater ET map.

In addition, all playa areas represented on the current-condition map were changed to reflect, as closely as possible, playa areas as documented in the NDWR/USGS Reconnaissance Series. These changes were particular to Spring Valley and Snake Valley. Rush and Kazmi (1965) describe two playas totaling 11,600 acres in Spring Valley. Hood and Rush (1965) describe a series of playas from Trout Creek southward to Bishop Springs totaling 3,200 acres in Snake Valley. In addition, 60,000 acres were added to include the Great Salt Lake Playa (the portion occurring within the hydrographic boundary of Snake Valley) as delineated in Hood and Rush (1965). Eakin (1962) defines a playa for Cave Valley but does not identify it as a discharging playa. This area, located in the southern portion of Cave Valley, is vegetated with a large greasewood community and is likely contributing to the total ET in the Basin. This area is illustrated on the steady-state map but is represented as a combination of Bare Soil/Low Vegetation and Phreatophyte/Medium Vegetation. An inherent challenge in all geographic information system (GIS) applications is attempting to create polygons of the exact acreage. Therefore, the acreages reflected on the steady-state map do not exactly match one-to-one with the NDWR/USGS reconnaissance maps. Polygons were created as accurately as possible to reflect the acreages reported. The predevelopment map developed by SNWA is shown on Figure 7-2.

Method 1 - Evaluation of Groundwater ET Areas

The predevelopment ET map developed by Method 1 (Figure 7-2) most likely includes all major groundwater ET areas. However, the type of aquifer that feeds each of the groundwater ET areas, whether local and disconnected or part of the main groundwater system, still remains unknown. The main groundwater system is defined here as the union of the regional and intermediate flow systems, which are generally hydraulically connected to each other. The main groundwater system is the only part of the flow system that may be included in a regional numerical model, such as the one constructed for this study. Perched or local groundwater is definitely not part of this main flow system. Semi-perched groundwater within the valley fill is part of the main flow system but may not be included in the numerical flow model.

The groundwater ET areas were evaluated for their level of connectivity to the main flow system. Three categories of groundwater ET areas were created based on the following criteria:

- Size of the groundwater ET area
- Topography of the groundwater ET area and its relative location within the basin

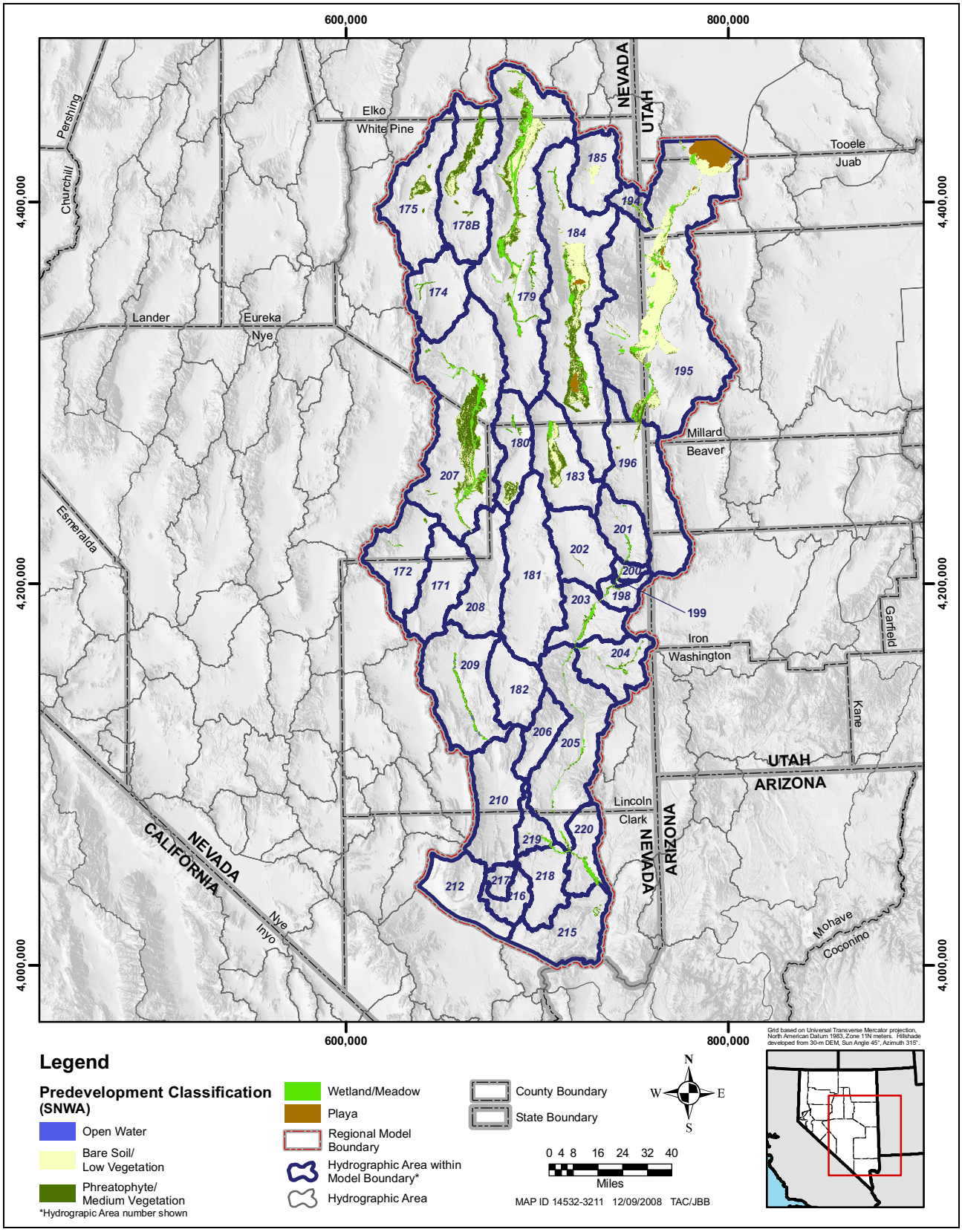


Figure 7-2
Method 1 - Predevelopment Groundwater ET Map

- Estimated depth to main groundwater flow system within the groundwater ET area
- Apparent source of water sustaining the groundwater ET area
- Previous classification of groundwater ET area

The depth to water on the valley floors was used as an indicator of groundwater-ET-extinction depths. A maximum extinction depth of 100 ft was selected as the cutoff value beyond which significant amounts of phreatophytes could not occur. Thus, the 100-ft depth-to-water contour was only used as a guide to identify the approximate location of the outermost (maximum) boundary of groundwater ET areas on the valley floors. An examination of the ET map superposed onto depth-to-water data including contours shows that most of the ET areas are located within the 50-ft contour line (SNWA, 2008a). The contours represent the depth to the main groundwater system. Some of the large ET areas extend outside of the 50-ft contour line. They, however, are within the 100-ft contour line. The main groundwater ET areas were assumed to occur where the depth to the main groundwater system is within 100 ft of the ground surface. These areas were assigned a category of 1 or 2 depending on the other criteria. A few isolated phreatophyte "islands" exist away from the main phreatophytic areas (Categories 1 and 2). A closer look at the depth-to-water data indicates that semi-perched or perched conditions may exist in these groundwater ET areas (categorized as 2 or 3, depending on their conditions).

The results of this evaluation are summarized in Table 7-2. The available depth-to-water information is sparse and provides an uncertain understanding of the water table. Thus, this information was only used as a guide. In addition, phreatophytes in areas where the water table is rather deep (about 50 to 100 ft bgs) may be facultative. This condition applies to the groundwater ET areas flagged as Category 2 (Table 7-2). Each category is further discussed in the following text.

Table 7-2
Categorization of Groundwater ET Areas

Category	Size of Groundwater ET Area	Location of Groundwater ET Area	Depth to Main Groundwater Flow System	Source of Water
1	Area > 1 km^2 or length > 1 km	Valley floor	< 100 ft	Shallow water table, or regional springs
2	Area > 1 km^2 or length > 1 km	Valley floor or alluvial fans	50 to 100 ft	Not fed by a spring
3	Area may be < 1 km^2 or length may be < 1 km	Alluvial fans or mountain block	> 100 ft	Ephemeral spring or stream

Category 1 - These groundwater ET areas are most likely either in complete hydraulic connection with the main groundwater system or known to be sustained by regional springs. These areas were considered appropriate for inclusion in numerical models at the regional scale.

Category 2 - These groundwater ET areas may have a complete or partial (semi-perched) hydraulic connection with the main groundwater system, but actual conditions are uncertain.

Category 3 - These groundwater ET areas are typically smaller than 1 km^2 (the resolution of the numerical model) or have no hydraulic connection with the main groundwater system (perched). These areas were not included in the numerical model.

The total areas categorized as 2 and 3 are small compared to the area categorized as 1. To allow calculation and evaluation of the associated ET volumes, groundwater ET areas categorized as 2 and 3 were not removed from the map (Table 7-3). Although the areas categorized as 2 or 3 may not have been appropriate for inclusion in the numerical groundwater flow model, they must be included in groundwater budgets designed to evaluate water resources because the groundwater supporting the associated phreatophytes is part of the water yield for the valley. The three categories of groundwater ET areas were superposed onto the extents of the predevelopment groundwater ET areas and are depicted on Figure 7-3.

7.1.4.2 Method 1 - ET Rates

To derive ET rates for use in the calculations of groundwater ET for Method 1, appropriate ET rates were selected from those available in the literature and were scaled by PET. The literature ET rates, the PET rates, and the data selected are described in the following text.

Available annual ET rates were compiled from the literature for the study area and the region surrounding it. The resulting data set comprises both field measurements and average rates estimated from basin ET volumes and is presented in Table E-1 (Appendix E).

The PET rates were calculated using a regression equation derived from PET data compiled by McCurdy and Albright (2004). The PET calculation details are provided in Appendix E. The spatial distribution is presented on Figure E-1 (Appendix E).

The available ET rates (Table E-1) were reviewed to select the most appropriate rates for each of the five ET classes defined for this analysis. The rates selected for each class were based on the similarities between the vegetation types and the climate, and the availability of supporting data, such as site coordinates, precipitation, and depth to water. The selected ET rates are presented in Table F-1 (Appendix F).

ET-rate measurements for a given ET class were adjusted before being applied to the basins in the study area. The adjustment was performed using PET rates and consisted of scaling the measurements by the ratio of the PET of ET class to that of the ET site (PET of ET class/PET of ET site). The final adjusted ET rates for all classes in all basins are also presented in Table F-2 (Appendix F).

7.1.4.3 Method 1 - Groundwater ET Volumes

Groundwater ET volumes for a given area were calculated as the difference between the total ET volume and the precipitation volume on the area. The volumes were calculated for each class in each basin by multiplying the rates by the groundwater ET area and were summed to derive a volume for the basin. The groundwater ET areas are based on the predevelopment ET map (Figure 7-3).

Total ET volumes were calculated for each ET class for each basin where groundwater ET occurs by multiplying the appropriate PET-scaled ET rate by the area of the ET class.

Table 7-3
Method 1 - Area of Groundwater ET Areas By Category

HA Number	HA Name	Category 1 Area	Category 2 Area	Category 3 Area
		(acres)		
Goshute Valley Flow System				
178B	Butte Valley South	51,100	0	0
179	Steptoe Valley	157,900	1,200	4,400
	Total	**209,000**	**1,200**	**4,400**
Great Salt Lake Desert Flow System				
184	Spring Valley	171,400	100	600
185	Tippett Valley	7,800	0	0
194	Pleasant Valley	0	0	2,100
195	Snake Valley	307,200	2,300	2,400
196	Hamlin Valley	2,900	400	100
	Total	**489,200**	**2,800**	**5,300**
Meadow Valley Flow System				
183	Lake Valley	47,400	0	0
198	Dry Valley	2,100	0	0
199	Rose Valley	300	0	0
200	Eagle Valley	600	0	0
201	Spring Valley	2,200	100	100
202	Patterson Valley	800	0	0
203	Panaca Valley	9,100	0	0
204	Clover Valley	500	0	3,000
205	Lower Meadow Valley Wash	7,800	0	0
	Total	**70,900**	**100**	**3,100**
White River Flow System				
172	Garden Valley	600	0	300
174	Jakes Valley	0	0	1,000
175	Long Valley	17,000	600	0
180	Cave Valley	1,800	14,700	200
207	White River Valley	140,800	3,300	700
209	Pahranagat Valley	8,700	0	0
215	Black Mountains Area	500	0	0
218	California Wash	1,400	0	0
219	Muddy River Springs Area	2,000	0	0
220	Lower Moapa Valley	7,500	0	0
	Total	**180,200**	**18,500**	**2,200**
	Grand Total	**949,300**	**22,600**	**15,000**

Note: Values are rounded to the nearest hundred (see Table F-2). Totals are rounded from the totals reported in Table F-2.

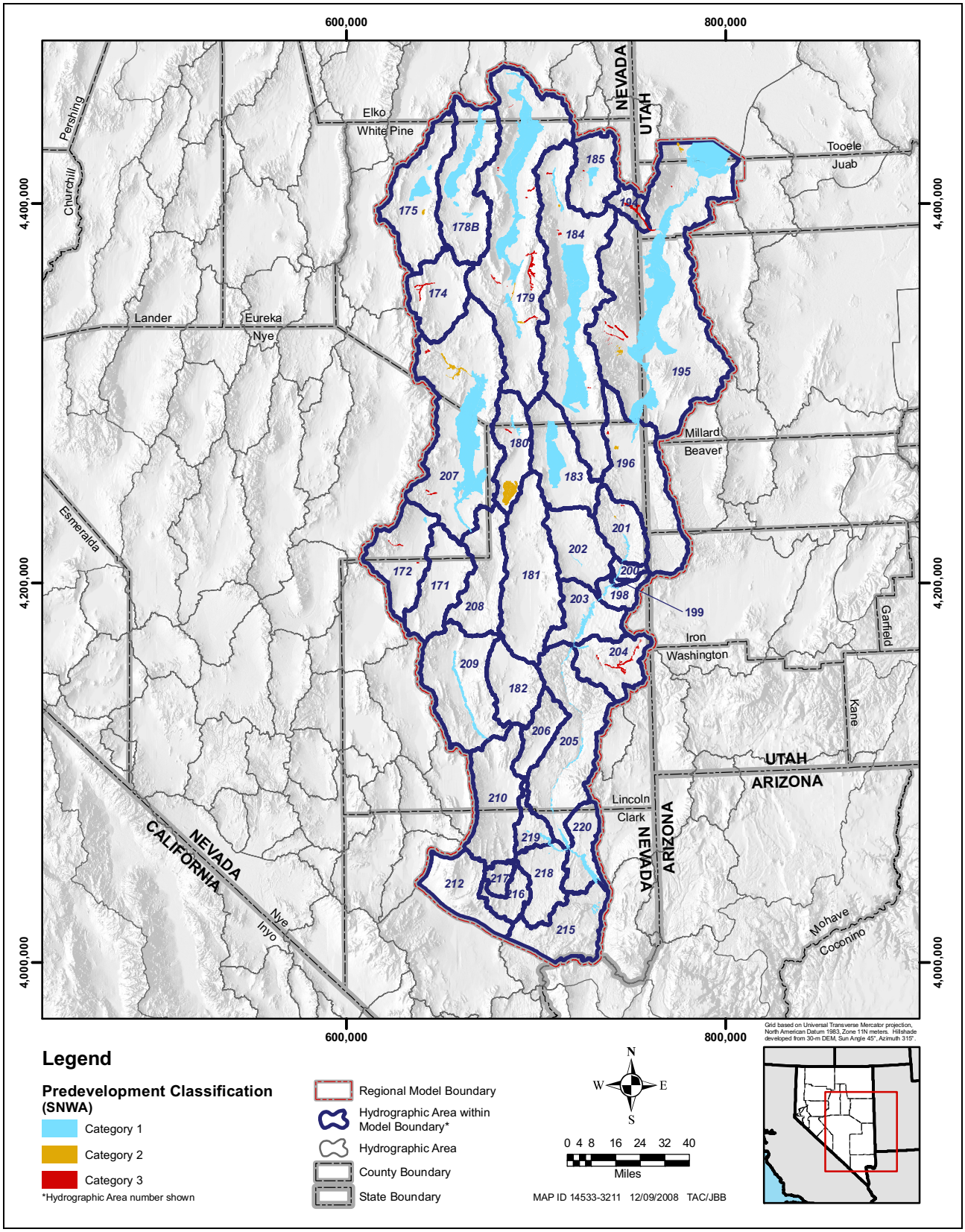


Figure 7-3
Method 1 - Predevelopment Groundwater ET Map Showing Categories

The precipitation rates were obtained from the 800-m PRISM grid by averaging the grid cell values for each ET class within basins where groundwater ET occurs. This is consistent with the simplifying assumption that the observed vegetation within the potential groundwater ET area uses both groundwater and soil moisture (from precipitation) as sources. The precipitation rates are presented in Table F-2 (Appendix F).

The groundwater ET volumes were calculated for each class by subtracting the corresponding precipitation volume (from the 800-m PRISM grid) from the total ET volumes. The groundwater ET volumes were then summed to derive the total volume for the basin. The ET areas and their ET, precipitation, and groundwater ET volumes are presented in Table F-2 (Appendix F). The groundwater ET volumes are summarized by category in Table 7-4. As can be seen from this table, most of the groundwater ET is from areas categorized as 1. The groundwater ET volumes from areas categorized as 2 and 3 constitute less than 5 percent of the total groundwater ET in the study area.

7.1.5 Method 2 (USGS) - Groundwater ET Estimates

The groundwater ET estimates derived for BARCASS (Welch et al., 2008) and for the southern part of the Colorado Regional Ground-Water Flow System (DeMeo et al., 2008) deserve further consideration in this study because they are more detailed than the estimates derived using Method 1. In fact, for BARCASS, Smith et al. (2007) used and refined SNWA's interpretation of the extent of the groundwater ET areas (described under Method 1). Summary descriptions of the methods and results of Welch et al. (2008) and DeMeo et al. (2008) follow.

7.1.5.1 Method 2 - Groundwater ET Areas

Smith et al. (2007) (BARCASS) and DeMeo et al. (2008) used similar methods to identify the ET units within their respective study area. The USGS identifies ET units as areas of similar plant type, density, and vigor (DeMeo et al., 2008). The two methods are summarized below.

BARCAS Study

Smith et al. (2007) used the boundaries delineated by Harrill et al. (1988), Nichols (2000), and SNWA (2008a) to refine the outer limits of the potential groundwater discharge areas located within the BARCASS area. They combined and compared these existing boundaries and resolved the discrepancies they found during field verification trips in mid-July 2005.

Smith et al. (2007) subdivided the potential groundwater ET areas into 11 units using data from SWReGAP ecological systems, interpreted Landsat data from multiple dates (2005), and Landsat MSAVI and Tasseled Cap products. The eleven ET units are as follows:

- Xerophytic
- Open water
- Marshland
- Meadowland
- Grassland
- Moist bare soil

Table 7-4
Method 1 - Groundwater ET Volumes by Category

HA Number	HA Name	Groundwater ET Volumes (afy)			
		Category 1	Category 2	Category 3	Total
Goshute Valley Flow System					
178B	Butte Valley South	11,300	0	0	11,300
179	Steptoe Valley	103,500	1,600	5,300	110,400
	GVFS Total	**114,800**	**1,600**	**5,300**	**121,700**
Great Salt Lake Desert Flow System					
184	Spring Valley	71,700	0	300	72,100
185	Tippett Valley	1,900	0	100	2,000
194	Pleasant Valley	0	0	1,000	1,000
195	Snake Valley	131,700	2,700	2,700	137,200
196	Hamlin Valley	1,300	200	100	1,500
	GSLDFS Total	**206,600**	**2,900**	**4,100**	**213,600**
Meadow Valley Flow System					
183	Lake Valley	6,800	0	0	6,800
198	Dry Valley	3,700	0	0	3,700
199	Rose Valley	600	0	0	600
200	Eagle Valley	1,000	0	0	1,000
201	Spring Valley	3,700	100	100	3,900
202	Patterson Valley	1,300	0	0	1,300
203	Panaca Valley	18,900	0	0	18,900
204	Clover Valley	800	0	4,400	5,200
205	Lower Meadow Valley Wash	21,900	0	0	21,900
	MVFS Total	**58,700**	**100**	**4,600**	**63,400**
White River Flow System					
172	Garden Valley	1,100	0	600	1,700
174	Jakes Valley	0	0	400	400
175	Long Valley	2,800	100	0	3,000
180	Cave Valley	1,100	0	200	1,300
207	White River Valley	63,200	3,900	500	67,600
209	Pahranagat Valley	28,500	0	0	28,500
215	Black Mountains Area	1,400	0	0	1,400
218	California Wash	4,500	0	0	4,500
219	Muddy River Springs Area	6,000	0	0	6,000
220	Lower Moapa Valley	25,300	0	0	25,300
	WRFS Total	**134,000**	**4,100**	**1,600**	**139,700**
	Grand Total	**514,100**	**8,700**	**15,600**	**538,400**

Note: Values are rounded to the nearest hundred (see Table F-2). Totals are rounded from the totals reported in Table F-2.

- Dense desert shrubland
- Moderately dense desert shrubland
- Sparse desert shrubland
- Dry playa
- Recently irrigated cropland—historically mixed phreatophyte

Except for the xerophytic areas, which consist of bare dry soil and/or sparse, non-phreatophytic vegetation, all other identified ET units may contribute to the volume of ET from groundwater. The derived distribution of potential groundwater ET areas is presented in Figure 7-4. The 10 areas of potential groundwater ET were used to estimate groundwater discharge for pre development conditions (Welch et al., 2008). The potential groundwater ET areas were further subdivided by sub-basins (Figure 7-4).

DeMeo et al. (2008)

DeMeo et al. (2008) delineated and classified the study area into eight ET units primarily based on information from multispectral satellite imagery and SWReGAP data. Similarly to BARCASS, the MSAVI method was used to classify the ET units. The eight ET units identified are as follows:

- Dense meadowland vegetation (DMV)
- Dense woodland vegetation (DWV)
- Moderate woodland vegetation (MWV)
- Dense shrubland vegetation (DSV)
- Moderate shrubland vegetation (MSV)
- Agricultural unit (AGU)
- Open water unit (OWU)
- Non-phreatophytic unit (NPU)

More than 99 percent of the study area is occupied by xerophytes (non-phreatophytic unit). Areas covered with xerophytes do not contribute to the volume of ET from surface water and groundwater. The distribution of the groundwater and surface-water ET areas delineated by DeMeo et al. (2008) are shown in their Plate 1 (DeMeo et al., 2008).

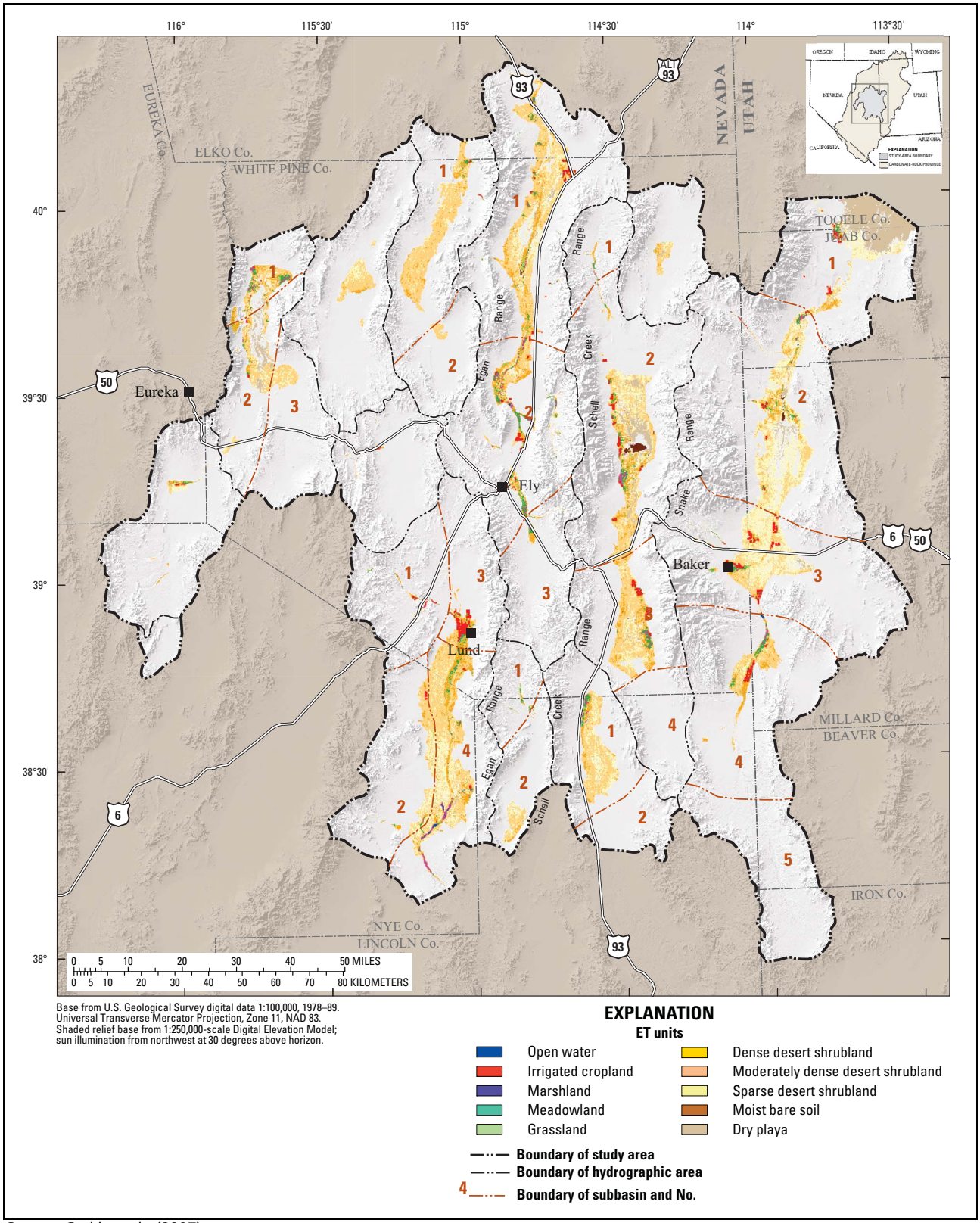
7.1.5.2 Method 2 - ET Rates

Welch et al. (2008) (BARCASS) and DeMeo et al. (2008) used different methods to identify the ET rates for the ET units they identified. The two methods are summarized below.

Welch et al. (2008) BARCASS

Welch et al. (2008) derived a range of ET rates for each of the ET units they identified from the literature. They state that:

> ET rates reported in the more recent literature (Nichols, 2000; Berger et al., 2001; Reiner et al., 2002; Cooper et al., 2006) were used to develop a range of average annual ET for each ET unit inclusive of the variations associated with the different vegetation and soil-moisture conditions making up the ET units delineated for the



Base from U.S. Geological Survey digital data 1:100,000, 1978–89.
Universal Transverse Mercator Projection, Zone 11, NAD 83.
Shaded relief base from 1:250,000-scale Digital Elevation Model;
sun illumination from northwest at 30 degrees above horizon.

EXPLANATION

ET units

- Open water
- Irrigated cropland
- Marshland
- Meadowland
- Grassland
- Dense desert shrubland
- Moderately dense desert shrubland
- Sparse desert shrubland
- Moist bare soil
- Dry playa

Boundary of study area

Boundary of hydrographic area

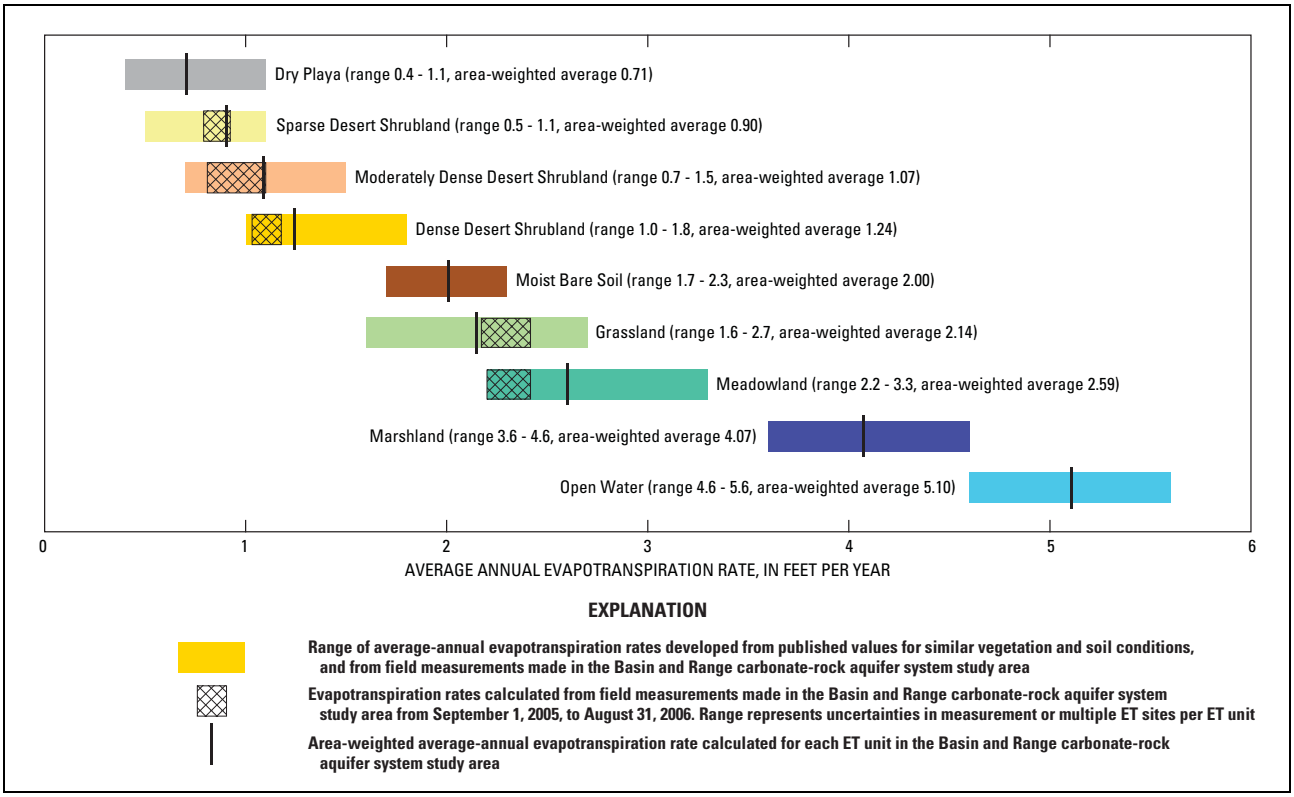
4 **Boundary of subbasin and No.**

Source: Smith et al. (2007)

Figure 7-4
BARCASS Spatial Distribution of Evapotranspiration Units

study area. Annual ET estimates developed from reported values vary from less than 1 ft over playa and sparse shrubland units to more than 5 ft from open water areas. (p. 56)

The derived literature rates are shown on Figure 7-5. Observed ET rates der ived from field data collected for BARCASS are also shown in this figure. They all fall within the literature ranges. The ET rates applied to the ET units were derived by adjusting the literature range of ET of a given zone in a given basin by the range of MSAVI grid values occurring within that zone. A mixed vegetation with a constant mean ET rate of 1.4 ft/yr was assumed for irrigated lands (Welch et al., 2008).



Source: Welch et al. (2008)

Figure 7-5
BARCASS Range of ET Rates from Literature and Measured Values

DeMeo et al. (2008)

ET rates were estimated using data collected at four micrometeorological stations located in ET units or using published ET rates for similar environments. The overall period of data collection extends from 2003 to 2006.

ET sites were installed in four types of ET units: DWV, MWV, DSV, and MSV. Two sites (dense grove of saltcedar trees along the Virgin River floodplain and a dense grove of mesquite trees along the Muddy River) were set up to collect data for analysis with the Bowen-ratio ET method. Two other sites (one in Rainbow Canyon just south of Caliente and one just north of Moapa in Lower Meadow Valley Wash) were set up for analysis with the eddy covariance ET method. A variant of the

Bowen-ratio method was also applied at two sites using data collected for the eddy covariance method. The data collected at these sites were analyzed and used to derive annual estimates of ET (Table 7-5).

Table 7-5
Annual ET Rates Estimated by DeMeo et al. (2008)

Site Name	ET-Unit Name	ET-Unit Identifier	Annual ET_T Rate (ft)
Virgin River	Dense woodland vegetation	DWV	3.9
Muddy River	Moderate woodland vegetation	MWV	3.6
Lower Meadow Valley Wash	Dense shrubland vegetation	DSV	2.8
Rainbow Canyon	Moderate shrubland vegetation	MSV	1.5

7.1.5.3 Method 2 - Precipitation

The precipitation estimates used by Welch et al. (2008) and DeMeo et al. (2008) to adjust the ET rates are presented.

Welch et al. (2008)

The precipitation distribution used in BARCASS is described by Welch et al. (2008) and by Flint and Flint (2007). Welch et al. (2008, p. 60-61) state:

> The average annual precipitation falling directly on ET units was estimated from a map of mean annual precipitation generated from model simulations of monthly precipitation distributions used to estimate average annual recharge for the BARCAS study area over the period 1970–2004 (Flint and Flint, 2007). Estimates of the average annual precipitation to discharge areas delineated within HAs range from about 6 in. in Little Smoky Valley to about 13 in. in Cave Valley (fig. 33, appendix A). In general, precipitation to discharge areas decreases from north to south. Contrarily, the highest annual precipitation occurs in Cave and Lake Valleys in the southern part of the study area. This anomaly is attributed to orographic effects that also contribute to higher annual precipitation in the southern subbasins of Snake and Steptoe Valleys.

Flint and Flint (2007, p. 10-11) describe the process they followed to generate the precipitation distribution they used in their recharge model:

> PRISM precipitation and temperature model results are available as monthly averages from 1895 to 2006 for a 1.8-mi (4-km) grid (Daly and others, 2004). The 1.8-mi grids were interpolated to 866-ft (270-m) grids for 1970–2004 by using spatial gradient and inverse distance squared weighting (Nalder and Wein, 1998)…A search radius of 4.5 mi (10,000 m) was used to limit the influence of distant data. Approximately 25 PRISM grid cells were used to estimate temperature and precipitation for each cell, with the closest cell having the most influence.

DeMeo et al. (2008)

DeMeo et al. (2008) installed a volumetric precipitation gage at each site to collect bulk rainfall during the ET data collection activities. The annual precipitation rates used to adjust ET are 6.0 in. for the Virgin River site, 4.8 in. for the Muddy River site, 6.0 in. for the Rainbow Canyon site, and 7.2 in. for the Lower Meadow Valley Wash site.

7.1.5.4 Method 2 - Groundwater ET Volumes

Welch et al. (2008) and DeMeo et al. (2008) used the general method described in Section 7.1.2.1 to calculate yearly net ET volumes for most of the ET areas they studied.

In the general method of groundwater/surface-water ET volume calculation, the yearly volume from a given ET area is calculated as the yearly groundwater ET rate (Welch et al., 2008) or groundwater/surface-water ET rate (DeMeo et al., 2008) (i.e., ET rate reduced by precipitation) times the ET area. However, DeMeo et al. (2008) did not have sufficient information from their ET sites. Thus, they obtained published rates of ET_{gs} (ET from both groundwater and surface water) from the literature. DeMeo et al. (2008) obtained rates from Laczniak et al. (1999) for the DMV unit (3.4 ft) and the OWU unit (4.9 ft) and from the Bureau of Reclamation (2005) for the AGU unit (5.2 ft). The OWU unit's annual ET_{gs} rate estimate is a mean value of open-water evaporation from the Lower Colorado River. The AGU unit's annual ET_{gs} rate is the ET consumptive-use rate for alfalfa.

For BARCASS, the groundwater ET volumes were calculated by ET unit (for each of the ten ET units) and each sub-basin. The basins were subdivided into sub-basins to account for the spatial variability of the precipitation. The groundwater net ET volumes calculated for BARCASS are included in Table 7-6.

For the southern CRFS ET study (DeMeo et al., 2008), the yearly ET volumes from both groundwater and surface water were calculated for each ET unit by (1) subtracting the local precipitation from the annual ET rate for that ET unit and (2) multiplying the resulting ET rate, ET_{gs}, by the acreage of the ET units. The annual ET_{gs} rate is the combined ET rate associated with groundwater and surface water.

7.1.6 Comparison of Method 1 and Method 2

The areas of potential ET and their classification are compared, followed by a comparison of estimated annual volumes of net ET.

7.1.6.1 ET Areas and Classifications

Areas of potential groundwater ET identified by SNWA for this study (Method 1) (Figure 7-2) and by the USGS for BARCASS and the southern CRFS (Method 2) (Welch et al., 2008 and DeMeo et al., 2008, respectively) were compared for common basins.

Table 7-6
Net ET Volumes Obtained by Method 2

HA Number	HA Name	Welch et al. (2008)[a]	DeMeo et al. (2008)
Goshute Valley Flow System			
179	Steptoe Valley	101,500	NE
178B	Butte Valley South	11,900	NE
Great Salt Lake Desert Flow System			
184	Spring Valley	75,600	NE
185	Tippett Valley	1,700	NE
254	Big Snake[b]	132,300	NE
Meadow Valley Flow System			
183	Lake Valley	6,100	NE
204	Clover Valley	NE	5,840
205	Lower Meadow Valley Wash	NE	16,168
White River Flow System			
174	Jakes Valley	900	NE
175	Long Valley	1,200	NE
180	Cave Valley	1,600	NE
207	White River Valley	76,700	NE
215	Black Mountains Area	NE	1,952
218	California Wash	NE	6,080
219	Muddy River Springs Area	NE	4,090
220	Lower Moapa Valley	NE	11,510

NE = Not Estimated
[a]Values are rounded to the nearest hundred
[b]Big Snake includes Pleasant, Snake, and Hamlin valleys.

Welch et al. (2008)

The acreages for Method 1 and Method 2 (BARCASS) and the differences are presented in Table 7-7. For the most part, total acreages of polygons were quite similar, but BARCASS acreages were generally larger. The average difference as a percent of the mean acreage is about 13 percent. For further comparison between the two groundwater ET maps, the BARCASS ET units were correlated to the ET units identified in this study based on similarities in species composition and percent cover. The correlation of the two units is shown in Table 7-8. The ET units from the two studies did not, however, correlate well spatially.

DeMeo et al. (2008)

A comparison of the ET acreages estimated by SNWA for Method 1 and by DeMeo et al. (2008) for Method 2 is presented in Table 7-9. Note that the table does not include the basins common to the two studies that do not have any groundwater/surface-water ET. Except for Lower Moapa, the ET acreages derived by Method 1 are generally less than those derived by Method 2 (DeMeo et al.,

Table 7-7
Basin ET Acreage Comparison between Method 1 and Method 2 (BARCASS)

HA Number	HA Name	ET Acreage		Absolute Difference as Percent of Mean Area
		Method 1	Method 2/ BARCASS[a]	
Goshute Valley Flow System				
179	Steptoe Valley	163,521	174,540	7
178B	Butte Valley South	51,132	69,671	31
Great Salt Lake Desert Flow System				
184	Spring Valley	172,154	177,698	3
185	Tippett Valley	7,819	7,775	1
254	Big Snake[b]	317,395	325,440	3
White River Flow System				
175	Long Valley	17,595	18,283	4
174	Jakes Valley	971	1,224	23
207	White River Valley	144,692	178,096	21
180	Cave Valley	16,649	13,348	22
Meadow Valley Flow System				
183	Lake Valley	47,445	55,472	16

[a]Smith et al. (2007, Table 4)
[b]Includes Pleasant (194), Snake (195), and Hamlin (196) valleys

Table 7-8
Correlation of Method 1 ET Class and Method 2 (BARCASS) ET Units

Method 1 - ET Class	Method 2-ET Unit Welch et al. (2008)
Open Water	Open Water
Bare Soil/Low Vegetation	Sparse to Moderate Desert Shrubland
Phreatophyte/Medium Vegetation	Dense Desert Shrubland
	Moderately Dense Desert Shrubland
	Recently Irrigated Cropland
Wetland/Meadow	Marshland
	Meadowland
	Grassland
Playa	Moist Bare Soil
	Playa

Table 7-9
Basin ET Acreage Comparison between Method 1 and Method 2 (DeMeo et al., 2008)

HA Number	HA Name	Method 1[a]	Method 2 DeMeo et al. (2008)	Absolute Difference as Percent of Mean Area
204	Clover Valley	3,500	3,500	0
205	Lower Meadow Valley Wash	7,800	9,410	19
215	Black Mountains Area	500	1,340	91
218	California Wash	1,400	2,400	53
219	Muddy River Springs Area	2,000	2,350	16
220	Lower Moapa Valley	7,500	4,250	55

[a]Values are rounded to the nearest hundred.

2008). The average difference as a percent of the mean acreage is about 39 percent. However, when these same percent differences are weighted by the mean ET areas, the mean percent error is only 5 percent. The correlation of ET units is shown in Table 7-10. A major difference in the ET classification is that in Method 1, the agr icultural areas were converted back to their likely natural state, whereas in Method 2 they were not.

Table 7-10
Correlation of Method 1 ET Class and Method 2 (DeMeo et al., 2008) ET Units

Method 1 - ET Class	Method 2 - ET Unit DeMeo et al. (2008)
Open Water	Open water unit
Phreatophyte/Medium Vegetation	Dense shrubland vegetation
	Moderate shrubland vegetation
Wetland/Meadow	Dense woodland vegetation
	Moderate woodland vegetation
	Dense meadowland vegetation
	Agricultural unit

Differences

The differences between the acreages and the classes identified for Method 1 and Method 2 stem from three differences between the two methods:

- The satellite imagery used was from two different years: 2005 im agery for BARCASS and southern CRFS (DeMeo et al., 2008; Welch et al., 2008, respectively) and 2002 imagery for SNWA. Whereas the year 2005 is considered to be a wet year, the year 2002 is considered to be a dry year. The potential ET areas may be more extensive during wet years.

- For BARCASS, USGS conducted field visits in areas that SNWA did not visit, identifying additional phreatophytic areas.

- Whereas DeMeo et al. (2008) and Welch et al. (2008) used the MSAVI method to derive their classifications of the phreatophytic areas, SNWA used the NDVI method. Although the two methods are quite similar, the MSAVI method accounts for the presence of soils and therefore may yield different classes than the NDVI method.

7.1.7 Comparison of Net ET Volumes

As stated in Section 7.1, net ET volumes are total ET minus precipitation. The net ET volumes obtained by Method 1 and Method 2 are listed in Table 7-11. The differences, when significant, and their causes are discussed in this section.

Despite the differences between the extent of the ET areas and the differences in the ET classes, the ET rates, and the precipitation distributions, the basin groundwater ET volumes derived for Method 2 (BARCASS) compare closely to those derived by Method 1.

The comparison between Method 1 and Method 2 (DeMeo et al., 2008) depends on the basin and the extent of the potential ET area. The differences in the net ET volumes for some of the basins are relatively large, but the areas themselves are small (less than 2,500 acres). This is the case for Black Mountains Area, California Wash, and Muddy River Springs Area. All three areas have annual net ET volumes of less than 10,000 afy (Table 7-11).

The comparison is more complicated for Lower Meadow Valley Wash and Lower Moapa Valley. The amounts are large and different. For Lower Meadow Valley Wash, the annual volume of net ET is 21,900 afy for Method 1 and 16,168 afy for Method 2. For Lower Moapa Valley, the annual volume of net ET is 25,300 afy for Method 1 and 11,510 afy for Method 2. Whereas DeMeo et al. (2008) state that their estimates of ET include both groundwater and surface water, SNWA (Method 1) assumed that the surface water flowing in Meadow Valley Wash was of groundwater origin. Thus, the Method 1 estimates of net ET are estimates of groundwater ET. Nonetheless, uncertainty in the source of water that evapotranspirates is acknowledged for all ET areas and may be larger in ET areas when open water bodies are present. For Lower Moapa Valley, the estimate derived by DeMeo et al. (2008) appears to be too low. The estimate of net ET derived by Method 1 is more consistent with the decrease in stream flow between two stream gages located on the Muddy River as described in Section 7.3.1.1.3.

7.1.8 Conceptual Model Groundwater ET Estimates

The groundwater ET estimates used in the conceptual model of the groundwater flow system of the model area are a combination of Method 1 and Method 2. The specifics are as follows:

- Northern basins: Method 2/BARCASS estimates (Welch et al., 2008).

Table 7-11
Net ET Volumes Obtained by Method 1 and Method 2

HA Number	HA Name	Method 1	Method 2	
		SNWA (This Study)[a]	Welch et al. (2008)[a]	DeMeo et al. (2008)
Goshute Valley Flow System				
179	Steptoe Valley	101,700	101,500	NE
178B	Butte Valley South	11,900	11,900	NE
Great Salt Lake Desert Flow System				
184	Spring Valley	75,400	75,600	NE
185	Tippett Valley	1,700	1,700	NE
254	Big Snake[b]	132,000	132,300	NE
Meadow Valley Flow System				
183	Lake Valley	5,900	6,100	NE
198	Dry Valley	3,700	NE	NE
199	Rose Valley	600	NE	NE
200	Eagle Valley	1,000	NE	NE
201	Spring Valley	3,900	NE	NE
202	Patterson Valley	1,300	NE	NE
203	Panaca Valley	18,900	NE	NE
204	Clover Valley	5,200	NE	5,840
205	Lower Meadow Valley Wash	21,900	NE	16,168
White River Flow System				
172	Garden Valley	1,700	NE	NE
174	Jakes Valley	900	900	NE
175	Long Valley	2,300	1,200	NE
180	Cave Valley	1,700	1,600	NE
207	White River Valley	76,400	76,700	NE
209	Pahranagat Valley	28,500	NE	NE
215	Black Mountains Area	1,400	NE	1,952
218	California Wash	4,500	NE	6,080
219	Muddy River Springs Area	6,000	NE	4,090
220	Lower Moapa Valley	25,300	NE	11,510

NE = Not Estimated
[a]Values are rounded to the nearest hundred.
[b]Big Snake includes Pleasant, Snake, and Hamlin valleys.

- Southern basins other than Lower Meadow Valley Wash and Clover Valley: Method 1/SNWA estimates.

- Lower Meadow Valley Wash and Clover Valley: Method 2/southern. CRFS estimates (DeMeo et al., 2008) adjusted to remove ET by surface water.

The BARCASS estimates (Welch et al., 2008) and Method 1 estimates were initially combined to produce a consistent set of estimates for the CCRP model. The southern CRFS estimates (DeMeo et al., 2008) were added later. The process is described below.

7.1.8.1 Combination of Method 1 and BARCASS (Method 2)

The use of the BARCASS estimates for the northern basins was deemed most appropriate based on the following considerations:

- BARCASS ET area extents are a refinement of SNWA extents.
- BARCASS ET mapping is more detailed: 10 units for BARCASS versus 5 classes for SNWA.
- Total ET rates were allowed to vary spatially (adjusted by MSAVI).

In order to use both Method 1 and Method 2 (BARCASS), the Method 2 data required simplification. The simplification was performed because the two methods are incompatible with respect to their ET unit classifications and different rates of ET and precipitation. The simplification was also performed to simplify ET in the numerical model. A consistent groundwater ET data set was derived by reducing the BARCASS data set to five ET classes and combining the two data sets. The Method 2 data set was modified as follows:

- The 10 BARCASS ET units were grouped into 5 ET classes that are similar to the 5 ET classes defined in Method 1.

- Mean ET rates were calculated for each of the 5 ET classes in each basin by averaging the ET rates associated with the 10 BARCASS ET units of each basin. These mean rates were weighted by the areas of the BARCASS ET units.

- Mean precipitation rates were calculated for each of the five ET classes in each basin by averaging the precipitation rates used by Welch et al. (2008) for the BARCASS ET units. These means were also weighted by the areas of the BARCASS ET units.

7.1.8.2 Resulting ET Estimates

The resulting ET areas and annual volumes of groundwater ET for the five ET classes for the basins of the study area are listed in Table 7-12 by category as previously described in Table 7-2. The simplification of Method 2 results in volumes that are slightly different from those reported by Welch et al. (2008). The combined ET data set was used to accomplish the following:

- Directly compare the ET rates and volumes derived using Methods 1 and 2.

Table 7-12
Groundwater ET Areas and Volumes by Basin Using Combined Data Set

HA Number	HA Name	Groundwater ET Area (acre)				Groundwater ET Volume (afy)			
		Categories				Categories			
		1	2	3	Total[a]	1	2	3	Total[a]
Goshute Valley Flow System									
178B	Butte Valley (South)	69,400	0	300	69,700	11,800	0	100	11,900
179	Steptoe Valley	169,000	400	5,200	174,600	96,600	200	4,900	101,700
	Total	**238,400**	**400**	**5,500**	**244,300**	**108,400**	**200**	**5,000**	**113,600**
Great Salt Lake Desert Flow System									
184	Spring Valley	176,800	300	700	177,800	74,900	100	400	75,400
185	Tippett Valley	7,700	0	0	7,800	1,700	0	0	1,700
194	Pleasant Valley	0	0	1,100	1,100	0	0	1,000	1,000
195	Snake Valley	316,600	1,400	2,300	320,300	126,500	1,100	1,800	129,400
196	Hamlin Valley	3,800	400	0	4,200	1,800	200	0	2,100
	Total	**504,900**	**2,100**	**4,100**	**511,200**	**204,900**	**1,400**	**3,200**	**209,600**
Meadow Valley Flow System									
183	Lake Valley	55,500	0	0	55,500	5,900	0	0	5,900
198	Dry Valley	2,100	0	0	2,100	3,700	0	0	3,700
199	Rose Valley	300	0	0	300	600	0	0	600
200	Eagle Valley	600	0	0	600	1,000	0	0	1,000
201	Spring Valley	2,200	100	100	2,300	3,700	100	100	3,900
202	Patterson Valley	800	0	0	800	1,300	0	0	1,300
203	Panaca Valley	9,100	0	0	9,100	18,900	0	0	18,900
204	Clover Valley	500	0	3,000	3,500	900	0	4,900	5,800
205	Lower Meadow Valley Wash	7,800	0	0	7,800	9,700	0	0	9,700
	Total	**78,900**	**100**	**3,100**	**82,000**	**45,700**	**100**	**5,000**	**50,800**
White River Flow System									
172	Garden Valley	600	0	300	900	1,100	0	600	1,700
174	Jakes Valley	0	0	1,200	1,200	0	0	900	900
175	Long Valley	17,800	500	0	18,300	2,200	100	0	2,300
180	Cave Valley	1,900	11,300	200	13,400	1,200	400	100	1,700
207	White River Valley	174,000	2,900	1,300	178,200	73,700	1,600	1,100	76,400
209	Pahranagat Valley	8,700	0	0	8,700	28,500	0	0	28,500
215	Black Mountain Area	500	0	0	500	1,400	0	0	1,400
218	California Wash	1,400	0	0	1,400	4,500	0	0	4,500
219	Muddy River Springs Area	2,000	0	0	2,000	6,000	0	0	6,000
220	Lower Moapa Valley	7,500	0	0	7,500	25,300	0	0	25,300
	Total	**214,400**	**14,700**	**3,000**	**232,100**	**143,900**	**2,100**	**2,700**	**148,700**

Note: Values are rounded to the nearest hundred.
[a]Hydrographic area totals are rounded from the totals reported in Table F-3.

- Calculate and compare groundwater ET volumes for each category of ET area in each basin.
- Derive stochastic estimates of groundwater ET volumes using a single ET data set.

The combined data set permits comparisons between the ET rates and the annual groundwater ET volumes. The rates derived using the two methods were found to be comparable (Appendix F, Figure F-1), particularly at the lower rates (less than 2 ft/yr). For mid-range ET rates (between 2 and 3 ft/yr), most rates derived by BARCASS are slightly larger than those used in Method 1. However, at the higher rates (larger than 4.5 ft/yr), the Method-1 ET rates are larger than those derived by BARCASS. These rates, which represent open water, differ by about 1 ft/yr or about 20 percent of the average between the two values. This difference is due to the fact that in BARCASS, the open-water evaporation rates were set at 5.2 ft/yr, whereas in Method 1, they were varied to account for spatial climate variations.

The combined groundwater ET map is shown on Figure 7-6. After the two maps were combined, the categories previously defined (Table 7-2) were applied to the ET areas. The groundwater ET map showing the three categories is shown on Figure 7-7. The areas of potential groundwater ET are presented in Table 7-13 by category. The combined groundwater ET volumes by ET class, by category, and by basin are also presented in Table 7-13.

To allow more flexibility in the selection of calibration targets for the numerical model, an additional subdivision of the groundwater ET areas was implemented. Sub-areas of similar topography and depth to water were identified and used to subdivide the potential groundwater ET areas of selected basins (highlighted in light blue in Figure 7-6).

7.1.8.3 Addition of Method 2 (DeMeo et al., 2008)

The BLM Hydrology Technical Group recommended that the estimates of groundwater ET obtained by Method 1 for Lower Meadow Valley Wash be updated with estimates derived by De Meo et al. (2008) and adjusted for surface water.

DeMeo et al. (2008) estimated a total of 16,168 afy of ET from both groundwater and surface-water for Lower Meadow Valley Wash. The BLM Hydrology Technical Group recommended that a volume equal to stream flow loss of 6,500 afy along the Meadow Valley Wash in Lower Meadow Valley Wash be removed from the estimate of net ET. The remainder of 9,668 afy is assumed to be from groundwater ET. The mean volume of stream flow loss along the Meadow Valley Wash for predevelopment conditions cannot be accurately calculated because of the lack of complete stream-gaging records for appropriate gages. It is, however, possible to estimate the amount of loss from the information reported by Rush (1964) and from stream-gaging records reported by the USGS (2005, 2008).

Rush (1964) reported a mean annual stream flow of 9,400 afy at a gage located 4.5 mi south of Caliente for the period of 1952 to 1959. Rush (1964) also reported a mean stream flow of 8,620 afy from 1951 to 1960. Based on stream flow measurements made on February 17, 1955, by the USGS, stream flow in Meadow Valley Wash near Rox, Nevada, was 2.5 cfs or 2,800 afy. The difference is 6,600 or 5,820 afy, depending on the Caliente measurement used (USGS, 2005).

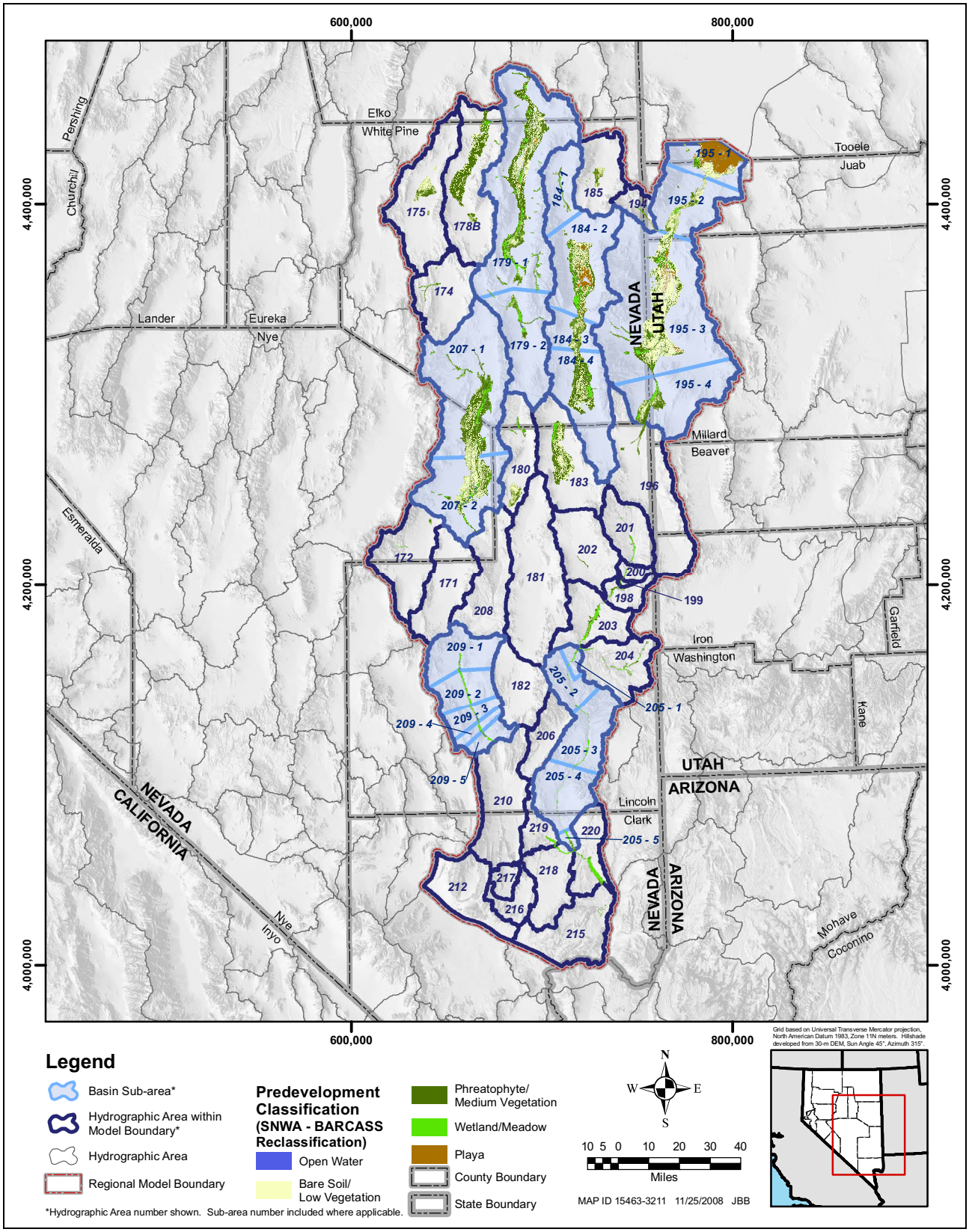


Figure 7-6
Project Predevelopment Groundwater ET Map Showing Basin Sub-Areas

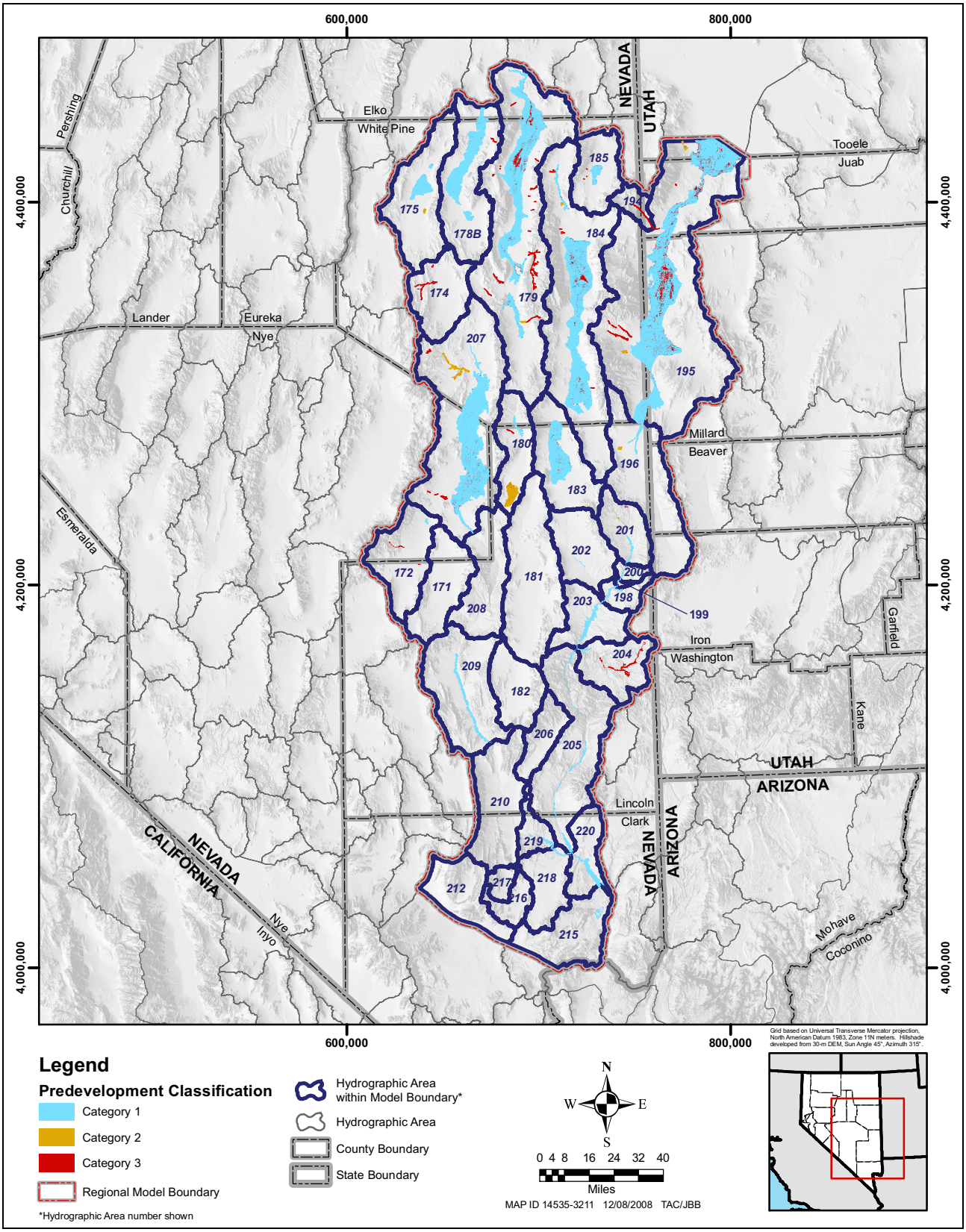


Figure 7-7
Project Predevelopment Groundwater ET Map Showing Categories

Table 7-13
CCRP Model Groundwater ET Volumes Estimates and Comparison to Reported Estimates in afy

HA Number	HA Name	CCRP Model	SNWA (This Study)[a]	Welch et al. (2008)[a]	Nichols (2000)	LVVWD (2001)	SNWA (2007)	DeMeo et al. (2008)	Reconnaissance Studies
Goshute Valley Flow System									
179	Steptoe Valley	101,500	101,700	101,500	128,000	NE	NE	NE	70,000
178B	Butte Valley South	11,900	11,900	11,900	44,500[b]	NE	NE	NE	1,200
Great Salt Lake Desert Flow System									
184	Spring Valley	75,600	75,400	75,600	90,000	NE	NE	NE	70,000
185	Tippett Valley	1,700	1,700	1,700	2,900	NE	NE	NE	NE
254	Big Snake[c]	132,300	132,000	132,300	NE	NE	NE	NE	80,000
Meadow Valley Flow System									
183	Lake Valley	6,100	5,900	6,100	NE	24,000	NE	NE	8,500
198	Dry Valley	3,700	3,700	NE	NE	4,000	NE	NE	3,600
199	Rose Valley	600	600	NE	NE	700	NE	NE	
200	Eagle Valley	1,000	1,000	NE	NE	1,000	NE	NE	
201	Spring Valley	3,900	3,900	NE	NE	1,000	NE	NE	
202	Patterson Valley	1,300	1,300	NE	NE	5,000	NE	NE	
203	Panaca Valley	18,900	18,900	NE	NE	26,000	NE	NE	
204	Clover Valley	5,840	5,200	NE	NE	2,000	NE	5,840	
205	Lower Meadow Valley Wash	9,668	21,900	NE	NE	27,000	NE	16,168	
White River Flow System									
172	Garden Valley	1,700	1,700	NE	NE	5,000	1,696	NE	2,000
174	Jakes Valley	900	900	900	600	600	392	NE	NE
175	Long Valley	2,300	2,300	1,200	11,000	11,000	2,952	NE	2,200
180	Cave Valley	1,700	1,700	1,600	NE	5,000	1,285	NE	200
207	White River Valley	76,400	76,400	76,700	NE	80,000	67,342	NE	37,000
209	Pahranagat Valley	28,500	28,500	NE	NE	38,000	28,516	NE	25,000
215	Black Mountains Area	1,400	1,400	NE	NE	0	1,432	1,952	1,200
218	California Wash	4,500	4,500	NE	NE	6,000	4,505	6,080	6,700[d]
219	Muddy River Springs Area	6,000	6,000	NE	NE	5,000	5,989	4,090	2,300
220	Lower Moapa Valley	25,300	25,300	NE	NE	26,000	25,311	11,510	24,000[d]

NE = Not Estimated
[a]Values are rounded to the nearest hundred.
[b]The reported value is the total ET for Butte Valley North and South.
[c]Big Snake includes Pleasant, Snake, and Hamlin valleys.
[d]The reported discharge value is a combination of water used by natural plants and crops.

Historical stream flow records are available for two gaging stations bracketing almost the entire length of the Meadow Valley Wash in the Meadow Valley Wash hydrographic area (USGS, 2005, 2008). Meadow Valley Wash near Caliente, Nevada (09418500) gaging station is located at the northern end of the hydrographic area, and Meadow Valley Wash near Rox, Nevada (09418700) gaging station is located at the southern end of the hydrographic area. The upstream gage near Caliente has stream flow records from 1951 to 2008 that reflect a mean annual flow of 9.94 cfs (USGS, 2008). The downstream gage near Rox, Nevada, was operated from 1987 to 2005 and has a mean annual flow of 2.37 cfs (USGS, 2005). The difference in stream flow between the two gages is 7.57 cfs or 5,481 afy.

The estimated flow loss along Meadow Valley Wash was derived from information provided by Rush (1964) and USGS (2005) and ranges between 5,481 and 6,600 afy. The amount used to adjust ET (6,500 afy) falls in that range. The adjusted ET estimate of 9,668 afy is assumed to represent groundwater ET in the CCRP model. The estimate of net ET derived by DeMeo et al. (2008) for Clover Valley (5,840 afy) was also used in the CCRP model.

The changes to the groundwater ET estimates of Clover Valley and Lower Meadow Valley Wash, although important for the MVFS, are minor at the regional scale. Therefore, the comparison of rates and the Monte Carlo simulations of groundwater ET described later in this section were not updated. The results would be essentially the same. It was, however, important to incorporate the new estimates in the deterministic estimates of groundwater ET prior to revising the groundwater-budget solutions.

To incorporate the updated estimates of groundwater ET into the CCRP estimates described in the previous section, the ET areas and the five ET classes were assumed to be the same as in Method 1. The total ET volume for Clover Valley and Lower Meadow Valley Wash were adjusted to represent those estimated by DeMeo et al. (2008). The ET volumes of each class and each category were adjusted by the ratio of the new ET volume (Method 2 - DeMeo et al., 2008) over the old ET volume (Method 1) for the basin.

7.1.8.4 Comparison to Other Studies

The volumes of groundwater ET estimated for the conceptual model were compared to volumes estimated by previous investigators (Table 7-13). These include SNWA (2007), Nichols (2000), and LVVWD (2001), and those related to the Reconnaissance studies conducted by the USGS. Each ET study is summarized and then compared to the CCRP estimates.

- Welch et al. (2008) and DeMeo et al. (2008) reflect the numbers that were used in Method 2.

- Nichols (2000) estimated groundwater ET for 16 valleys in central and eastern Nevada. For some basins, the annual groundwater ET volume estimates are substantially larger than estimates made by others.

- LVVWD (2001) estimated groundwater ET for all basins in the White River and Meadow Valley flow systems. Potential groundwater ET areas were delineated using satellite imagery and previous mapping efforts available at that time. ET rates were based on the work of

Devitt et al. (1998) on the Virgin River and on published rates by USGS and the NRCS (formerly the Soil Conservation Service).

- SNWA (2007) estimated groundwater ET for the basins of the WRFS in support of the water-rights hearing for SNWA's groundwater applications in Cave, Dry Lake, and Delamar valleys. The information used to derive the estimates was very similar to that used in Method 1 of this study.

- In the NDWR/USGS reconnaissance studies (1940s–1970s), the areas of groundwater ET were mapped in the field. Groundwater ET rates were derived from ET tank experiments conducted by Lee (1912), White (1932), Young and Blaney (1942), Gatewood et al. (1950) and Robinson (1970).

The volumes derived by this study are generally comparable to the literature values (Table 7-13). Some significant differences do exist, however, and may be due to two reasons:

- The estimates of ET derived for this study are based on conditions observed in 2002 (Method 1) and 2005 (Method 2). The previous estimates were made for earlier years when natural and anthropogenic conditions were different. The conditions prevailing at the time of the estimates affect the extent of the phreatophytic areas and the plant makeup of these areas.

- The method of groundwater ET estimation affects the estimated volumes. For example, the volume of groundwater ET (101,500 afy) estimated for Steptoe Valley (HA 179) by BARCASS (Welch et al., 2008) and adopted in this study is much less than the 128,000 afy estimated by Nichols (2000). The reason may be that the groundwater ET rates used by Nichols (2000) actually contain some precipitation, whereas all contributions of precipitation to ET were removed from the estimates of this study.

7.1.9 Stochastic Estimates

Stochastic estimates of groundwater ET were derived for the study area. In addition to mean values of groundwater ET, the stochastic method provides estimates of the range of uncertainty. Uncertainty in the groundwater ET estimates is due to uncertainty in the areas, the ET rates, and the precipitation estimates. The magnitude of the uncertainty in the calculated volumes of groundwater ET was estimated using Monte Carlo simulations implemented in the Crystal Ball software.

The Monte Carlo analysis requires estimates of the uncertainty on each of the input variables: potential ET area, ET rate, and precipitation rate. The uncertainty ranges for each input variable were estimated and are presented in Section F.1.2.1 (Appendix F).

Statistics describing the uncertainty in the groundwater volumes of each ET class in each area of each basin were derived from 10,000 realizations. Realizations resulting in a negative value of groundwater ET were removed from the resulting set of estimates. Statistics derived include stochastic means, coefficient of variation (COV), and ranges of uncertainty by ET class and by basin. Even though the Monte Carlo simulations were conducted for the five ET classes, the results are reported for four major ET classes, as two of the five classes were grouped. The two grouped classes,

Bare Soil/Low Vegetation and Phreatophyte/Medium Vegetation, are not easily distinguishable at the regional scale. The results by sub-area are presented in Table 7-14. The detailed results for the four ET classes in each sub-area of each basin are provided in Table F-8 (Appendix F).

The results were compared with those similar to an uncertainty analysis conducted by DRI (Zhu et al., 2007) as part of BARCASS. Stochastic groundwater ET volumes were derived for the BARCASS basins using the Monte Carlo method. Zhu et al. (2007) calculated the groundwater ET volume as the difference between the total ET volume and the local precipitation volume. They used estimates of the uncertainties associated with the three input parameters, i.e., potential groundwater ET areas, the total ET rates, and the precipitation rates, to quantify the level of uncertainty associated with their groundwater discharge estimates.

Ten thousand Monte Carlo simulations were conducted for each ET unit found within each sub-basin of the BARCASS area. The input parameters, potential groundwater ET areas, ET rates, and precipitation rates, were assumed to follow normal distributions (Laczniak et al., 2001). The mean values of each parameter for each ET class of each sub-basin were set equal to the mean values derived from the deterministic analysis of groundwater ET (Welch et al., 2008).

The uncertainties associated with the three input parameters were characterized by COV estimated from the available information. The mean and COV values are provided by Zhu et al. (2007) in their Tables 2 and 3 for the ET rates, Table 4 for mean acreage, and Table 5 for mean precipitation and COVs. The COV for the area of each ET unit was assumed to be 10 percent. To derive COVs for the ET rates, the literature ranges were assumed to represent ±2 standard deviations of a normal distribution.

The COV values derived by the Monte Carlo analysis (Zhu et al., 2007) are highly variable depending on the sub-basin and the ET unit. However, the COV values of basin groundwater discharge volumes are moderate. This indicates that the overall uncertainty of total groundwater discharge estimate is moderate even if uncertainties on the volumes of smaller areas may be large.

As was the case for the COV values derived by Zhu et al. (2007) for BARCASS, the COVs derived in this study vary greatly depending on the sub-area and the ET unit. The variability in the COVs, however, is much less at the basin level.

The estimates of variances derived from this uncertainty analysis were used in the numerical model to derive appropriate weights for the groundwater ET values. The weighted values were incorporated in the objective function during the model calibration process. The estimates of standard deviations were used to derive a range of potential groundwater ET values.

7.2 Major Springs and Muddy River

Surface-water features located in the study area are discussed in SNWA (2008a). The spring data set is included in Volume 3, and the stream data set is in Volume 2. The springs and streams that have a connection to the main flow system were of interest to the development of the groundwater flow model. An evaluation of the available surface-water features was conducted to identify such features at the regional scale.

Table 7-14
Uncertainty on Annual Volumes of Groundwater ET by Sub-Area
(Page 1 of 2)

Forecast Name	HA Name	Groundwater ET Volume (afy)		Standard Deviation (afy)	COV	Groundwater ET Volume Confidence Interval (afy)			
		Deterministic Mean	Monte Carlo Mean			95 Percent Lower | Upper		99 Percent Lower | Upper	
172-Basin	Garden Valley	1,696	1,703	466	0.27	946	2,477	659	2,800
174-Basin	Jakes Valley	864	885	308	0.35	430	1,424	323	1,667
175-Basin	Long Valley	2,321	3,608	3,331	0.92	14	10,076	10	13,309
178B-Basin	Butte Valley South	11,893	16,522	14,728	0.89	1,484	44,955	1,050	59,165
179-Sub-basin 1	Steptoe Valley	90,297	90,991	26,840	0.29	47,225	136,309	33,968	155,064
179-Sub-basin 2		11,418	11,477	2,200	0.19	7,958	15,186	6,801	16,759
180-Basin	Cave Valley	1,710	3,113	2,192	0.70	869	7,546	553	9,900
183-Basin	Lake Valley	5,944	13,333	9,464	0.71	3,668	32,459	2,660	43,515
184-Sub-basin 1	Spring Valley	2,870	2,881	605	0.21	1,903	3,894	1,556	4,369
184-Sub-basin 2		38,374	38,705	9,532	0.25	23,329	54,854	18,293	62,734
184-Sub-basin 3		8,111	8,234	3,875	0.47	1,872	14,813	762	17,802
184-Sub-basin 4		26,080	26,324	10,394	0.39	9,573	44,045	6,799	51,455
184-Basin		75,435	76,144	14,769	0.19	52,692	100,910	43,837	112,581
185-Basin	Tippett Valley	1,727	1,992	1,355	0.68	202	4,480	91	5,655
194-Basin	Pleasant Valley	1,023	1,027	154	0.15	782	1,291	696	1,402
195-Sub-basin 1	Snake Valley	12,304	13,885	6,418	0.46	5,724	25,971	4,621	31,481
195-Sub-basin 2		15,124	15,217	3,819	0.25	9,282	21,859	7,077	24,764
195-Sub-basin 3		82,324	82,484	26,155	0.32	44,159	129,427	32,139	153,115
195-Sub-basin 4		19,600	19,704	4,957	0.25	11,637	28,094	8,748	31,586
195-Basin		129,352	131,290	27,694	0.21	89,731	179,926	75,669	203,818
196-Basin	Hamlin Valley	2,054	2,063	792	0.38	789	3,405	266	3,959
198-Basin	Dry Valley	3,710	3,716	996	0.27	2,120	5,382	1,481	6,120
199-Basin	Rose Valley	594	596	193	0.32	285	919	170	1,062
200-Basin	Eagle Valley	1,033	1,033	361	0.35	443	1,654	258	1,927
201-Basin	Spring Valley	3,912	3,925	1,232	0.31	1,915	6,002	1,183	6,918
202-Basin	Patterson Valley	1,346	1,350	525	0.39	500	2,226	158	2,635
203-Basin	Panaca Valley	18,895	18,868	4,740	0.25	11,174	26,912	8,297	30,499
204-Basin	Clover Valley	5,840	5,244	1,745	0.33	2,405	8,099	1,338	9,509
205-Sub-basin 1	Lower Meadow Valley Wash	1,293	2,935	796	0.27	1,658	4,276	1,174	4,885
205-Sub-basin 2		959	2,182	737	0.34	1,016	3,438	533	3,978
205-Sub-basin 3		3,194	7,252	2,207	0.30	3,786	11,074	2,340	12,663
205-Sub-basin 4		1,216	2,756	763	0.28	1,556	4,051	1,074	4,647
205-Sub-basin 5		3,006	6,801	1,404	0.21	4,548	9,151	3,681	10,168
205-Basin		9,668	21,927	2,932	0.13	17,186	26,831	15,286	29,020
207-Sub-basin	White River Valley	41,558	43,656	23,682	0.54	10,562	86,243	7,265	105,241
207-Sub-basin		34,888	37,497	15,824	0.42	16,217	67,315	13,213	86,725
207-Basin		76,446	81,154	28,633	0.35	38,792	132,373	28,736	156,913

Table 7-14
Uncertainty on Annual Volumes of Groundwater ET by Sub-Area
(Page 2 of 2)

Forecast Name	HA Name	Groundwater ET Volume (afy)		Standard Deviation (afy)	COV	Groundwater ET Volume Confidence Interval (afy)			
		Deterministic Mean	Monte Carlo Mean			95 Percent Lower | Upper		99 Percent Lower | Upper	
209-Sub-basin 1	Pahranagat Valley	5,683	5,677	836	0.15	4,334	7,076	3,817	7,728
209-Sub-basin 2		8,701	8,682	2,402	0.28	4,912	12,746	3,382	14,580
209-Sub-basin 3		5,865	5,874	829	0.14	4,560	7,267	4,022	7,886
209-Sub-basin 4		3,203	3,193	738	0.23	2,024	4,439	1,544	5,045
209-Sub-basin 5		5,070	5,073	708	0.14	3,923	6,259	3,496	6,796
209-Basin		28,522	28,499	2,840	0.10	23,937	33,298	22,130	35,423
215-Basin	Black Mountains Area	1,432	1,435	290	0.20	970	1,926	782	2,142
218-Basin	California Wash	4,505	4,505	1,126	0.25	2,698	6,415	2,035	7,270
219-Basin	Muddy River Springs Area	5,988	5,998	1,497	0.25	3,613	8,517	2,725	9,780
220-Basin	Lower Moapa Valley	25,311	25,242	5,878	0.23	15,720	35,148	12,379	39,461
	All Basins	**521,940**	**557,638**	**54,984**	**0.10**	**469,806**	**650,950**	**437,930**	**689,576**

7.2.1 Major Springs

An evaluation of the springs present within the study area was conducted to identify and document those that play an important role in the regional groundwater flow system. The purpose of the spring evaluation was to derive information to support the water-budget calculations and the conceptual model of groundwater flow. The specific objectives of the spring evaluation were to (1) classify the springs of the study area by the type of groundwater system and identify springs that are important to the main groundwater system; (2) estimate long-term flow rates; and (3) identify the source depths of regional springs when enough data are available.

7.2.1.1 Spring Classification

The spring data set compiled in SNWA (2008a) was evaluated for completeness. A few springs were found to be missing and were added to the data set. All springs in the new data set were then classified following the classification postulated by Mifflin (1968). His classification is based on the groundwater system from which the springs originate. Groundwater systems were classified as local, intermediate, and regional. Springs may be classified as local, intermediate, or regional based on the following criteria:

- Location within basin
- Water temperature
- Spring flow rate
- Magnitude of fluctuations of spring flow rate
- Geologic and topographic settings

- Geochemical and isotopic data relative to recharge source areas

Regional Springs

A regional spring is defined as a spring that discharges from the carbonate-rock aquifer system. Therefore, regional springs provide an invaluable source of information on the carbonate flow system of the study area. Regional springs have the following characteristics:

- Location on the valley floor
- Water temperatures greater than 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

Previous investigations, including the following selected references, were used to identify all known regional springs present in the study area:

- Meinzer (1942)
- Mifflin (1968)
- Thomas et al. (1986)
- Prudic et al. (1995)

The annual flow volumes of all identified regional springs were included either explicitly or implicitly in the groundwater budget of the conceptual model. Their locations are plotted on Plate 1.

Intermediate Springs

Intermediate springs are also important at the regional scale because they represent a part of the flow system that connects the basin's 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)
- 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

Groundwater flowing out of all identified intermediate springs was implicitly accounted for in the groundwater budget of the conceptual model. Their locations are plotted on Plate 1.

Local Springs (Perched)

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.

The locations of local springs are not shown on Plate 1 because of the large number of springs.

7.2.1.2 Spring Description

Regional and intermediate springs of interest in the basins of the study area are shown in Plate 1. Long-term mean annual spring flows were derived from USGS yearly mean values when available. Otherwise, they were derived from the available spring discharge records. The mean flow rates and standard deviations are presented in Table G-1 (Appendix G). A summary discussion of the regional springs and the intermediate springs selected as flow observation targets are discussed below.

Regional Springs

Regional springs in the study are concentrated within the regional groundwater discharge areas of White River and Pahranagat valleys, the Muddy River Springs area, and Fish Springs Flat.

White River Valley - The groundwater discharge area in White River Valley contains a number of regional springs. Spring discharge measurements for the regional springs are listed in Table G-1. The most significant of these springs are Hot Creek Spring, Preston Big Spring, Moorman Spring, and Moon River Spring. The total average annual discharge measured at these springs is approximately 24 cfs or approximately 17,000 afy.

Pahranagat Valley - The groundwater discharge area in Pahranagat Valley contains a number of springs. Most notable are the Hiko Springs, Crystal Springs, and Ash Springs. Other smaller springs and seeps occur in the southern portion of the discharge area. Hiko, Crystal, and Ash springs have the most significant discharge (Table G-1) and, when combined, produce a total spring discharge of about 36 cfs or about 26,000 afy (Eakin, 1963b). This discharge flows along the Pahranagat Wash and sustains the riparian vegetation located along the wash.

Muddy River Springs Area - The Muddy Springs are located in the eastern part of the Muddy River Springs Area and consist of numerous springs and seeps, including several large thermal spring groups. The springs and seeps are spread over an area of approximately 3 mi^2. The Muddy Springs represent the principal source of groundwater discharge in the southern portion of the WRFS and form the headwaters of the Muddy River. The Muddy River near Moapa gage (09416000) measures the combined spring discharge from the Muddy River Springs Area minus the diversions for municipal and industrial water use.

Fish Springs Flat - Several groups of springs are located in Fish Springs Flat. The largest group is located on and near the NWR and is described by Mundorff (1970) as the Fish Springs Group, which consists of Wilson Hot Springs (aka Wilson Health Springs), Cold Spring, (C-11-14) 4bbb-S1, Big

Spring (aka North Spring), Deadman Spring, Walter Spring and Fish Springs (includes House, Mirror, Thomas, Middle, Lost, Crater, South, and Percy springs). The total discharge from the Fish Springs Group of springs is about 21,000 afy or 29 cfs (USFWS, 2004). Bolke and Sumsion (1978) estimated the total spring discharge at about 27,000 afy. Although the total discharge from Fish Springs is known (described above), the source of the spring flow is much larger than the estimated recharge within Fish Springs Flat. Thus, the source of groundwater flow to the springs must be from neighboring basins through the regional carbonate aquifer. However, the actual flow patterns and individual basin contributions are subject to interpretation.

Intermediate Springs

Significant intermediate springs located in Snake Valley, White River Valley, Steptoe Valley, and the Black Mountains area were included as such in the conceptual model. These intermediate springs were selected because of their relatively large discharge rates, their importance as natural resources, or their geographic locations. For the intermediate springs, the spring pool elevation is used to approximate the spring head potential. The selected intermediate springs include Rogers, Blue Point, McGill, Gandy Warm, Big, and Lund springs. These springs are discussed in greater detail in the following paragraphs.

Rogers and Blue Point Springs - Rogers and Blue Point springs are located in the Black Mountains area hydrographic basin (Plate 1). They are located in the far southern portion of the study area near the terminal end of the WRFS. The source of their water is believed to be a mixture of water from the carbonate aquifer and water from intermediate aquifers (Pohlmann et al., 1998). These springs were selected for inclusion in the conceptual model because of the importance of their geographic location near several important fault structures and their proximity to Lake Mead.

McGill Spring - McGill Spring is located in Steptoe Valley in the northern portion of the study area (Plate 1). It is located near the town of McGill, Nevada. The spring discharges water from alluvial materials between two parallel faults on the valley floor of Steptoe Valley. It is classified intermediate because the source of its water is within Steptoe Valley (Frick, 1985) and because it has a relatively large discharge. The average spring discharge is approximately 10.6 cfs.

Gandy Warm Springs - Gandy Warm Springs is located on the western edge of Snake Valley in the northern portion of the study area (Plate 1). It discharges water from alluvial materials approximately 1.6 mi west of a normal fault. The spring was selected for inclusion in the conceptual model because of its large discharge. The average spring discharge is approximately 17 cfs.

Big Springs - Big Springs is located on the western edge of Snake Valley in the far southern portion of Snake Valley (Plate 1). It discharges from a scarp, in alluvium, 0.6 mi east of a normal fault. The spring is also located 1 mi east of a carbonate-rock outcrop. The spring was selected for inclusion in the conceptual model because of its large discharge of approximately 10 cfs. The spring discharge flows into Big Spring Creek and feeds Lake Pruess.

Lund Spring - Lund Spring is located in the northern portion of White River Valley near the town of Lund, Nevada (Plate 1). It discharges water from a contact between alluvial materials and carbonate bedrock. The deuterium content of Lund Spring water is -113.0‰ and is similar to the deuterium

content of local recharge water (Thomas and Mihevc, 2007). The spring is included in the conceptual model because of its relatively large discharge of approximately 8 cfs.

7.2.1.3 Estimated Depths of Spring Sources

Spring source depths cannot be measured directly. However, they can be estimated using various methods, including the geothermal-gradient method, which is the most straightforward. In this method, the depth of the groundwater source of a given spring is estimated using the temperature of the spring flow and the prevailing temperature-depth relationship (geothermal gradient). The available estimates of the geothermal gradients in Nevada are described in Appendix G. A summary is provided in this section, followed by the estimates of the depths of the source aquifers of major springs in the study area.

Estimates of the geothermal gradients for the study area were obtained from a study by Mifflin (1968) from data and estimates made by the UNR Great Basin Center for Geothermal Energy and from thermal logs obtained from monitor wells drilled by SNWA (Appendix A). Three temperature-depth relationships (presented as red, black, and purple lines on Figure 7-8) were derived from the information discussed by Mifflin (1968). Two relationships were derived from the information obtained from the UNR Great Basin Center. The blue line and blue diamonds on Figure 7-8 represent temperature-depth data compiled by the UNR Great Basin Center for deep wells in Nevada. The brown symbols represent the mean temperature-depth values derived from the thermal logs obtained from monitor wells drilled by SNWA. The thermal logs were conducted before the temperature in the wells stabilized and therefore are not fully representative of formation conditions.

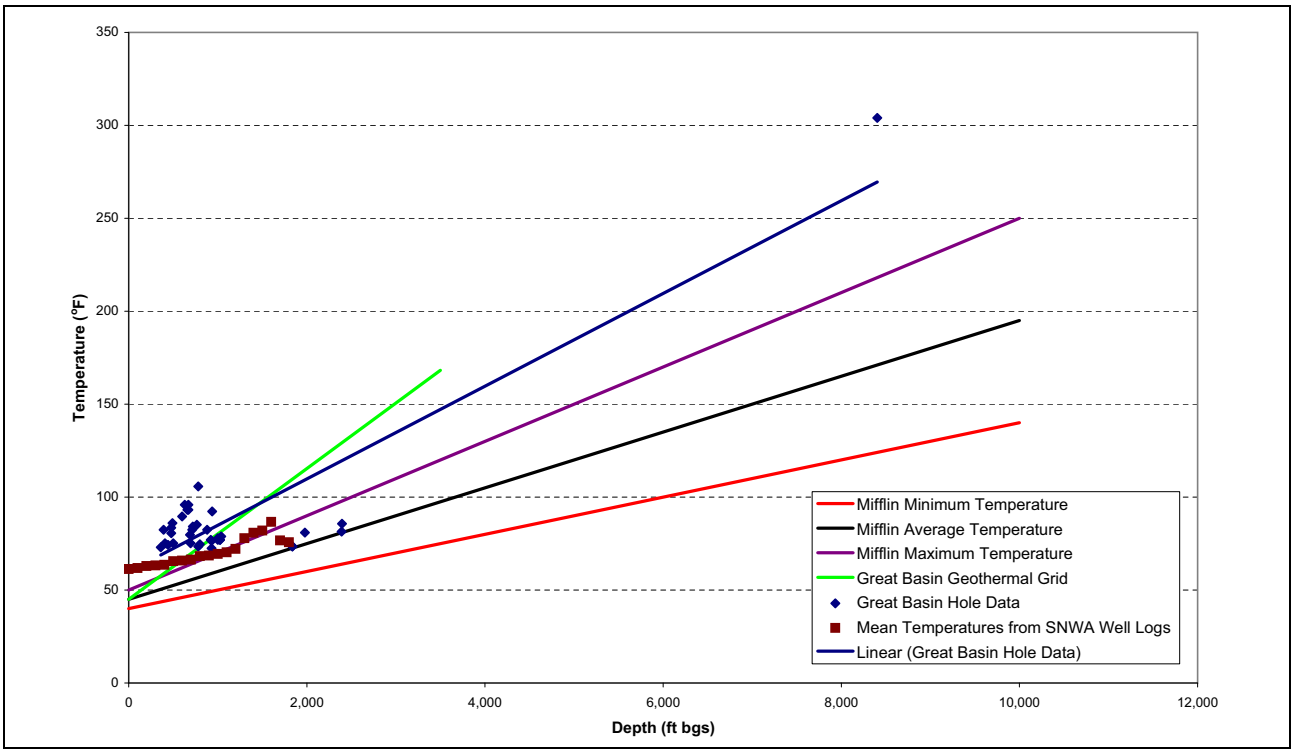


Figure 7-8
Geothermal-Gradient Trends for Nevada

The mean thermal gradient derived from the middle temperature-depth relationship interpreted by Mifflin (1968) was selected to estimate the depth of the source aquifer of major springs in the study area. These estimated depths are listed in Table G-5 (Appendix G). The estimated spring depths range from 81 to 8,422 ft bgs. The depth estimated for one intermediary spring (Stonehouse Spring) was negative because the temperature was too low for the thermal-gradient relationship to be applicable. These source depths are only estimates and do not necessarily represent the only source of water to the springs. Spring flow may originate from an aquifer at a given depth but mix with waters of differing temperatures from overlying aquifers on its way to the surface.

7.3 Streams

Streams of importance to the simulation of the groundwater flow system of the model area include the Muddy River and other smaller spring-fed streams located in Pahranagat and Snake valleys.

7.3.1 Muddy River

The Muddy River is an important hydrologic feature in the model area for several reasons (Figure 7-9). It receives the water discharged from the Muddy Springs and forms a flow path from the Muddy Springs area to the Colorado River (now Lake Mead). In addition, the Muddy River interacts with the aquifer system along its path. The stream aquifer interactions of the Muddy River are not fully understood. However, stream-gaging data acquired at surface sites located along the river channel were evaluated to provide some information (Figure 7-9). The purpose of this evaluation was (1) to derive estimates of predevelopment mean annual stream flow rates at selected stream gages with long periods of records and (2) to estimate the amount of seepage into the stream from groundwater, where possible, from the available synoptic discharge measurements.

7.3.1.1 Estimates of Predevelopment Mean Annual Stream Flow Rates

Estimates of mean annual predevelopment stream flow rates were made at three major gages located along the Muddy River: Muddy River near Moapa, Muddy River near Glendale, and Muddy River at St. Thomas (Figure 7-9). Data on stream flow are included in SNWA (2008a). Mean annual stream flow measurements for the Muddy River near Moapa gage and the Muddy River near Glendale gage are provided in Appendix G.

7.3.1.1.1 Muddy River near Moapa Gage

The Muddy River near Moapa gage (09416000) is located at White Narrows near the intersection of the Muddy River with the boundary of the Muddy River Springs Area hydrographic area (Figure 7-9). It is located downstream from all regional springs and seeps in the Muddy River Springs area. Therefore, stream flow rates measured at this gage represent the total discharge from the springs and seeps located upstream. This gage has a long record starting in 1913. The record of mean annual stream flow rates used in this study is from 1913 to 2004 (Table G-6 in Appendix G). However, records from 1918 to 1943 are missing, and records for 1913 and 1915 are low and constitute outliers.

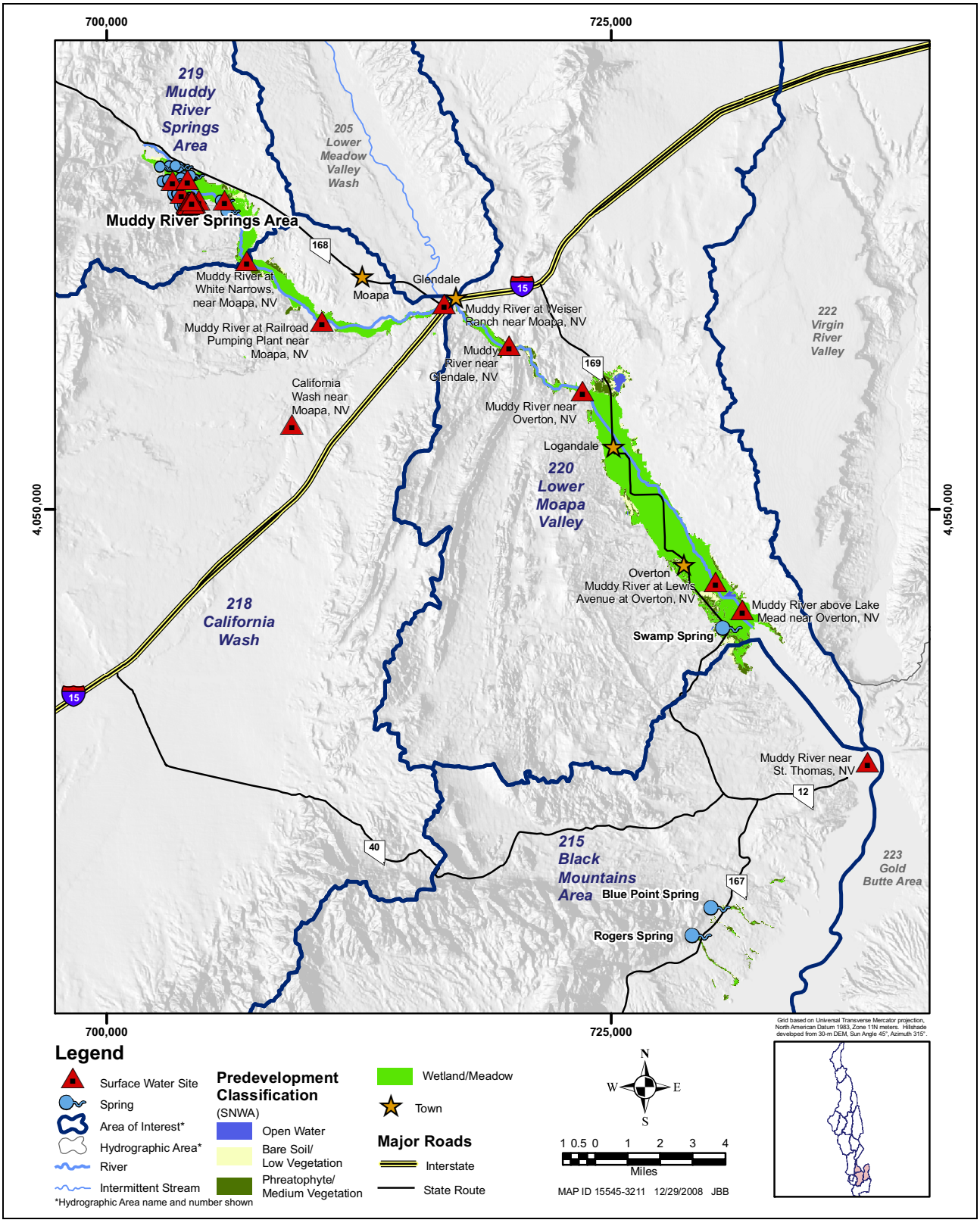


Figure 7-9
Important Hydrologic Features in Muddy River Springs Area and Vicinity under Predevelopment Conditions and Locations of Surface-Water Sites

This gage currently measures the combined spring discharge from the Muddy River Springs area minus the diversions for municipal and industrial water use. Prior to 1962, the measurements represented predevelopment conditions, as no significant diversions were made. From 1913 to 1918, the mean annual discharge at this location was about 34,000 afy (47 cfs). From 1914 to 1962, the mean annual discharge was reported as 33,700 afy (46.5 cfs) (Eakin, 1964). These measurements account for the flow observed at the gage but not the consumptive uses by the riparian vegetation along the spring channels and river corridor or by the phreatophytes that likely existed in the area during predevelopment conditions (Figure 7-9). Eakin (1964) estimated 2,000 to 3,000 afy were being consumed by phreatophytes between the spring area and the gaging station. The discharge from the springs flows into the Muddy River and is believed to support the phreatophytic areas in down-gradient basins, at least in part.

The predevelopment stream flow at the Muddy River near Moapa gage is assumed to be equal to the average annual flow of 33,700 afy (adjusted for precipitation runoff events) (Eakin, 1964). This value corresponds to approximately the same as the value measured in 1945, the assumed end of predevelopment conditions in this study. An estimate of the variability of this estimate may be derived from the historical record up to 1962. The COV of stream flow at that location prior to 1962 was about 0.13 for the raw record (unadjusted) and about 0.02 for the adjusted record, not including suspect measurements.

7.3.1.1.2 Muddy River near Glendale Gage

The Muddy River near Glendale gage is located downstream from the gage near Moapa, within California Wash, and near its hydrographic boundary with Lower Meadow Valley Wash (Figure 7-9). The historical record for the Muddy River near Glendale gage begins in 1951 (Table G-6 in Appendix G). The record of mean annual stream flow rates used in this study is from 1951 to 2004 with the 1984 record missing. Therefore, no data are available for this gage prior to 1945. However, estimates may be derived from the available record using the similarities of this gage with the gage near Moapa discussed in the previous subsection.

An estimate of the correlation between stream flow rates at the Glendale gage and the Moapa gage was derived using the mean annual stream flow rates of the two gages for the period of 1951 to 2004, not including 1984 (Appendix G). The derived correlation coefficient is 0.92, indicating a high degree of correlation between stream flow at the two gages. Considering this high degree of correlation with the gage near Moapa, it is assumed that the gage near Glendale is subject to the same stress conditions as the gage near Moapa. Thus, based on the fact that the stream flow rates measured at the gage near Moapa were relatively stable up to 1962, it is assumed that the stream flow rates measured at the gage near Glendale were also relatively stable up to 1962. Therefore, the predevelopment stream flow at the Muddy River near Glendale gage is assumed to be equal to the average annual flow recorded in 1951, the first recorded year, adjusted for precipitation runoff events, or 31,500 afy. Using the 1951 to 1962 record for this gage, a COV of about 0.11 was derived from the unadjusted measurements and 0.03 for the adjusted measurements. Given the high correlation with the Moapa gage record and the shorter record available for this station, it can be assumed that the variability of stream flow at both locations was similar prior to 1962.

The predevelopment stream flow in the Muddy River decreases from 33,700 afy at the Muddy River near Moapa gage to 31,500 afy at the Muddy River near Glendale gage. Most of the difference of 2,200 afy is lost to ET by riparian vegetation located along the stream in California Wash.

7.3.1.1.3 Muddy River near St. Thomas Gage

The Muddy River near the St. Thomas gaging station was located just upstream from the confluence of the Muddy and Virgin rivers (Figure 7-9). This gaging station was flooded and destroyed when Lake Mead was created. Because of its early record and location with respect to the Colorado River, the gage records for this station were most representative of predevelopment conditions of flow from the Muddy River to the Colorado River. Gage records are available for Water Years (WY) 1913 through 1916 (Wells, 1954).

The gage records began in June of WY 1913 and ended in September of WY 1916, during which time there was a 7-month period of missing records from June of WY 1915 to December of WY 1916 (Wells, 1954). The mean annual flow for the only complete year (WY 1914) was 19.3 cfs, or about 14,000 afy (Wells, 1954). This measurement includes contributions from both groundwater and storm runoff. The period of record mean annual flow was calculated to be 19.6 cfs based on the mean monthly values; however, this value reflects large flood events during February of WY 1914 (136 cfs). Given the limitations of the available records, it is impossible to determine the magnitude of the groundwater component. Rush (1968b) estimated this flow to be 10,000 afy but qualified the estimate as a rough approximation based on few data gathered in 1967. This flow most likely represented agricultural return flows.

For this analysis, it is estimated that about half of the stream flow measured in WY 1914 was groundwater discharge, or 7,000 afy. Furthermore, this value is assumed to represent the portion of stream flow of groundwater origin reaching the Colorado River (pre-lake) or Lake Mead under predevelopment conditions. No data are available to derive COVs for this gage; however, they can be assumed to be at least as large as the COV estimated for the other two gages. Considering the lack of information, they are probably larger.

Stream flow in the Muddy River between the Glendale gage and the St. Thomas gage (Figure 7-9) decreases from 31,500 afy to 7,000 afy, or a difference of about 24,500 afy. This amount is very close to the annual volume of groundwater ET estimated by Method 1 for Lower Moapa Valley. This amount, when reduced by the amount of ET located above the gage near Glendale (2,200 afy), is equal to about 23,100 afy. Therefore, stream flow between the two gages is most probably infiltrating into the groundwater flow system and sustaining the riparian vegetation located along the banks of the Muddy River in Lower Moapa Valley.

7.3.1.2 Seepage into the Muddy River

Two synoptic discharge measurement studies of the Muddy River stream flow (Rush, 1968b, Beck and Wilson, 2006) provide evidence of groundwater seepage into the Muddy River (Figure 7-10). Although these two studies were conducted after 1945, they provide valuable information about the interactions of the Muddy River with the aquifer system.

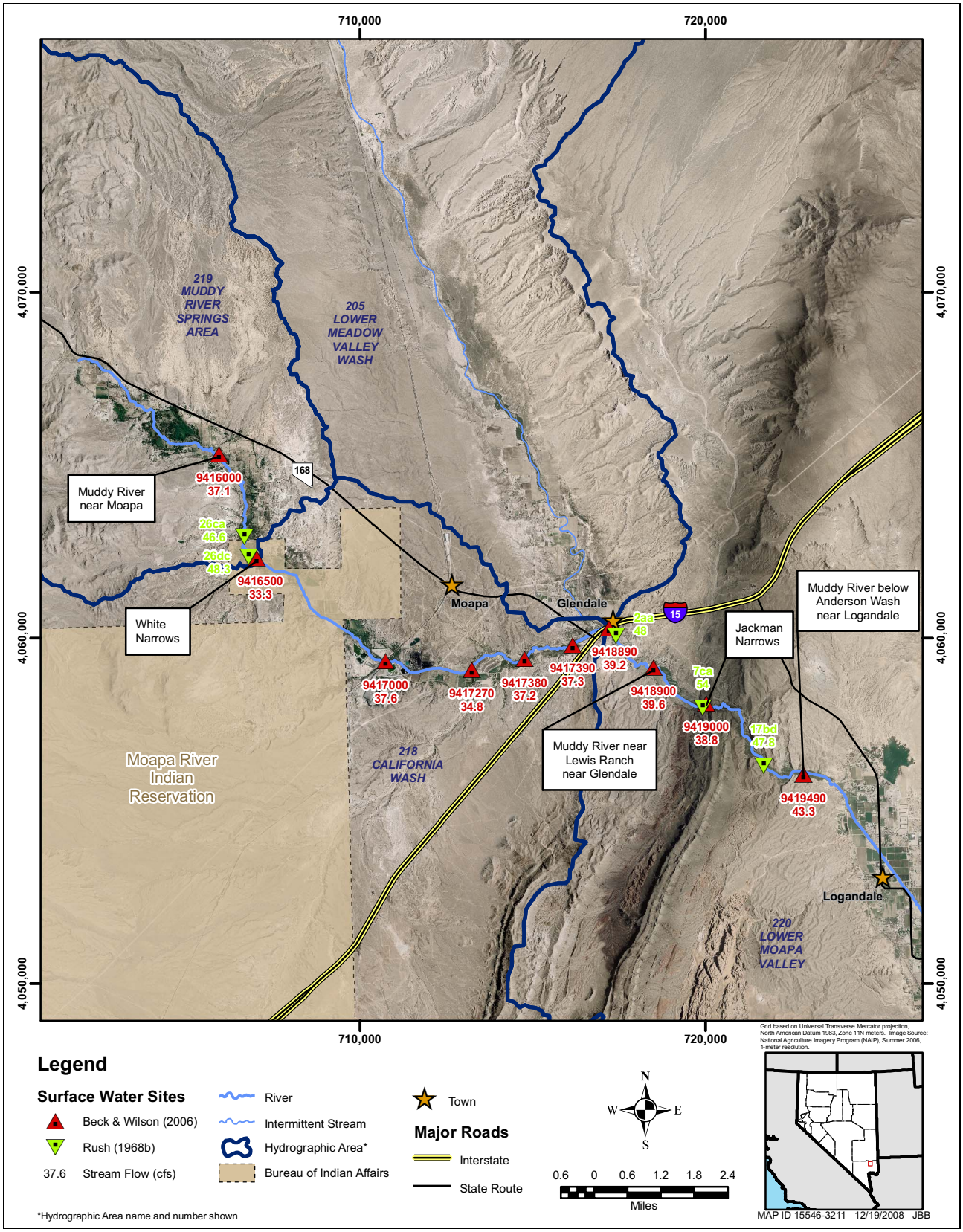


Figure 7-10
Two Sets of Synoptic Discharge Measurements along Muddy River

Rush (1968b) reports measurements from a February 5, 1968, study in which the gage flow above White Narrows was 46.6 cfs, while a measurement made minutes later above Jackman Narrows near Glendale was 48.3 cfs (Figure 7-10). On February 6, 1968, measurements were made at three sites: near Glendale, at Jackman Narrows, and at a site about 1 mi below Jackman Narrows. Flow rates of 48, 54, and 47.8 cfs, respectively, were recorded at these sites. Based on this study, the net gain from above White Narrows to Jackman Narrows is about 7.4 cfs, or 5,360 afy. Rush (1968b) suggests that the observed increase in flow is likely due to inflow from alluvial sediments and/or underlying consolidated rocks, namely the carbonate-rock aquifer.

The second and more recent study (Beck and Wilson, 2006) corroborates the findings of Rush (1968b). Beck and Wilson (2006) describe the results of a synoptic discharge study for approximately the same river reaches described by Rush (1968b) (Figure 7-10). This study was conducted on February 7, 2001, and involved many of the measurement sections. For essentially the same reach, from White Narrows to Jackman Narrows near Glendale, the river gained about 2.5 cfs (about 1,800 afy) based on the maximum values of the gage record for the Muddy River near Moapa gage (09416000) and the measurement section at Muddy River near Lewis Ranch near Glendale (09418900). Maximum flow rates at these sites were measured at 37.1 cfs and 39.6 cfs, respectively (Beck and Wilson, 2006, p. 9). From the gage near Glendale (09418900) to the Muddy River below Anderson Wash near Logandale gage (09419490), an apparent increase in flow of 3.7 cfs (about 2,700 afy) was observed. In total, from the Muddy River near Moapa gage to the Muddy River below Anderson Wash near Logandale gage, an apparent increase in flow of 6.2 cfs, or about 4,500 afy, was observed.

7.3.2 Other Streams Related to Groundwater

Other streams sustained by regional or intermediate springs include the Pahranagat Wash in Pahranagat Valley and Big Spring Creek in Snake Valley (Plate 1). Detailed descriptions of the areas in which these springs and associated streams are located are provided in Volumes 2 and 3 of the Baseline Report (SNWA, 2008a).

The Pahranagat Wash flows south along the central axis of Pahranagat Valley and is sustained by groundwater discharge from three regional springs located in the northwestern part of Pahranagat Valley: Hiko, Crystal, and Ash springs (Plate 1). Spring flow moving down the Pahranagat Wash sustains a significant extent of riparian vegetation along the wash. Spring flow recharges a shallow alluvial aquifer that sustains the phreatophytes. No flow is present in the Pahranagat Wash at the hydrographic-area boundary with Coyote Spring Valley.

In southern Snake Valley, Big Springs discharges into Big Springs Creek, which flows to the northeast toward the Nevada-Utah boundary. In Utah, stream flow occurs in Lake Creek and then Pruess Lake where the water accumulates. Some flow continues slightly after the lake toward Baker before ending (Plate 1). Several other springs (other than Big Springs) contribute additional water to the stream. The gain in the stream below Big Springs has been measured to be approximately 10 cfs (Walker, 1972).

8.0 SELECTED INTERBASIN FLOW LOCATIONS

As stated in Section 5.0, locations, directions, and rates of interbasin flow in the model area are uncertain in many locations. However, it was necessary to quantify interbasin flow at specific locations for two reasons: (1) to use them as constraints in the groundwater-balance method of calculating recharge, and (2) to define boundary conditions for the numerical model. The implementation of the groundwater-budget-method described in Section 9.0 required the selection of specific flow-routing patterns. The groundwater-budget method calculations yielded a recharge distribution, more refined estimates on interbasin flow at selected locations, and groundwater budgets for the model area. Boundary conditions were defined in the numerical model for sufficiently transmissive portions of the model external boundary.

8.1 Location Selection

Potential, regional groundwater flow within the flow systems of the study area occurs through the geologic units present along basin boundaries. Potential locations of boundary segments where interbasin flow could occur within the study area were identified based on the three-dimensional hydrogeologic framework described in SNWA (2008a). The lithology and structure along each of the basin boundaries were examined to assess the likelihood of interbasin groundwater flow across them. Each basin boundary was classified, based on its potential for flow, as likely, permissible, or unlikely (SNWA, 2008a, Volume 1, Figure 4-10).

The basin boundaries through which flow was deemed likely or permissible were further examined for their likelihood to transmit groundwater flow, using the available potentiometric data (SNWA, 2008a, Volume 2).

Arrows in the direction of flow potential were posted on basin boundaries across which a hydraulic potential exists to represent locations where interbasin flow likely occurs under natural conditions (Plate 1).

Thus, some interbasin flow directions were selected over others in areas of conflicting interpretations. However, no single interpretation was dismissed from this study. Rather, interpretations not used to derive initial recharge distributions and groundwater budgets were included in the uncertainty envelope of the conceptual model. The final interbasin flow directions and volumes were derived from the calibrated numerical model.

8.2 Estimates of Interbasin Flow Rates

A subset of the interbasin flow locations shown on Plate 1 were selected for the purpose of estimating flow rates. The selected flow-routing configuration (Figure 8-1) matches the interpretation of Harrill

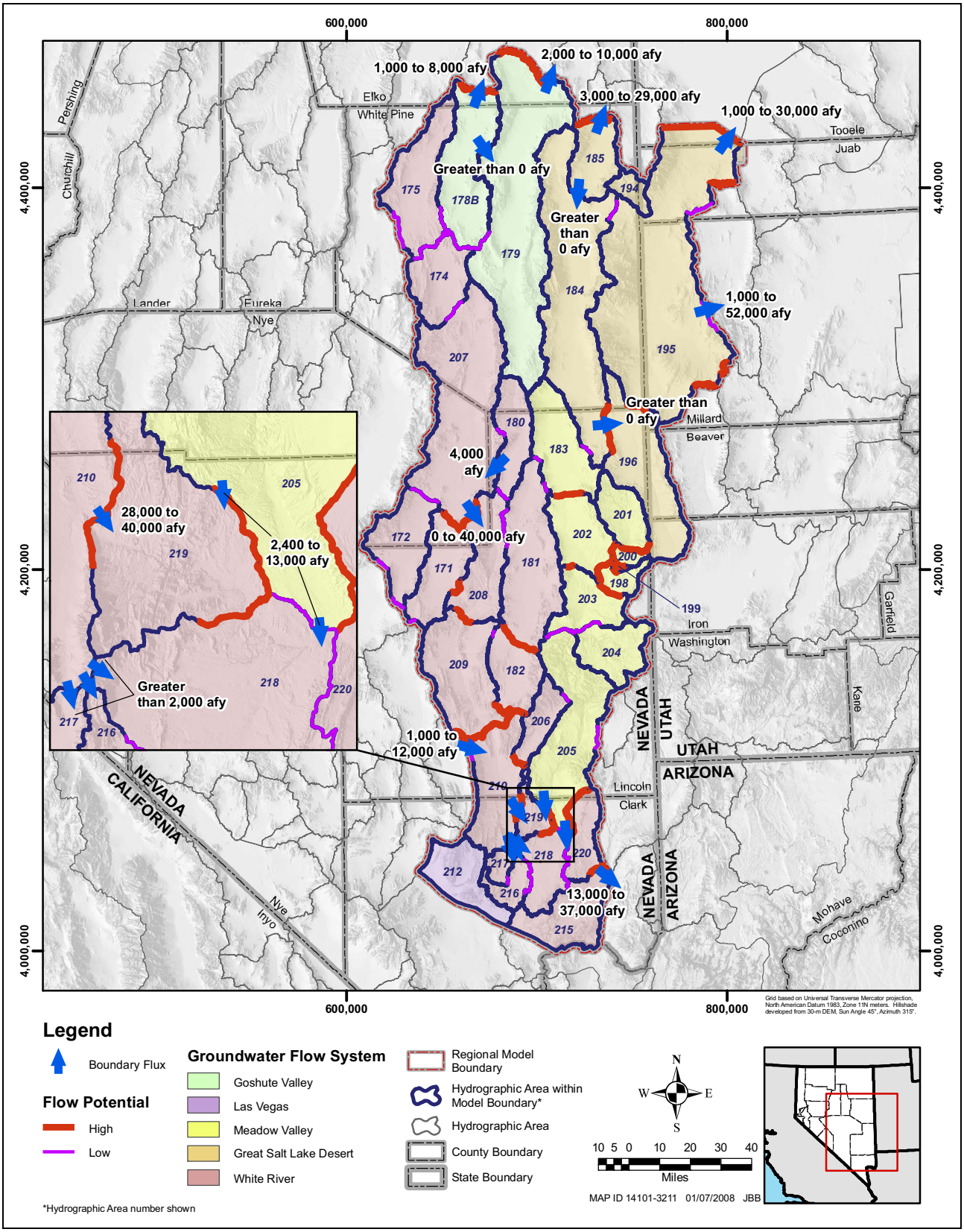


Figure 8-1
Interbasin Flow Locations and Volume Ranges Used in Solver

et al. (1988) for the most part. Interbasin flow volumes across the external boundaries of the model area were estimated using Darcy's equation and Monte Carlo simulations. Others were estimated using available information from the literature. These methods are presented within this section.

8.2.1 Estimates of Interbasin Flow by Monte Carlo Method

Flux through each RMU present across a flow-boundary segment was calculated using Darcy's equation:

$$Q = T \times I \times W \qquad \text{(Eq. 8-1)}$$

where,

Q = Flow rate (ft^3/day)
T = Transmissivity (ft^2/day)
I = Hydraulic gradient
W = Flow width (ft)

Data requirements are as follows:

- Identification of potential flux boundaries
- Identification of RMUs present across each flux boundary
- Probability distributions of transmissivity (T) data for each RMU present
- Probability distributions of hydraulic gradient (I) across each flow-boundary segment
- Probability distributions of flow widths (W) along each flow-boundary segment

The method consisted of conducting multiple calculations of flux across a given flow-boundary segment to derive stochastic estimates of the flux. Each flux calculation is a Monte Carlo realization. A group of realizations constitutes a Monte Carlo simulation, and the simulations were implemented using the Crystal Ball software. A Monte Carlo simulation consisting of 10,000 realizations was conducted for each flow-boundary segment.

8.2.2 Description of Input Data

Estimates of lateral interbasin flow were derived for all external boundaries, except Las Vegas Valley, using the available information.

Probability distributions of transmissivities were derived from the hydraulic-property database described in Appendix C. For RMUs with sufficient data records, the probability distributions were confirmed to be log-normal. The statistics, means, and standard deviations were as calculated. For others, the probability distributions were assumed to also be log-normal.

Hydraulic gradients across permeable-basin boundary segments were derived from a combination of water-level data and previous interpretations of the potentiometric surface. Water-level data were used to calculate the hydraulic gradients. Potentiometric contours for the region (Prudic et al., 1995)

were used to identify the approximate directions of groundwater flow. To approximate the regional hydraulic gradient between basins, water levels from the central parts of the basins were used rather than water levels on the mountain blocks. Because carbonate wells are scarce, water levels in the central parts of the basins were assumed to represent regional potentiometric levels, i.e., carbonate aquifer is connected to alluvial aquifers. Also, water levels from groups of wells, rather than single-well measurements, were preferred to capture the magnitude of the mean gradient. The probability distribution was assumed to be normal with COVs between 0.5 and 1. The input data are provided in Appendix H.

The flow widths across permeable segments of the model boundary were identified from a combination of information: (1) the map of permissible flow segments, (2) the regional potentiometric map (Prudic et al., 1995), and (3) the hydrogeologic map including the locations of major structural features. The probability distribution was assumed to be normal with COVs between 0.5 and 1.

8.2.3 Results

The estimates derived for each boundary segment using Darcy flux calculations coupled with Monte Carlo simulations are presented in Table 8-1. The table lists the simulated mean values and 95 percent confidence intervals.

Table 8-1
Estimates of Boundary Fluxes by the Monte Carlo Method

External Flow-Boundary Description	Flow Direction	Annual Volume (afy)			COV
		Mean	5th Percentile	95th Percentile	
Snake Valley to Tule Valley	Out	19,082	1,101	51,576	0.86
Long Valley to Newark Valley	Out	3,670	135	11,002	0.97
Butte Valley South to Butte Valley North	Out	4,006	768	8,426	0.60
Steptoe Valley to Goshute Valley	Out	5,861	2,297	10,152	0.41
Tippett Valley to Antelope Valley	Out	13,718	2,528	29,087	0.60
Snake Valley to Great Salt Lake Desert	Out	11,526	1,138	29,241	0.79
Tikaboo Valley South to Coyote Springs Valley	In	5,042	664	11,544	0.68
Lower Moapa Valley to Colorado River (pre-Lake Mead)	Out	14,727	4,771	27,109	0.48
Lower Moapa Valley to Lake Mead	Out	10,808	3,362	20,144	0.48

8.3 Estimates of Interbasin Flow for Other Boundary Segments

Interbasin flow for selected basin boundaries located on the outer boundaries of the flow systems, or internal to the flow system, was also estimated using the available information to be used in the groundwater-balance method calculations to derive a recharge distribution and groundwater budgets.

Descriptions of these estimates, including the information used to derive them, are provided in this section by flow system.

8.3.1 Goshute Valley Flow System

Interbasin flow may occur at one location within the GVFS (Figure 8-1): from Butte Valley South to Steptoe Valley. Prudic et al. (1995) simulated about 2,100 afy of interbasin flow from Butte Valley South to Steptoe Valley. In the solver, the annual volume of flow across this basin boundary was treated as a constrained unknown greater than zero.

8.3.2 Great Salt Lake Desert Flow System

Interbasin flow may occur at two locations within the GSLDFS (Figure 8-1): from Spring Valley to Hamlin Valley and from Tippett Valley to Spring Valley.

The amount of outflow from Spring Valley to Hamlin Valley has been estimated at 4,000 afy by Rush and Kazmi (1965) and Nichols (2000) and at 51,000 afy by Welch et al. (2008). For flow between North Spring Valley and South Tippet Valley, Scott et al. (1971) estimated 2,000 afy of inflow from Tippett Valley to Spring Valley. This estimate was also used by Harrill et al. (1988). In short, previous investigators estimated small volumes of flow in the same direction for both interbasin boundaries. Thus, the annual volume of flow across these basin boundaries was treated as constrained unknowns greater than zero in the solver.

8.3.3 White River Flow System

Reasonable ranges of flow may be derived from the available information for several interbasin flow locations internal to the WRFS. They are as follows, from north to south: (1) outflow from Cave Valley to White River Valley and Pahroc Valley, (2) outflow from White River Valley to Pahroc Valley, (3) outflow from Coyote Spring Valley to the Muddy River Springs area and other basins, and (4) inflow from Lower Meadow Valley Wash (Figure 8-1). Estimates of these interbasin flow volumes are summarized in this section.

1. Outflow from Cave Valley is most probably to the west and south. Outflow to the west is through Shingle Pass to White River Valley and has been estimated at 4,000 afy (SNWA, 2007). A detailed estimate is provided by SNWA (2007, Appendix D). The interbasin flow at this location was treated as a fixed constraint in the solver. Potentiometric contours also support flow from Cave Valley to the south to Pahroc Valley (Plate 1). The quantity of interbasin flow in this case was derived from the solution.

2. Outflow from Pahroc Valley is most probably to Dry Lake and Pahranagat valleys. Outflow to Dry Lake Valley has been estimated to be small at 2,000 afy (SNWA, 2007). A detailed estimate is provided by SNWA (2007, Appendix D). The interbasin flow at this location was treated as a fixed constraint in the solver. Potentiometric contours also support flow from Pahroc Valley to Pahranagat Valley (Plate 1). The quantity of interbasin flow in this case was derived from the solution.

3. Maxey and Eakin (1949) estimate the groundwater outflow from White River Valley to Pahroc Valley to be between about 6,300 and 19,000 afy. Their minimum estimate is based on the assumption that the outflow consists of spring flow. No evidence exists to substantiate this assumption. Thus, this flow was set to be unknown in the solver with a flow range constrained to vary between 0 and 40,000 afy.

4. Outflow from Coyote Spring Valley is likely to occur within the carbonate-rock aquifer. Most of this outflow probably enters the Muddy River Springs area. The rest of it probably moves into California Wash, Garnet Valley, and Hidden Valley (Plate 1). These quantities were set as constrained unknowns in the solver. The outflow from Coyote Spring Valley to Muddy River Springs area was constrained to be between 28,000 and 40,000 afy. The 28,000 afy is the difference between the spring discharge (34,000 afy) and the inflow from Lower Meadow Valley Wash (6,000 afy). The 40,000 afy is the sum of the spring discharge and the volume of groundwater ET from the Muddy River Springs area. The outflow to the other three basins was constrained to be greater than 2,000 afy, based on the discharge of Rogers and Blue Point springs. A hydraulic link between the Muddy River and Rogers springs is uncertain because of the difference in the geochemistry of their waters. This outflow was then subdivided equally among the three basins.

5. A portion of the flow into the WRFS originates from the MVFS. This inflow is from Lower Meadow Valley Wash to the Muddy River Springs Area and California Wash. The two annual inflow volumes were treated as constrained unknowns in the solver. The total flow volume was constrained to be between 2,400 and 13,000 afy. Buqo (2002) estimated the interbasin flow from Lower Meadow Valley Wash to the Lewis Farm area (California Wash) to range between 2,400 and 7,200 afy. In the same report, Buqo (2002) also suggested that, if the groundwater fluxes through the deep Tertiary units and the thick upper carbonate aquifer are taken into consideration, appreciably more subsurface flow through the area could occur at depth. Based on the RASA model, Prudic et al. (1995) found that 13,000 afy of Muddy River Springs area water may originate from the MVFS. Using isotope-balance models, Thomas et al. (1996) and Kirk and Campana (1990) derived an estimate of interbasin flow from the MVFS that falls within the 2,400–13,000-afy range. LVVWD (2001) estimated an interbasin flow rate of 32,000 afy from the MVFS to Lower Moapa Valley.

8.3.4 Las Vegas Valley

No consensus exists about flow across the boundary between the model area and the rest of the Las Vegas Valley. To account for the diverging interpretations, the flow is assumed to be zero with an uncertainty range of ±3,000 afy. The magnitude of the uncertainty range is based on the recharge volume estimated for the portion of the Las Vegas Valley located in the model area.

8.4 Flow Summary

The interbasin flow volumes described above are summarized in Table 8-2. F or comparison purposes, the estimates reported in the literature are also listed in this table. The ranges of lateral flow across the external boundaries of the four flow systems along with selected internal locations of internal basin flow were used in the Excel® Solver to derive the solutions described in Section 9.0. The interbasin flow locations and c onstraints on the annual flow volumes are shown in Figure 8-1. The estimated ranges of lateral flow along the external boundary of the model area were used in the numerical model. Their locations are shown in Figure 8-2. The corresponding estimated fluxes are listed in Table 8-3.

Table 8-2
Estimated Interbasin Flow Volumes and Reported Values
(Page 1 of 2)

Flow Section	This Study	Reported	Source
Goshute Valley Flow System			
Outflow (afy)			
Butte Valley South to Butte Valley North	1,000 to 8,000	8,000	Welch et al. (2008)
		~3,000[a]	Glancy (1968)
		~1,000[b]	Harrill et al. (1988)
Steptoe Valley to Goshute Valley	2,000 to 10,000	7,000	Welch et al. (2008)
		4,000	Nichols (2000)
		~1,000	Eakin et al. (1967)
		Minor (1,000)	Harrill et al. (1988)
		~1,000 (some)	Scott et al. (1971)
		2,130 to 5,330	Frick (1985)
Butte Valley South to Jakes Valley	NE	16,000	Welch et al. (2008)
Steptoe Valley to Jakes Valley	NE	14,000	
Steptoe Valley to White River Valley	NE	8,000	
Steptoe Valley to Lake Valley	NE	20,000	
Steptoe Valley to Spring Valley	NE	4,000	
Inflow (afy)			
NA	NA	NA	NA
Great Salt Lake Desert Flow System			
Outflow (afy)			
Snake Valley to Great Salt Lake Desert	1,000 to 30,000	29,000	Welch et al. (2008)
		10,000	Hood and Rush (1965)
		10,000	Gates and Kruer (1981)
		10,000	Harrill et al. (1988)
Tippett Valley to Antelope Valley	3,000 to 29,000	12,000	Welch et al. (2008)
		5,000	Scott et al. (1971)
		5,000	Harrill et al. (1988)
		5,000	Harrill (1971)
Snake Valley to Tule Valley	1,000 to 52,000	22,000 to 42,000 (33,000)	Harrill et al. (1988)
		15,000	Hood and Rush (1965)
		15,000[c]	Gates and Kruer (1981)
Inflow (afy)			
Steptoe Valley to Spring Valley	NE	4,000	Welch et al. (2008)
Lake Valley to Spring Valley	NE	29,000	
Wah Wah Valley to Snake Valley	NE	9,750[d]	Harrill et al. (1988)
Pine Valley to Snake Valley	NE		
Lower Meadow Valley Flow System			
Outflow (afy)			
Lake Valley to Spring Valley	NE	29,000	Welch et al. (2008)
Lower Meadow Valley Wash to WRFS	2,400 to 13,000	13,000	Prudic et al. (1995)
		2,400 to 7,200	Buqo (2002)
		7,000	Rush (1964)
		8,000	Thomas et al. (1996)
		5,500 to 9,000	Kirk and Campana (1990) as reported by Thomas et al. (1996)
		32,000	LVVWD (2001)
Inflow (afy)			
Steptoe Valley to Lake Valley	NE	20,000	Welch et al. (2008)

Table 8-2
Estimated Interbasin Flow Volumes and Reported Values
(Page 2 of 2)

Flow Section	This Study	Reported	Source
White River Flow System			
Outflow (afy)			
Long Valley to Newark Valley or Railroad Valley	0 to 12,000	NE	Harrill et al. (1988)
		10,000	Nichols (2000)
		13,000	
		5,000	Welch et al. (2008)
		12,700	Prudic et al. (1995)
Garden Valley to Three Lakes Valley	-1,000 to 1,000	1,226	San Juan et al. (2004)
Pahranagat Valley to Tikaboo Valley South	NE	7,000	Thomas et al. (1996)
		0	Thomas et al. (2001) and Thomas et al. (2006)
		6,000	D'Agnese et al. (1997)
		3,700 to 4,600	Kirk and Campana (1990)
Lower Moapa Valley and Black Mountain to Colorado River	5,000 to 28,000	NE	Harrill et al. (1988)
		1,100	Scott et al. (1971)
		1,100	Rush (1968b)
		3,000	Prudic et al. (1995)
Groundwater Components in the stream	6,600 to 7,400	10,000	Scott et al. (1971)
		10,000	Rush (1968b)
Rogers and Blue Point Springs	1,500 to 1,700	---	---
Total outflow (Lower Moapa and Black Mt.)	13,000 to 37,000	49,000	LVVWD (2001)
Inflow (afy)			
Lower Meadow Valley Wash to WRFS	2,400 to 13,000	7,000	Harrill et al. (1988)
		7,000	Scott et al. (1971)
		7,000	Rush (1968b)
		8,000	Welch (1988) as reported by Thomas et al. (1996)
		13,000	Prudic et al. (1995)
		2,400 to 7,200	Buqo (2002)
		32,000	LVVWD (2001)
		8,000	Thomas et al. (1996)
		5,500 to 9,000	Kirk and Campana (1990) as reported by Thomas et al. (1996)
Tikaboo Valley North to Pahranagat Valley	NE	824	San Juan et al. (2004)
Tikaboo Valley South to Coyote Springs Valley	1,000 to 12,000	5,551	
Muddy River Spring Discharge			
Inflow to Muddy River Spring Area	28,000 to 40,000	37,000	Harrill et al. (1988)
		37,000	Scott et al. (1971)
		28,000	Thomas et al. (1996)
		37,000	Thomas et al. (2001)
		35,000	Eakin (1966)
		16,500 to 19,100	Kirk and Campana (1990) as reported by Thomas et al. (1996)
Las Vegas Flow System			
Outflow (afy)			
Las Vegas to Three Lakes	-3,000 to 3,000	5,000	Harrill et al. (1988)
		5,000	Scott et al. (1971)
Inflow (afy)			
Three Lakes to Las Vegas	NA	1,355	San Juan et al. (2004)

NA = Not applicable, NE = Not estimated
[a]Value estimated as recharge minus discharge.
[b]Reported value is the flow volume out of Butte Valley North.
[c]Reported value is for flow from Snake Valley to possibly Fish Springs Flat.
[d]Reported value is half of the total flow volume into Snake Valley from Pine and Wah Wah valleys (19,500 afy).

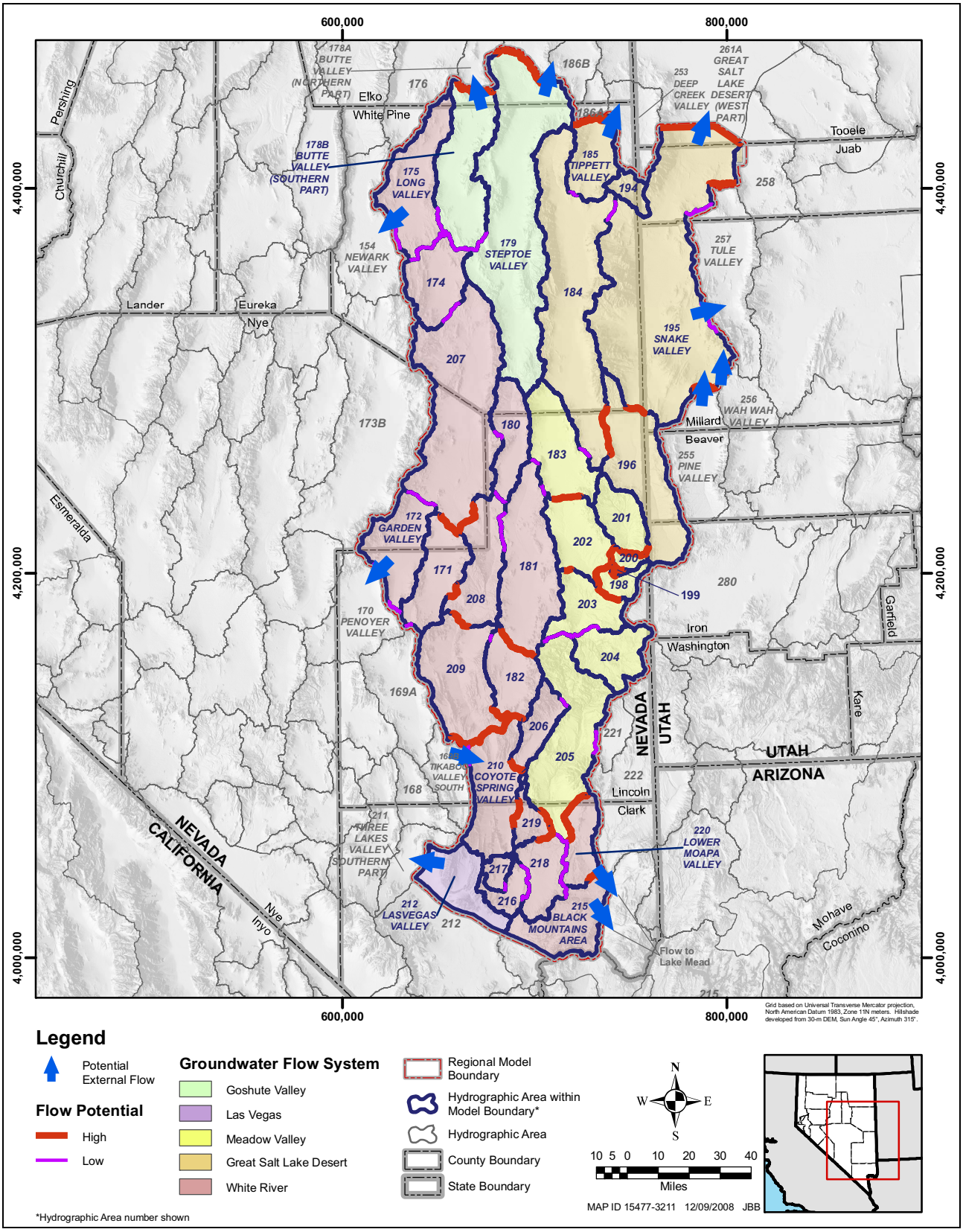


Figure 8-2
Initial Configuration of Flow Information Used in Numerical Model

Table 8-3
External Boundary Flux Estimates for Numerical Model

Lateral Flow-Boundary Description	Flow Direction	Estimated Flux (afy)			Comment
		Expected	Minimum[a]	Maximum	
Pine Valley to south Snake Valley	In/Out	0	-5,000	5,000	Boundary permeable but no hydraulic gradient across, under predevelopment conditions. Flux is estimated.
Wah Wah Valley to south Snake Valley	In/Out	0	-5,000	5,000	
Snake Valley to Tule Valley	Out	21,000	1,000	52,000	Expected value from solver solution. Range rounded from Monte Carlo analysis results.
Long Valley to Newark Valley	Out	0	0	12,000	
Butte Valley South to Butte Valley North	Out	1,000	1,000	8,000	
Steptoe Valley to Goshute Valley	Out	2,000	2,000	10,000	
Tippett Valley to Antelope Valley	Out	3,300	3,000	29,000	
Snake Valley to Great Salt Lake Desert	Out	13,000	1,000	30,000	
Tikaboo Valley South to Coyote Springs Valley	In	5,000	1,000	12,000	
Garden Valley to Three Lakes Valley	In/Out	0	-1,000	1,000	Boundary permeable but no hydraulic gradient across, under predevelopment conditions. Flux is estimated.
Las Vegas Valley to Three Lakes Valley	In/Out	0	-3,000	3,000	Based on recharge volume estimated for portion of Las Vegas Valley in model area.
Lower Moapa Valley to Colorado River (pre-Lake Mead)	Out	16,000	5,000	28,000	Range rounded from Monte Carlo analysis results. Hydraulic gradient observed between wells in Lower Moapa Valley and St. Thomas Well. Includes spring flow of 2,000 afy and stream flow of 7,000 afy.
Black Mountain to Colorado River (pre-Lake Mead)	Out	0	0	2,000	Flux is estimated.
Lower Moapa Valley to Colorado River (post-Lake Mead)	Out	11,000	3,000	20,000	Expected value, range rounded from Monte Carlo analysis results. Does not include spring flow and stream flow. Hydraulic gradient observed between wells in Lower Moapa Valley and mean Lake Mead water level.
Black Mountain to Colorado River (post-Lake Mead)	Out	0	0	1,000	Flux is estimated.

[a]Negative values are shown where flow direction may be in or out at the same volume.

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9.0 POTENTIAL RECHARGE

Given that precipitation recharge cannot be measured directly, it must be estimated by some other means. In this section, relevant methods to estimate groundwater recharge, previous recharge studies, the use of the groundwater-balance method to estimate recharge distributions for this study, the resulting estimates, and a discussion of uncertainty analysis are presented.

9.1 Review of Relevant Recharge Methods

Recharge methods that have been used to estimate basin-scale groundwater recharge in the study area 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.

9.1.1 Groundwater-Balance Methods

The groundwater-balance method is applied to a groundwater basin, usually under estimated predevelopment steady-state conditions, to derive an estimate of the basin's recharge volume. 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.

9.1.1.1 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) 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 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, 1963a) 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, to similar power functions expressing recharge as a continuous function of precipitation.

9.1.1.2 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) simplified the relationship to represent recharge on nonirrigated lands as a function of precipitation as follows:

$$\text{Recharge} = K \times \text{Precipitation}^{N} \qquad \text{(Eq. 9-1)}$$

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 to 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) 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:

$$R = 0.63(P - 15.28)^{0.76} \qquad \text{(Eq. 9-2)}$$

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) 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:

$$Log\ R = -1.40 + 0.98 \times Log\ P \qquad \text{(Eq. 9-3)}$$

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):

$$R = 0.042P^{0.98} \qquad \text{(Eq. 9-4)}$$

where,

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

9.1.2 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 BCM. Brief descriptions of these two models follow.

9.1.2.1 INFIL Code

The INFIL code (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 stream flow 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.

9.1.2.2 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 noninclusion 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.

9.1.3 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).

9.2 Previous Recharge Estimates

Annual volumes of recharge from precipitation and their uncertainty have been estimated for basins of the study area by several investigators. Short descriptions of their work on recharge follow.

- 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.

- Watson et al. (1976) conducted a study to evaluate the statistical validity of the Maxey-Eakin method. Using a set of criteria, they identified 63 adequate basin estimates from the NDWR/USGS Reconnaissance Series and developed regressions of recharge estimates versus precipitation to derive estimates of recharge efficiencies and the associated uncertainties.

- Gates and Kruer (1981) estimated recharge for hydrographic areas in west-central Utah using a method similar to the Maxey-Eakin method but with different precipitation interval zones and recharge efficiencies. Gates and Kruer (1981) also tried to incorporate the effect of geology on their recharge estimates. Big Snake Valley (Snake, Pleasant, and Hamlin valleys) was included in this study. The total recharge estimated for Big Snake Valley is 100,000 afy, which is the same as the value estimated by Hood and Rush (1965).

- Frick (1985) used an initial recharge distribution based on the Maxey-Eakin method in her numerical flow model of Steptoe Valley. The Maxey-Eakin recharge efficiencies were applied to Maxey-Eakin elevation zones. The precipitation rate for each elevation zone was estimated using available precipitation station data. An annual recharge volume of 98,900 afy was derived from the calibrated model. Based on the model's sensitivity analysis, Frick (1985) concluded that the annual ET volume estimated by Eakin et al. (1967) is grossly inaccurate.

- Carlton (1985) derived an initial recharge distribution using a method developed by Hood and Waddell (1968) in his groundwater flow model for the Fish Springs flow system. This is the same method as the one described by Gates and Kruer (1981). The annual recharge volume estimated by Carlton (1985) for Big Snake Valley was 104,000 afy, which is almost identical to the value estimated by Hood and Rush (1965). Carlton (1985) assumed that the estimated precipitation recharge was correct and did not vary it during model calibration.

- 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 (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. Because the solution of the model is nonunique, the recharge volumes estimated by this method have large uncertainties.

- Avon and Durbin (1994) compared recharge estimates derived using the Maxey-Eakin method with independent estimates for basins located in Nevada. They found that the standard Maxey-Eakin method provides reasonable first-order approximations of basin recharge volumes. They concluded that the upper bound on the standard deviation for an individual basin is 4,800 afy, and the corresponding coefficient of variation of the Maxey-Eakin estimate is no greater than 44 percent for the group of 40 water-budget estimates they considered.

- Brothers et al. (1993, 1994, 1996) are part of the 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.

- Nichols (2000) estimated recharge from precipitation for several basins of Nevada. He reevaluated the Maxey-Eakin recharge efficiencies using new estimates of groundwater discharge and the PRISM normal precipitation map (1961 to 1990). The recharge efficiencies were calculated using a multi-linear regression model. The efficiencies derived from the regression model were used to estimate groundwater recharge. Initial groundwater recharge was estimated using estimates of groundwater ET from this study and estimates of groundwater ET modified by interbasin groundwater flow from this study or previous studies.

- LVVWD (2001) estimated annual recharge from precipitation for hydrographic areas of the WRFS and MVFS 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.

- 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) used the BCM code to derive potential recharge estimates for basins in the Desert Southwest.

- SNWA (2006) estimated recharge for Spring Valley by applying the standard Maxey-Eakin method to an updated spatial precipitation distribution. Linear regression was performed on precipitation station data that consisted of measured precipitation rates and altitudes. The regression equation was used to derive the precipitation distribution for the area, assuming that no recharge occurs in areas where precipitation is less than 8 in. or altitude is less than 6,000 ft.

- SNWA (2007) derived recharge estimates for the WRFS using the groundwater-balance method and the Excel® Solver. The latest 800-m PRISM grid was used for the precipitation distribution. The annual volumes of subsurface inflow and outflow to and from the flow system were independently estimated. New estimates of groundwater ET were derived using satellite imagery and other information.

- As part of BARCASS, Welch et al. (2008) 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 2000) grid. Mizell et al. (2007) also estimated recharge for basins in the BARCASS area using the chloride mass-balance method. The recharge estimates reported by Mizzell et al. (2007) carry an uncertainty that is similar to the estimates reported by Dettinger (1989).

- Halford (2008) estimated annual recharge volumes for the entire study area using the groundwater-balance method. Different recharge efficiencies were derived for carbonate and noncarbonate areas using an optimization technique implemented with a customized solver. Halford found that most of the uncertainty associated with this method is due to the large uncertainties associated with locations and volumes of interbasin flow.

9.3 Rationale for Selected Recharge Method

The groundwater-balance method was selected as the approach for estimating natural recharge for the flow systems of the study area because it provides the best means of deriving a calibrated recharge estimate by incorporating measurable budget components, namely groundwater ET. The PRISM precipitation distribution was used and a trial-and-error approach taken to solve for a relationship between recharge efficiencies and precipitation to produce a total recharge estimate that balances with the total groundwater discharge estimate for each flow system. This method also provided an initial spatial distribution of recharge based on the spatial distribution of precipitation.

For this study, it was concluded that a nonlinear equation would best reflect the relationship between recharge efficiency and precipitation. Many investigators have expressed this relationship as a nonlinear function rather than a linear relationship or a step-wise function such as that defined by the standard Maxey-Eakin method. Hevesi et al. (2002) modified the standard Maxey-Eakin method by developing an exponential curve to define recharge as a continuous function of precipitation. This approach was also used by Donovan and Katzer (2000) and Wilson and Guan (2004). Contor (2004) adapted a relationship used by Rich (1951) to describe a basin's total yield and simplified the relationship to represent recharge on nonirrigated lands as a nonlinear function of precipitation.

Application of the standard Maxey-Eakin efficiencies to the PRISM precipitation distribution was rejected because this would result in an overestimation of the natural recharge. 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 (Nevada State Engineer, 2007a and b). If new recharge estimates are to be derived based on updated precipitation maps, the appropriate recharge efficiencies should be obtained using the groundwater-balance method and updated estimates of groundwater discharge.

The BCM method offers the best approach for distributing recharge, as it uses spatial distributions for the parameter data sets considered in the model. However, the recharge values derived by this method are unconstrained by observed data. In addition, BCM-based models have never been calibrated to the groundwater-budget components for a basin. For this reason, the BCM method was not used in this analysis.

The chloride mass-balance method offers an alternative method of deriving recharge estimates, but the 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 flow systems of the study area.

9.4 Technical Approach Using the 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 measured within the bounds of reasonable uncertainty (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 amount of boundary flow is known to be small relative to the total budget for that basin or flow system. For this study, the groundwater-balance method was used to derive a relationship (e.g., a power function) between recharge efficiencies and precipitation that yielded a balanced groundwater budget for the flow systems. A different set of efficiencies was derived for each of the four flow systems in the study area. The annual recharge volume for the portion of Las Vegas Valley contained within the model area was calculated using the recharge efficiencies derived for the WRFS. This was completed using a spatial distribution of precipitation (Section 6.0) and estimates of groundwater ET (Section 7.0) and outflow (Section 8.0).

The Excel® Solver was used to calculate estimates of basin recharge volumes and boundary fluxes across predefined boundary segments for each flow system. Input data consisted of the following:

1. Groundwater ET volume estimates for each basin

2. One-inch precipitation bands within predefined potential recharge areas extracted from the 800-m PRISM grid

3. Flow ranges for each permeable boundary segment for the four flow systems

4. Additional estimates of interbasin flow at selected locations to further constrain the WRFS solution

The detailed analysis, including the solver setup, targets, parameters, constraints, and results, are described in detail in Appendix I. Analysis results relevant to the flow systems, including recharge-precipitation relationships and recharge efficiencies, and spatial recharge distribution are discussed within this section.

9.4.1 Recharge-Precipitation Relationships and Recharge Efficiencies

The power functions computed by the solver are recharge-precipitation relationships requiring two coefficients (see Appendix I). A graph of these relationships is presented on Figure 9-1, which also includes the relationship for Maxey-Eakin (1949) and other sources for comparison. As shown on Figure 9-1, all relationships have the expected general trend of increasing recharge with increasing precipitation, and the relationships developed by this study (WRFS, MVFS, GVFS and GSLDFS) fall within the range defined by the others. All relationships shown are similar to each other at the lower precipitation rates but diverge at larger rates.

The relationships derived by this analysis for the four flow systems fall significantly above the Maxey-Eakin line (black triangles) at higher precipitation rates. However, they are similar at middle to lower precipitation rates, i.e., for precipitation rates up to 25 in./yr (curves outside of the gray zone in Figure 9-1). The recharge-precipitation relationships derived by this study are considered to be more representative than the Maxey-Eakin relationships because this study bases its relationships on more accurate estimates of precipitation and groundwater ET.

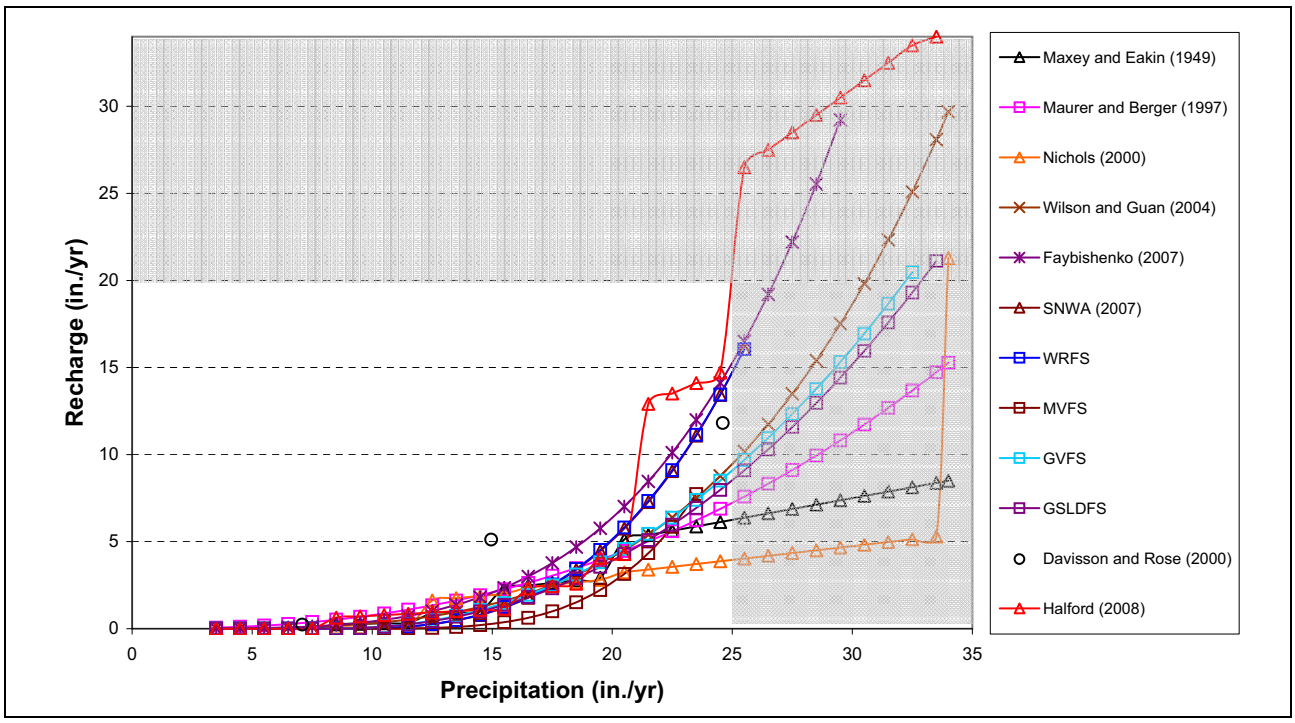

Figure 9-1
Recharge-Precipitation Relationship for the Flow Systems of the Study Area

The recharge efficiencies derived by this analysis are presented in Table 9-1 along with the standard Maxey-Eakin precipitation zones and efficiencies for comparison. For all flow systems, except the MVFS, the efficiencies for the >20 in./yr zone are much greater than the Maxey-Eakin efficiency for the same interval. However, they are very similar for the middle to lower zones. This places greater volumes of recharge at the higher altitudes, where the precipitation is greater. For the MVFS, all efficiencies, except the one for the maximum precipitation zone, are well below the Maxey-Eakin efficiencies.

A test was conducted to evaluate the relative importance of the higher portions of the curves derived in this study. The volume of recharge was calculated for each Maxey-Eakin precipitation band for the entire study area, and area-weighted recharge efficiencies (Table 9-1) were applied to the appropriate band. The resulting recharge volumes are shown in Figure 9-2. The majority of the recharge corresponds to precipitation bands of less than or equal to 25 in./yr. Actually, only less than 12 percent of the total recharge calculated for the study area corresponds to areas where precipitation rates are greater than 25 in./yr. The areas where precipitation rates are larger than 25 in./yr are small because they are located only at the tops of mountains or along the crests of mountain ranges.

Table 9-1
Mean Recharge Efficiencies as Percentage of Precipitation

Precipitation Zone (in.)	WRFS	MVFS	GVFS	GSLDFS	Maxey-Eakin
<8	0	0	0	0	0
8 to 12	0.61	0.06	1.41	1.05	3
12 to 15	3.47	0.89	5.30	4.47	7
15 to 20	11.86	4.92	12.66	9.86	15
>20	37.28	17.55	31.65	30.97	25

Note: Recharge efficiencies are weighted by the areas of the corresponding precipitation zone.

9.4.2 Spatial Recharge Distribution

Recharge efficiencies derived for 1-in. precipitation bands were used to calculate recharge rates and depict the spatial distribution of recharge from precipitation over the study area. The same information was used to compute recharge volumes for the individual basins composing the four flow systems.

The derived spatial recharge distribution is presented on Figure 9-3. The calculated groundwater recharge rates are largest in the northern part of the study area, which coincides with the highest mountain ranges of the GSLDFS and GVFS (Figure 9-3). Groundwater recharge rates are generally lower in the middle of the study area. No groundwater recharge occurs in most of the southern basins. It must be noted that this spatial distribution only accounts for variation of recharge rates with altitude. It does not explicitly account for the geology of the units through which precipitation infiltrates to recharge the flow system, and it 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. Although the recharge

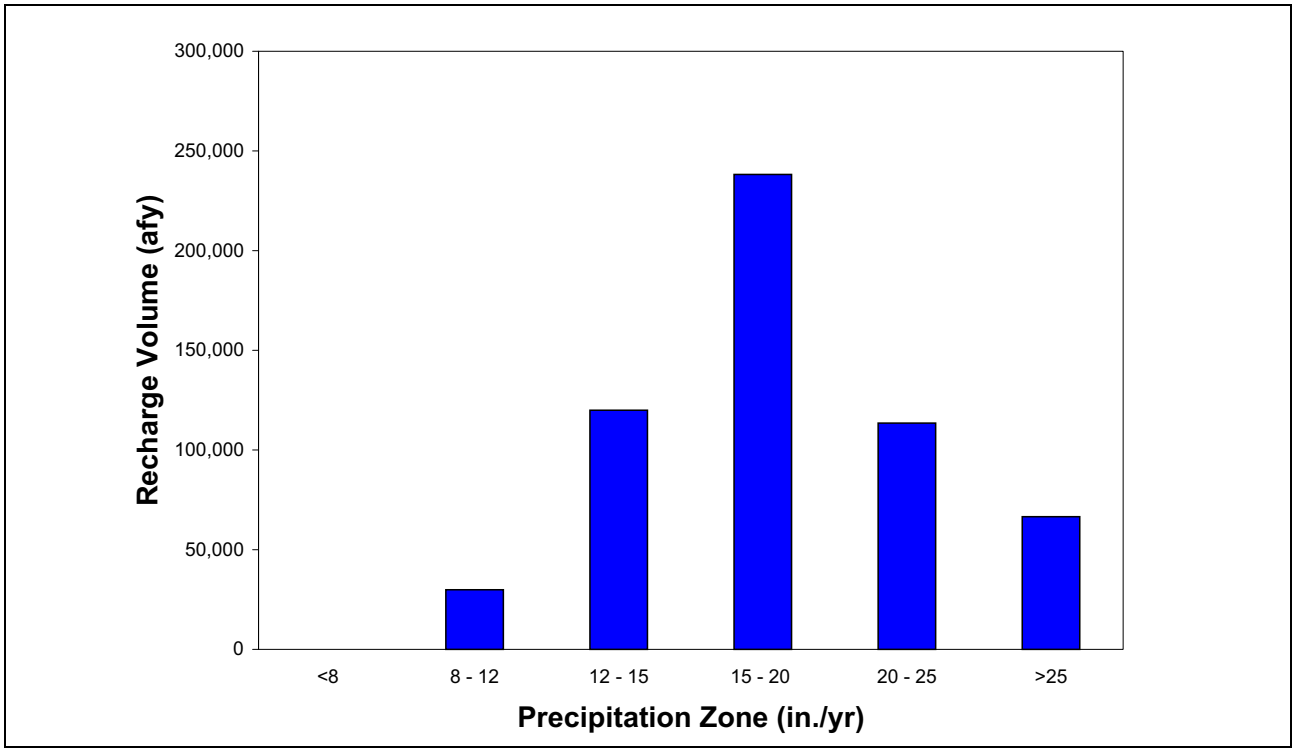

Figure 9-2
Recharge Volume Distribution by Maxey-Eakin Precipitation Zone for Study Area

map shown on Figure 9-3 does not accurately depict the spatial distribution of recharge, it does provide an approximate distribution on a basin-by-basin basis.

The recharge volumes were calculated by multiplying the recharge efficiency by the volume of precipitation calculated for each band. The recharge values were then summed for each basin and compared to previously reported estimates (Section 9.2). Table 9-2 lists the calculated annual recharge volumes as compared to the ranges of recharge estimates from previous studies. Two detailed tables listing each of the reported estimates are located in Appendix I. As shown in Table 9-2, all calculated basin recharge volumes fall within the ranges of previous estimates.

The total recharge estimated for the entire study area is 570,933 afy. This value falls within the overall range derived from the estimates reported in the literature: 396,029 to 1,264,363 afy (Epstein, 2004). The extreme values defining the range of total annual recharge volume correspond to estimates derived by Epstein (2004) in his reevaluation of previous methods using his model. The minimum value corresponds to the numerical version of the Maxey-Eakin (1949) Method (N-ME), and the maximum value corresponds to the numerical version of the Nichols (2000) Method (N-N).

The annual recharge volume for each basin was also calculated as a percentage of the annual precipitation volume of that basin (Table 9-3). The basin recharge volumes range between 0 and 7 percent of the corresponding basin's precipitation volumes. This range is similar to the percentage of 3 to 7 percent reported by Eakin et al. (1976) for the Great Basin region. Similar numbers were generated for each of the flow systems and for the whole study area. The largest annual recharge volume as a percentage of precipitation volume was calculated for the GVFS (7 percent) and

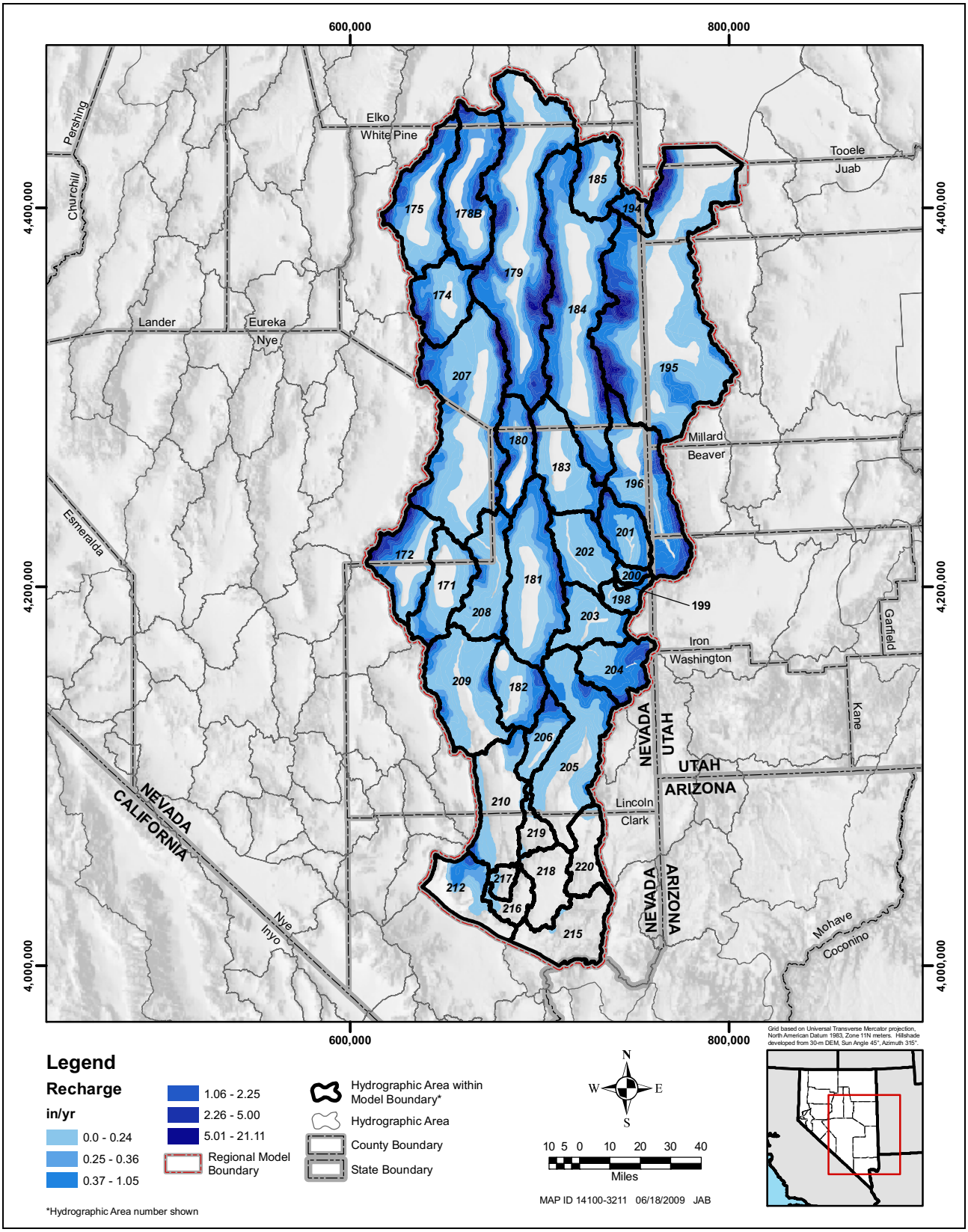

Figure 9-3
Recharge Distribution for Study Area

Table 9-2
Comparison of Recharge Estimates to Reported Ranges in afy

HA Number	HA Name	This Study	Reported Value		Source
			Minimum	Maximum	
Goshute Valley Flow System					
178B	Butte Valley South	24,688	12,165	55,029	Dettinger (1989); Epstein (2004)[a]
179	Steptoe Valley	91,685	84,885	171,952	Epstein (2004)[b]; Epstein (2004)[a]
	Total (Flow System)	**116,373**	**100,000**	**226,981**	Scott et al. (1971); Epstein (2004)[a]
Great Salt Lake Desert Flow System					
184	Spring Valley	81,339	53,335	139,194	Epstein (2004)[b]; Epstein (2004)[a]
185	Tippett Valley	5,616	4,282	18,418	Halford (2008); Epstein (2004)[a]
194	Pleasant Valley	5,388	2,931	10,756	Epstein (2004)[c]; Epstein (2004)[a]
195	Snake Valley	104,210	34,697	106,556	Epstein (2004)[b]; Halford (2008)
196	Hamlin Valley	41,358	6,451	50,269	Epstein (2004)[b]; Halford (2008)
	Total (Flow System)	**237,911**	**104,502**	**295,884**	Epstein (2004)[b]; Epstein (2004)[a]
Meadow Valley Flow System					
183	Lake Valley	9,861	10,875	62,123	Epstein (2004)[b]; Epstein (2004)[a]
202	Patterson Valley	5,656	6,000	51,852	Scott et al. (1971); Epstein (2004)[a]
201	Spring Valley	9,644	8,892	43,969	Epstein (2004)[b]; Epstein (2004)[a]
200	Eagle Valley	1,465	890	7,509	Flint et al. (2004) (Mean year); Epstein (2004)[a]
199	Rose Valley	79	43	1,541	Flint et al. (2004) (Time series); Epstein (2004)[a]
198	Dry Valley	1,953	1,300	14,055	Scott et al. (1971); Epstein (2004)[a]
203	Panaca Valley	2,381	1,500	28,408	Scott et al. (1971); Epstein (2004)[a]
204	Clover Valley	15,110	1,700	46,946	Scott et al. (1971); Epstein (2004)[a]
205	Lower Meadow Valley Wash	8,078	1,300	44,841	Scott et al. (1971); Epstein (2004)[a]
	Total (Flow System)	**54,227**	**35,900**	**301,244**	Scott et al. (1971); Epstein (2004)[a]
White River Flow System					
175	Long Valley	20,496	5,011	52,736	Kirk and Campana (1990); Epstein (2004)[a]
174	Jakes Valley	12,658	7,242	39,000	Mizell et al. (2007); Halford (2008)
207	White River Valley	42,037	30,759	89,570	Flint et al. (2004) (time series); Epstein (2004)[a]
180	Cave Valley	15,044	8,964	45,913	Halford (2008); Epstein (2004)[a]
172	Garden Valley	25,292	5,331	32,223	Epstein (2004)[b]; Epstein (2004)[a]
171	Coal Valley	4,020	2,000	12,107	Scott et al. (1971); Epstein (2004)[a]
208	Pahroc Valley	4,705	1,994	19,362	Kirk and Campana (1990); Epstein (2004)[a]
181	Dry Lake Valley	16,208	5,000	50,389	Scott et al. (1971); Epstein (2004)[a]
182	Delamar Valley	6,627	1,000	21,442	Scott et al. (1971); Epstein (2004)[a]
209	Pahranagat Valley	5,726	1,508	15,979	Kirk and Campana (1990); Epstein (2004)[a]
206	Kane Springs Valley	4,329	460	13,864	Epstein (2004)[d]; Epstein (2004)[a]
210	Coyote Spring Valley	2,215	535	8,331	Epstein (2004)[d]; Epstein (2004)[a]
219	Muddy River Springs Area	41	0	509	Epstein (2004)[d, e]; Epstein (2004)[c]
217	Hidden Valley	45	0	571	Epstein (2004)[d]; Flint et al. (2004) (Time series)
216	Garnet Valley	101	0	1,000	Epstein (2004)[d]; Flint et al. (2004) (Time series)
218	California Wash	0	0	1,738	SNWA (2006, 2007); Epstein (2004)[c]
215	Black Mountains Area	0	0	3,644	SNWA (2006, 2007); Epstein (2004)[b]
220	Lower Moapa Valley	35	0	1,454	Flint et al. (2004) (Mean year); Epstein (2004)[c]
	Total (Flow System)	**159,580**	**104,500**	**396,389**	Scott et al. (1971); Epstein (2004)[a]
Las Vegas Flow System					
212	Las Vegas Valley (Partial)	2,843	---	---	---
	Total (Project Study Area)	**570,933**	**396,029**	**1,264,363**	Epstein (2004)[b]; Epstein (2004)[a]

[a]Numeric Nichols Method
[b]Numeric Maxey-Eakin Method
[c]Bootstrap Brute-Force Model
[d]Maxey-Eakin Method Evaluation
[e]Nichols Method Evaluation

Table 9-3
Recharge as a Percentage of Precipitation

HA Number	HA Name	Precipitation[a] (afy)	Recharge (afy)	Recharge as Percentage of Precipitation
Goshute Valley Flow System				
178B	Butte Valley South	502,030	24,688	5%
179	Steptoe Valley	1,271,360	91,685	7%
	Total (Flow System)	**1,773,390**	**116,373**	**7%**
Great Salt Lake Desert Flow System				
184	Spring Valley	1,115,613	81,339	7%
185	Tippett Valley	212,996	5,616	3%
194	Pleasant Valley	79,362	5,388	7%
195	Snake Valley	1,592,560	104,210	7%
196	Hamlin Valley	649,174	41,358	6%
	Total (Flow System)	**3,649,705**	**237,911**	**7%**
Meadow Valley Flow System				
183	Lake Valley	400,964	9,861	2%
202	Patterson Valley	317,671	5,656	2%
201	Spring Valley	242,839	9,644	4%
200	Eagle Valley	46,367	1,465	3%
199	Rose Valley	8,738	79	1%
198	Dry Valley	91,900	1,953	2%
203	Panaca Valley	233,956	2,381	1%
204	Clover Valley	306,717	15,110	5%
205	Lower Meadow Valley Wash	551,874	8,078	1%
	Total (Flow System)	**2,201,026**	**54,227**	**2%**
White River Flow System				
175	Long Valley	449,902	20,496	5%
174	Jakes Valley	289,002	12,658	4%
207	White River Valley	1,010,761	42,037	4%
180	Cave Valley	265,033	15,044	6%
172	Garden Valley	350,969	25,292	7%
171	Coal Valley	267,397	4,020	2%
208	Pahroc Valley	309,740	4,705	2%
181	Dry Lake Valley	571,040	16,208	3%
182	Delamar Valley	235,967	6,627	3%
209	Pahranagat Valley	418,495	5,726	1%
206	Kane Springs Valley	145,587	4,329	3%
210	Coyote Spring Valley	272,214	2,215	1%
219	Muddy River Springs Area	53,504	41	0%
217	Hidden Valley	33,040	45	0%
216	Garnet Valley	54,873	101	0%
218	California Wash	106,283	0	0%
215	Black Mountains Area	168,683	0	0%
220	Lower Moapa Valley	94,697	35	0%
	Total (Flow System)	**5,097,186**	**159,580**	**3%**
Las Vegas Flow System				
212	Las Vegas Valley (Partial)	193,145	2,843	1%
	Total	**193,145**	**2,843**	**1%**
	Total (Project Study Area)	**12,914,452**	**570,933**	**4%**

[a]Total precipitation volume derived from 800-m PRISM grid, Version 2.

GSLDFS (7 percent); percentages are only 2 and 3 percent for the MVFS and WRFS, respectively. For the entire study area, recharge represents 4 percent of precipitation. The range of percentages are comparable to those reported in the NDWR/USGS Reconnaissance Series.

9.5 Uncertainty Analysis

An uncertainty analysis was conducted to identify the potential ranges of recharge for basins of the study area. The uncertainty associated with the solutions was examined from multiple angles as follows:

- Evaluation of uncertainty in solver solutions
- Evaluation of the BARCASS groundwater budgets

9.5.1 Evaluation of Uncertainty in Solver Solutions

The uncertainty of recharge estimates derived by the groundwater-balance method is directly related to the uncertainty associated with the estimates of precipitation and groundwater ET and lateral boundary flow volumes. The uncertainty in the precipitation distribution is not included in this analysis. Only the errors associated with the estimates of groundwater ET and lateral boundary flow are propagated to the derived estimate of recharge.

Given that the recharge volume of each flow system was calculated as the algebraic sum of the groundwater ET volumes and the lateral boundary flow volumes, the error propagation is expressed through the variances as follows:

$$VAR_R = VAR_{ET} + VAR_{BF} \qquad \text{(Eq. 9-5)}$$

where,

VAR_R = Variance of recharge volume estimate (afy^2)
VAR_{ET} = Variance of groundwater ET volume estimate (afy^2)
VAR_{BF} = Variance of lateral boundary flow volume (afy^2)

The resulting recharge variances were then used to calculate a standard deviation and a coefficient of variation for each flow system as follows:

$$COV = \frac{STD}{R} \qquad \text{(Eq. 9-6)}$$

where,

COV = Coefficient of variation (-)
STD = Standard deviation (afy) [STD = VAR$^{1/2}$]
R = Recharge volume for flow system (afy)

The uncertainties associated with groundwater ET and lateral boundary fluxes are as described in Section 7.0 and processed as follows:

- The variances of each component of the groundwater discharge were compiled for each flow system.
- They were then summed to yield a variance for the total recharge volume of each flow system (Equation 9-5).
- The square root of this variance was calculated and divided by the recharge volume of the flow system to yield a coefficient of variability.

The calculations and results are shown in Table 9-4. The coefficients of variation for flow system recharge volumes vary between 0.13 and 0.25. Assuming that the recharge probability distributions are normal, a range of recharge volume can be derived using the value derived from the solution and the standard deviations listed in Table 9-4. The resulting recharge ranges are listed in Table 9-5. The listed ranges represent the 95 per cent confidence range, i.e., the mean value plus or minus two standard deviations.

Assuming that the uncertainty associated with recharge is dominant, it can be transferred to the recharge efficiencies (Table 9-6). The uncertainty in the actual recharge efficiencies may in reality be larger due to the uncertainty associated with precipitation. However, for the purpose of the numerical model, it is assumed that precipitation is invariable, as its magnitude has no effect on the estimates of recharge derived by the groundwater-balance method. Thus, the uncertainty of the recharge volumes is only dependent on the uncertainty associated with the discharge estimates.

9.5.2 Evaluation of BARCASS Groundwater Budgets

The BARCASS interpretations of groundwater flow in the basins common to the two studies were evaluated. The purpose of this evaluation was two-fold: (1) to derive recharge efficiencies that correspond to the groundwater budgets interpreted by Welch et al. (2008) for the BARCASS basins and compare them with the recharge efficiencies derived for this study and (2) to apply the derived recharge efficiencies to the four flow systems and evaluate the impact on the flow system's budget components.

The basins, flow-routing patterns, and discharge components of the groundwater budgets reported for BARCASS were entered into the solvers. The precipitation distribution used in the solvers was unchanged. The grid used in BARCASS is not available. Comparison of the results are summarized in Table 9-7 for recharge efficiencies and in Table 9-8 for annual recharge volumes. The solvers were initially run for each flow system in the study area. If a solution could not be found for the flow system, solutions were derived for each of the basins separately. The solver runs are described by flow system in the following sections.

Table 9-4
Calculations of Recharge Uncertainty

Budget Component	Groundwater Volume (afy)	Coefficient of Variation	Standard Deviation (afy)	Variance (afy^2)
Goshute Valley Flow System				
Groundwater ET from Butte Valley South	**11,876**	0.89	10,586	112,073,878
Groundwater ET from Steptoe Valley	**101,497**	0.26	26,698	712,765,121
Outflow from Butte Valley South	**1,000**	0.60	597	356,559
Outflow from Steptoe Valley	**2,000**	0.41	825	681,141
Total Recharge	**116,373**	**0.25**	**28,738**	**825,876,699**
Great Salt Lake Desert Flow System				
Groundwater ET from Spring Valley	**75,615**	0.19	14,666	215,099,235
Groundwater ET from Tippett Valley	**1,742**	0.68	1,185	1,403,368
Groundwater ET from Pleasant Valley	**912**	0.15	137	18,770
Groundwater ET from Snake Valley	**129,041**	0.21	27,219	740,892,465
Groundwater ET from Hamlin Valley	**2,333**	0.38	896	802,068
Outflow from Snake Valley to Tule Valley	**15,000**	0.86	12,900	166,410,000
Outflow from Tippett Valley	**3,874**	0.60	2,325	5,403,524
Outflow from Snake Valley to Great Salt Lake Desert	**9,374**	0.79	7,417	55,016,423
Total Recharge	**237,891**	**0.14**	**34,424**	**1,185,045,853**
Meadow Valley Flow System				
Groundwater ET from Lake Valley	**6,134**	0.71	4,354	18,958,543
Groundwater ET from Dry Valley	**3,709**	0.27	995	989,282
Groundwater ET from Rose Valley	**594**	0.32	192	36,895
Groundwater ET from Eagle Valley	**1,034**	0.35	361	130,583
Groundwater ET from Spring Valley	**3,913**	0.31	1,228	1,508,369
Groundwater ET from Patterson Valley	**1,346**	0.39	523	273,481
Groundwater ET from Panaca Valley	**18,895**	0.25	4,747	22,533,926
Groundwater ET from Clover Valley	**5,840**	0.33	1,943	3,774,922
Groundwater ET from Lower Meadow Valley Wash	**9,668**	0.13	1,293	1,670,766
Outflow to WRFS	**3,095**	0.44	1,362	1,854,499
Total Recharge	**54,228**	**0.13**	**7,192**	**51,731,266**
White River Flow System				
Groundwater ET from Garden Valley	**1,696**	0.27	464	215,150
Groundwater ET from Jakes Valley	**858**	0.35	298	89,006
Groundwater ET from Long Valley	**1,233**	0.92	1,138	1,296,024
Groundwater ET from Cave Valley	**1,550**	0.70	1,091	1,191,051
Groundwater ET from White River Valley	**76,701**	0.35	27,062	732,374,506
Groundwater ET from Pahranagat Valley	**28,516**	0.10	2,842	8,075,260
Groundwater ET from Muddy River Springs Area	**5,989**	0.25	1,495	2,234,441
Groundwater ET from California Wash	**4,505**	0.25	1,126	1,267,469
Groundwater ET from Lower Moapa Valley	**25,311**	0.23	5,894	34,737,000
Groundwater ET from Black Mountain Area	**1,432**	0.20	289	83,715
Inflow from Tikaboo Valley	**7,200**	0.68	4,896	23,970,816
Inflow from Meadow Valley Flow System	**3,095**	0.44	1,362	1,854,499
Outflow via Muddy River (at Overton)	**7,000**	0.05	350	122,500
Discharge from Rogers and Blue Point Springs	**1,600**	0.05	80	6,400
Outflow from Lower Moapa Valley	**13,482**	0.48	6,471	41,878,500
Total Recharge	**159,578**	**0.18**	**29,144**	**849,396,336**

Table 9-5
Flow System Ranges of Annual Recharge Volumes in afy

Flow System	Mean	95 Percent Confidence Interval[a]	
		Lower	Upper
Goshute Valley	116,373	58,897	173,849
Great Salt Lake Desert	237,891	169,042	306,740
Meadow Valley	54,228	39,843	68,613
White River	159,578	101,289	217,867
Total[b]	**568,070**	**369,072**	**767,069**

[a]95 percent confidence interval estimated as mean ±2 x STD.
[b]Not including portion of Las Vegas Valley in the model area.

Table 9-6
Flow System Recharge Efficiency Uncertainty by Maxey-Eakin Zone

Maxey-Eakin Precipitation Zone (in.)	Area (acres)	Precipitation Volume (afy)	Mean Recharge Efficiency (percent)	Mean Recharge Volume (afy)	COV	Recharge Efficiency (percent)		Recharge Volume (afy)	
						Minimum	Maximum	Minimum	Maximum
Goshute Valley Flow System									
<8	51,243	32,027	0.00	0	0.25	0.00	0.00	0	0
8 to 12	550,537	475,031	1.41	6,705	0.25	0.71	2.12	3,353	10,058
12 to 15	464,543	515,331	5.30	27,327	0.25	2.65	7.95	13,664	40,991
15 to 20	278,696	388,510	12.66	49,195	0.25	6.33	18.99	24,598	73,793
>20	54,258	104,739	31.65	33,146	0.25	15.82	47.47	16,573	49,718
Total or Mean	**1,399,277**	**1,515,637**	**7.68**	**116,373**	**0.25**	**3.84**	**11.52**	**58,186**	**174,559**
Great Salt Lake Desert Flow System									
<8	156,131	95,960	0.00	0	0.14	0.00	0.00	---	---
8 to 12	1,388,238	1,171,173	1.05	12,328	0.14	0.76	1.35	8,876	15,780
12 to 15	705,995	788,183	4.47	35,221	0.14	3.22	5.72	25,359	45,082
15 to 20	549,652	773,466	9.86	76,253	0.14	7.10	12.62	54,902	97,604
>20	187,463	368,440	30.97	114,110	0.14	22.30	39.64	82,159	146,061
Total or Mean	**2,987,479**	**3,197,222**	**7.44**	**237,912**	**0.14**	**5.36**	**9.52**	**171,296**	**304,527**
Meadow Valley Flow System									
<8	144,584	79,040	0.00	0	0.13	0.00	0.00	---	---
8 to 12	380,970	330,228	0.06	210	0.13	0.05	0.08	155	264
12 to 15	756,932	857,470	0.89	7,665	0.13	0.66	1.13	5,672	9,658
15 - 20	569,180	795,638	4.92	39,157	0.13	3.64	6.20	28,976	49,338
>20	23,536	40,996	17.55	7,196	0.13	12.99	22.12	5,325	9,067
Total or Mean	**1,875,202**	**2,103,372**	**2.58**	**54,228**	**0.13**	**1.91**	**3.25**	**40,129**	**68,327**
White River Flow System									
<8	1,072,005	572,741	0.00	0	0.18	0.00	0.00	---	---
8 to 12	1,988,199	1,741,618	0.61	10,660	0.18	0.39	0.83	6,822	14,498
12 to 15	1,295,142	1,433,007	3.47	49,720	0.18	2.22	4.72	31,821	67,619
15 to 20	449,876	620,595	11.86	73,608	0.18	7.59	16.13	47,109	100,106
>20	37,702	68,647	37.28	25,591	0.18	23.86	50.70	16,378	34,804
Total or Mean	**4,842,924**	**4,436,607**	**3.60**	**159,579**	**0.18**	**2.30**	**4.89**	**102,130**	**217,027**
Total or Mean	**11,104,883**	**11,252,839**	**5.05**	**568,091**	---	**3.30**	**6.79**	**371,742**	**764,440**

Table 9-7
Recharge Efficiencies Derived from BARCASS Discharge Estimates

Goshute Valley Flow System						
Precipitation (in.)	BARCASS[a]			This Study[a]		
	Steptoe Valley	Butte Valley South	Mean[b]	Mean	95 Percent CI[c] Lower	Upper
<8	0	0	0	0.00	0.00	0.00
8 to 12	3.57	3.72	3.65	1.41	0.71	2.12
12 to 15	11.59	8.03	9.81	5.30	2.65	7.95
15 to 20	21.71	15.66	18.69	12.66	6.33	18.99
≥20	39.83	33.62	36.73	31.65	15.82	47.47
Great Salt Lake Desert Flow System						
Precipitation (in.)	BARCASS[a]			This Study[a]		
	Big Snake Valley	Spring Valley	Mean[b]	Mean	95 Percent CI[c] Lower	Upper
<8	0	0	0	0.00	0.00	0.00
8 to 12	0.25	1.82	1.04	1.05	0.76	1.35
12 to 15	2.21	6.30	4.25	4.47	3.22	5.72
15 to 20	7.05	13.93	10.49	9.86	7.10	12.62
≥20	24.15	35.49	29.82	30.97	22.30	39.64
Meadow Valley Flow System						
Precipitation (in.)	BARCASS[a]			This Study[a]		
	Lake Valley	---	---	Mean	95 Percent CI[c] Lower	Upper
<8	0	---	---	0.00	0.00	0.00
8 to 12	0.07	---	---	0.06	0.05	0.08
12 to 15	1.11	---	---	0.89	0.66	1.13
15 to 20	6.46	---	---	4.92	3.64	6.20
≥20	23.94	---	---	17.55	12.99	22.12
White River Flow System						
Precipitation (in.)	BARCASS[a]			This Study[a]		
	BARCASS Basins Only	---	---	Mean	95 Percent CI[c] Lower	Upper
<8	0	---	---	0.00	0.00	0.00
8 to 12	0.66	---	---	0.61	0.39	0.83
12 to 15	3.29	---	---	3.47	2.22	4.72
15 to 20	11.73	---	---	11.86	7.59	16.13
≥20	37.51	---	---	37.28	23.86	50.70

[a]Value shown as percentage.
[b]Average of Steptoe Valley and Butte Valley South for the Goshute Valley Flow System and Big Snake Valley and Spring Valley for the Great Salt Lake Desert Flow System.
[c] 95 percent confidence interval (CI) estimated as mean ±2 x STD.

Table 9-8
Flow System Annual Groundwater Budgets Based on BARCASS Discharge Estimates in afy

Goshute Valley Flow System			
		BARCASS	
Budget Component	**This Study**	**Steptoe Valley**	**Butte Valley South**
Recharge	116,373	203,880	35,876
Boundary Inflow	0	0	0
Groundwater ET	113,373	113,373	11,876
Boundary Outflow	3,000	90,507	24,000
Great Salt Lake Desert Flow System			
		BARCASS	
Budget Component	**This Study**	**Big Snake Valley**	**Spring Valley**
Recharge	237,912	166,568	301,634
Boundary Inflow	0	33,000	33,000
Groundwater ET	209,642	209,642	209,642
Boundary Outflow	28,270	-10,074	124,992
Meadow Valley Flow System			
		BARCASS	
Budget Component	**This Study**	**Lake Valley**	**---**
Recharge	54,228	82,326	---
Boundary Inflow	0	20,000	---
Groundwater ET	51,133	62,730	---
Boundary Outflow	3,095	39,596	---
White River Flow System			
		BARCASS	
Budget Component	**This Study**	**All Basins**	**---**
Recharge	159,579	152,198	---
Boundary Inflow	10,295	48,295	---
Groundwater ET	147,792	147,792	---
Boundary Outflow	22,082	52,702	---

9.5.2.1 Goshute Valley Flow System

The BARCASS area includes the same portion of the GVFS as in the study area, which consists of Butte Valley South and Steptoe Valley. The groundwater ET volumes are unchanged. However, boundary flow locations and volumes estimated by Welch et al. (2008) for these two basins are different. This information was entered into the solver to derive a single solution; however, the solver yielded no solution. Solutions were then derived for each basin separately. The derived efficiencies for the two lower precipitation zones are larger than those derived by this study (Table 9-7). However, the derived recharge volumes for the flow system (Table 9-7), as a whole, fall within the range of uncertainty derived by this study (Table 9-8).

9.5.2.2 Great Salt Lake Desert Flow System

The BARCASS area includes the same portion of the GSLDFS as in the study area, which consists of Spring, Tippett, Snake, Pleasant and Hamlin valleys. Two solver configurations were attempted. In the first configuration, all basins were included. The groundwater ET volumes for all basins and the boundary flow locations and volumes were assigned as interpreted by Welch et al. (2008). The solver yielded no solution in this case. Two separate solutions were then derived: one for Spring Valley and one for Big Snake Valley. The resulting recharge efficiencies are listed in Table 9-7. Overall groundwater budgets were then developed by entering the efficiencies derived for each case in all other basins (Table 9-8). The total outflow from the GSLDFS was 124,992 afy in the Spring Valley case and -10,074 afy in the Big Snake Valley case as compared to this study's volume of 28,270 afy. In the Spring Valley case, the negative volume means that groundwater would need to flow into the flow system to satisfy the mass balance. This is because the BARCASS Spring Valley recharge efficiencies yield less recharge than necessary as compared to the other two cases (Table 9-8).

9.5.2.3 Meadow Valley Flow System

The BARCASS area only includes one of the basins composing the MVFS: Lake Valley. A solver configuration consisting of only Lake Valley was set up. Groundwater ET and lateral boundary flows were set to represent the BARCASS results (Welch et al., 2008). The solver was executed to identify the recharge efficiencies associated with this flow configuration. The other basins of the MVFS were then added to Lake Valley, as configured by BARCASS, and the recharge efficiencies derived for Lake Valley were assigned to the other valleys. The resulting groundwater budget for the entire MVFS is presented in Table 9-8.

9.5.2.4 White River Flow System

The BARCASS area includes a portion of the WRFS, which consists of Long, Jakes, Cave, and White River valleys. Three test cases were examined.

- Test Case 1: The solver configuration was limited to the four BARCASS basins listed above, and all discharge volumes and interbasin flow directions were modified to match the flow routing used in the BARCASS interpretation (Welch et al., 2008). Modifications were then made to flow routing from Cave to White River and Pahroc valleys. The solver was executed, and a solution was found.

- Test Case 2: The remainder of the WRFS basins were added to the Test Case 1 solver setup. Groundwater ET and interbasin flow were as they were in the main solution for this flow system. However, the recharge efficiencies derived from Test Case 1 were applied to the additional basins. The solver was not run in this case. However, interbasin flow volumes were calculated.

- Test Case 3: The solver was setup as in the Test Case 2 solver setup, and a solution was sought for the whole flow system. The solver did not converge to a solution.

The recharge efficiencies derived for Test Case 1 are listed in Table 9-7. They are very close to the efficiencies derived for this study (Section 9.4.1). A remarkable result of the second test case is the amount of total outflow from the WRFS. The total outflow in this case is 47,702 afy, an amount more than double the one derived from the main solution: 22,082 afy (Table 9-8). This amount of outflow (47,702 afy) is similar to that simulated by LVVWD (2001).

10.0 PREDEVELOPMENT GROUNDWATER BUDGET

Analyses of the available hydrologic data were conducted and described in the previous sections of this report to derive independent estimates of groundwater discharge to the surface, interbasin groundwater flow, and recharge using Version 2 of the 800-m PRISM precipitation grid. This information was used to estimate the predevelopment groundwater budgets for the flow systems of the study area.

The resulting combined groundwater budget for the study area is presented in Table 10-1. The recharge and groundwater ET volumes reflect the total for all flow systems in the model area. The annual recharge volume for the portion of Las Vegas Valley contained within the model area was calculated using the recharge efficiencies derived for the WRFS and is included in the groundwater budgets presented in Table 10-1. The boundary flow only reflects flow into and out of the external boundaries of the study area. Discharge from Fish Springs is not explicitly included in the budget. Contributions of Snake Valley to Fish Springs, if any, would be through interbasin flow from Snake Valley.

These estimates for the groundwater-budget components as well as the uncertainty analyses were used to develop the numerical groundwater flow model.

Table 10-1
Predevelopment Groundwater Budget for Study Area

HA Name	Recharge (afy)	Groundwater ET (afy)	Inflow (afy)	Inflow From	Outflow (afy)	Outflow To
Goshute Valley Flow System[a]	116,373	113,373	0	---	3,000	Out of model boundary
Great Salt Lake Desert Flow System[a]	237,912	209,642	0	---	28,270	Out of model boundary
Meadow Valley Flow System	54,228	51,133	0	---	3,095	Out of MVFS
White River Flow System	159,579	147,792	10,295	MVFS and Tikaboo Valley	22,082	Out of model boundary
Las Vegas[a]	2,843	0	0	---	2,843	Out of model boundary
Project Model	570,933	521,940	7,200	Tikaboo Valley	56,193	Out of model boundary

[a]These flow systems are only partially represented in the Project model.

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11.0 SUMMARY

A conceptual model of the groundwater flow system underlying the project study area of Southern Nevada Water Authority's Clark, Lincoln, and White Pine Counties Groundwater Development Project was developed. The conceptual model was used to develop a regional three-dimensional numerical flow model of the flow system underlying the study area (SNWA, 2009b). The numerical model was used to perform preliminary regional-scale simulations of the effects of SNWA-proposed groundwater pumping under alternate scenarios (SNWA, 2009a). The simulation results, in turn, will be used to assist in evaluations of the potential water-related effects on the environment. A summary of the conceptual model is presented in this section, followed by a list of the specific products used to develop the numerical model (SNWA, 2009b).

11.1 Conceptual Model

The conceptual model was developed for an area extending over portions of Clark, Lincoln, and White Pine counties in Nevada and a small portion of western Utah. The flow system underlying the study area is within the Central Carbonate-Rock Province in the Great Basin Region, and includes five flow systems: the MVFS and WRFS and portions of the GVFS, GSLDFS, and Las Vegas Flow System. See Plate 1 for the locations of many of the features of the conceptual model under predevelopment conditions.

Components of the conceptual model include (1) a simplified hydrogeologic framework, (2) a description of groundwater occurrence and movement under natural conditions, (3) estimates of a predevelopment groundwater budget, and (4) anthropogenic stresses and their effects included in (SNWA, 2009b). Each of these components is summarized below. Estimates of predevelopment groundwater budgets were derived using the groundwater-balance method. In the groundwater-balance method, recharge from precipitation is equated to the net discharge from the flow system (groundwater ET + subsurface outflow - subsurface inflow). Recharge from precipitation is derived as a function of the other estimated budget components. Information needed to implement this method consists of a precipitation distribution, estimates of groundwater ET, and estimated ranges of interbasin flow, where possible.

A simplified hydrogeologic framework was developed for the flow system underlying the study area. The simplified framework consists of several RMUs, which are groups of HGUs. Among the RMUs, two are classified as major aquifers: the basin-fill aquifer (composed of the upper and lower valley fill) and the carbonate-rock aquifer. Other RMUs include basement rocks that compose the base of the flow system (clastic rocks), plutons, plateau sediments, and an upper aquitard that separates the carbonate aquifer into upper and lower carbonate aquifers throughout much of the northern study area. The available aquifer-property data were compiled and analyzed, and ranges of properties were assigned to each of the RMUs.

The groundwater flow system is a finite three-dimensional body, bounded by the saturated zone at the top, low hydraulic-conductivity geologic units at the bottom, and variable hydrogeologic features on the sides corresponding to the hydrographic-area boundaries of the peripheral basins. Flow into or out of the flow system may occur through permeable segments of the boundaries. The regional flow model comprises two full flow systems—WRFS and MVFS—and two partial flow systems—GVFS and GSLDFS. In addition, a small portion of Las Vegas Valley located north of the LVVSZ is included in the conceptual model area. Most of the groundwater recharge occurs in the mountain ranges present across the northern part of the study area. Regional groundwater discharge occurs by ET through major springs and associated streams or through the subsurface. General regional groundwater flow directions are north to south in the WRFS and MVFS, mostly south to north in GVFS, and to the north and potentially to the east in the GSLDFS.

Groundwater ET was estimated using two methods. Method 1 was developed as part of this study and was applied to the southern basins of the study area. Method 2 was developed by the USGS and was used by Welch et al. (2008) (BARCASS) and by DeMeo et al. (2008) (southern CRFS ET study). Method 2 estimates of ET were applied to selected basins of the study area. Spring data including locations, land-surface elevations, and flow rates were compiled and evaluated. All regional springs and selected intermediate springs were included in the conceptual model as such. Estimated ranges of external and selected internal interbasin flow volumes were derived independently using either the Monte Carlo method or the available information. These estimates of interbasin flow were used to constrain the groundwater-budget solutions and to support the definition of boundary conditions in the numerical flow model.

The spatial distribution of precipitation was represented by the PRISM grids. Estimates of predevelopment groundwater budgets were derived for each of the main flow systems using the groundwater-balance method. The budgets were then combined and simplified to express an overall budget for the entire regional flow system composing the study area. First, recharge from precipitation was derived as a function of estimates of the other budget components (summarized above). Second, to distribute the precipitation recharge, recharge efficiencies were expressed as a power function of precipitation, and the function's coefficients were derived through an optimization process. The optimization process was implemented using the Excel® Solver and consisted of solving for parameter values (i.e., unknowns), including the power function coefficients, under a set of constraints (i.e., estimated ranges of interbasin flow at selected locations). The optimization process also yielded estimates of selected interbasin flow annual volumes and groundwater budgets for each basin in the study area.

A combined groundwater budget representing predevelopment conditions was developed for the entire groundwater flow system (Table 10-1). The budget components are as follows, rounded to the nearest 1,000 afy:

- Precipitation recharge totaling about 571,000 afy
- Groundwater discharge from ET areas totaling about 522,000 afy
- Net boundary outflow totaling about 56,000 afy, outflow totaling 63,000 afy, and inflow totaling 7,000 afy

Anthropogenic stresses, including historical consumptive groundwater-use rates and their effects on water levels, and spring and stream flows were evaluated and are presented within the numerical model report (SNWA, 2008b).

11.2 Products for Numerical Model

Several specific products describe the four main components of the conceptual model that were used to construct the numerical model. These products are listed along with their locations in the reports.

- Simplified hydrogeologic framework
  - A list of simplified hydrogeologic units (Table 4-1)
  - A surficial map of the simplified hydrogelogic units (Plate 2)
  - A map of major structural features affecting groundwater flow (Plate 2)
  - Simplified hydrogeologic cross sections (Plate 3)
  - Maps depicting the extent and topography of each simplified HGU (Figures B-1 to B-12)
  - Hydraulic properties for the simplified HGUs and major structural features (Section 4.6)
- Groundwater occurrence and movement under natural conditions
  - Locations of hea d measurements and mean predevelopment heads and unc ertainty (SNWA, 2008a)
  - Contours of regional potentiometric head (Plate 1)
  - Delineated areas of groundwater ET under predevelopment conditions (Plate 1)
  - Locations of major springs, their elevations, and source depths (Plate 1, and Tables G-1 and G-2)
  - Locations of interbasin flow segments (Plate 1)
  - Approximate locations of recharge from precipitation (Plate 1)
  - Location of streams (Plate 1)
- Estimates of a predevelopment groundwater budget
  - Mean annual volumes and uncertainty of groundwater ET (Tables F-3 and 7-14)

- Mean annual flow rates and uncertainty of regional and selected intermediate springs (Table G-1)

- Mean annual rates of interbasin flow and range of uncertainty (Tables 8-2 and 8-3)

- Spatial distribution of precipitation (Figure 6-4)

- Recharge efficiencies and uncertainty range by recharge zones for each flow system (Table 9-6)

- Approximate spatial distribution of potential recharge from precipitation (Figure 9-3)

- Annual potential recharge volumes by basin (Table 9-2) and uncertainty ranges by flow system (Table 9-4)

• Anthropogenic stresses and their effects on flow system (SNWA, 2009b)

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Appendix A

Status of SNWA Data Collection Activities

A.1.0 STATUS OF SNWA DATA COLLECTION ACTIVITIES

In support of the Project, SNWA has been conducting various field activities to collect hydrologic, geologic, and water-chemistry data. Of particular interest to this report are the data obtained from drilling and aquifer testing for SNWA monitor and test wells and ongoing ET studies. These data collection activities are discussed within this section.

A.1.1 SNWA Monitor and Test Wells

Wells provide invaluable data in regard to regional and local hydrogeologic conditions. Numerous wells exist within the study area; however, most are completed within the basin-fill aquifer. SNWA has performed multiple drilling programs within the project basins (Figure A-1) with well completions in the basin-fill, carbonate and volcanic aquifers. In 2005, a monitor well program consisting of 10 monitor wells was conducted within Delamar (HA 182), Dry Lake (HA 181), Cave (HA 180), Pahranagat (HA 209), and Tikaboo North (HA 169A) valleys. From 2006 to 2008, eight 8-in.-diameter monitor and six 20-in.-diameter test wells were drilled in Spring Valley. An additional monitor and test well were drilled in Cave Valley in 2007. Prior to these programs, SNWA installed monitor wells in Coyote Spring Valley (HA 210) and Muddy River Springs Area (HA 219).

Geologic data within the study area were collected and evaluated using existing literature, well completion logs, SNWA geologic mapping, and surface geophysical surveys. Borehole lithology and fracture characteristics were evaluated through logging of cuttings and downhole geophysics. The monitor wells were pump tested for a short period, usually under eight hours, to evaluate general well performance characteristics, collect water-chemistry samples, and, in Spring Valley, assess the viability of a test well at the site.

Test wells were installed at six locations in Spring Valley and one location in Cave Valley. The purpose of the test wells was to collect more extensive hydrologic and water-chemistry data, perform a step-drawdown test, and conduct a 72- to 120-hr constant-rate test. The test wells are more extensively developed and hydraulically tested at a higher discharge rate than is possible in the smaller-diameter monitor wells.

A.1.1.1 Objectives

The primary objective of the well-drilling activities is to refine the current interpretations of the hydrogeologic framework and regional flow system through the acquisition and analysis of new data. These data include aquifer properties, geologic, water-chemistry, and water-level data. The wells provide monitoring points for collection of baseline and long-term data.

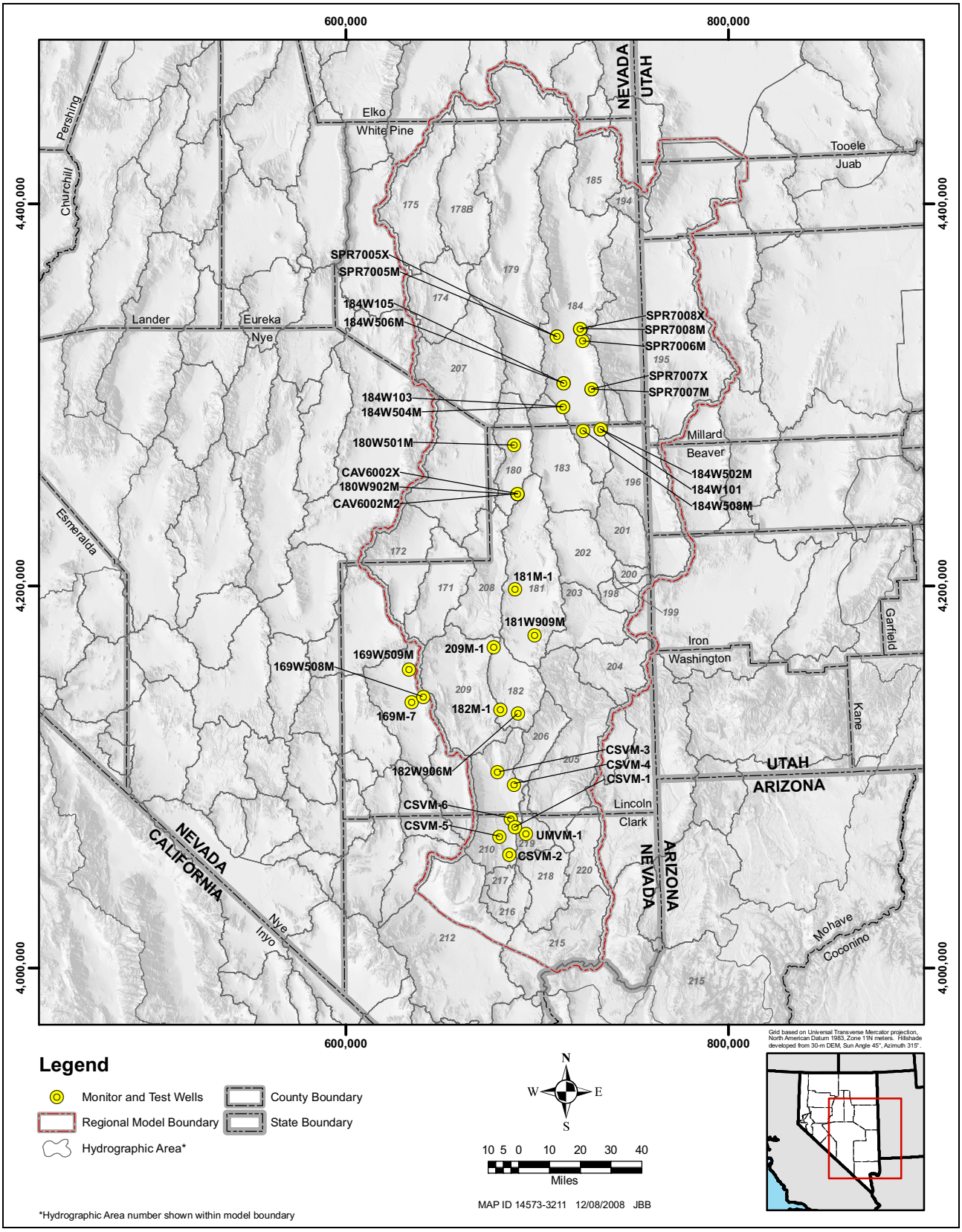


Figure A-1
Location of SNWA Wells within the Project Basins and Vicinity

SNWA has drilled 33 monitor and test wells within the following basins in the study area and vicinity (Figure A-1):

- Cave Valley: 3 monitor wells and 1 test well
- Coyote Spring Valley: 6 monitor wells
- Delamar Valley: 2 monitor wells
- Dry Lake Valley: 2 monitor wells
- Muddy River Springs Area: 1 monitor well
- Pahranagat Valley: 1 monitor well
- Spring Valley (Southern): 4 monitor wells and 3 test wells
- Spring Valley (Northern): 4 monitor wells and 3 test wells
- Tikaboo Valley North: 3 monitor wells

A.1.1.2 Well Status

A summary of monitor and test well locations and completion specifications are presented in Table A-1. Lithologic and downhole geophysical logging, including temperature logs, were performed during the drilling program. Temperature profile logs are available for all new wells. With a few exceptions, temperature logs were used in the analysis of thermal gradients in the study area and in the analysis conducted to estimate source depths for the major springs (Appendix G). Recent water-level data for each well are presented in Table A-2.

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 (Figure A-2). Water-chemistry samples were collected for a limited suite of chemical parameters at the end of the short-term test. Results of the short-term tests were used to assess the viability of a test well at the site for extended aquifer testing to evaluate aquifer properties. Test wells underwent extensive development after completion. A step-drawdown test, followed by a 72- to 120-hr constant-rate test, and recovery measurements were performed on each test well. Water-chemistry samples were collected during the constant-rate test for an extensive suite of chemical parameters; the resulting data are reported in SNWA (2008). Table A-3 presents a summary of the aquifer-test information for the test wells.

Data analysis has been completed for tests performed at Wells 184W101, 184W103, and 184W105. Analyses are currently being performed for the other tests. Additional test details and the preliminary estimates of aquifer properties derived from the data are presented in Appendix C.

A.1.2 Evapotranspiration Studies

In 2004, SNWA initiated a study to estimate groundwater ET within Spring and White River valleys in cooperation with the University of Nevada, Las Vegas (UNLV). The study was expanded to Snake Valley in 2007. Spring and Snake valleys were selected for the study because of their large discharge areas and their potential for water-resource development. White River Valley was included in the study because it is the largest discharge area of the WRFS. Descriptions of the objectives, locations, data collection methods, and data reduction methods are presented within this section. The resulting

Table A-1
SNWA Well Information

Well Name	HA Number	UTM Northing	UTM Easting	Surface Elevation	Aquifer	Well Depth	Hole Depth	Screen Interval
		(m)		(ft amsl)		(ft bgs)		
169M-7	169	4,139,267	634,523	4,290.93	Basin-Fill	1,490	1,500	995 to 1,480
169W508M	169	4,141,933	640,527	4,796.01	Carbonate	1,601	1,617	1,160 to 1,580
169W509M	169	4,156,097	632,997	5,157.81	Carbonate	1,558	1,560	1,448 to 1,548
180W501M	180	4,273,713	687,971	6,428.63	Carbonate	1,212	1,215	785 to 1,189
180W902M	180	4,248,356	689,816	5,984.89	Carbonate	903	915	196 to 882
CAV6002M2	180	4,248,366	689,783	5,982.81	Basin-Fill	887	893	159 to 882
CAV6002X	180	4,248,308	689,819	5,986.97	Carbonate	901	917	219 to 901
181M-1	181	4,198,200	688,535	4,963.07	Carbonate	1,472	1,501	765 to 1,451
181W909M	181	4,174,463	698,676	4,799.41	Basin-Fill	1,260	1,285	637 to 1,240
182M-1	182	4,135,293	680,867	4,597.78	Volcanic	1,321	1,345	996 to 1,300
182W906M	182	4,133,305	690,065	4,796.96	Volcanic	1,702	1,735	1,275 to 1,678
184W101	184	4,282,062	733,298	6,190.90	Carbonate	1,749	1,760	796 to 1,728
184W103	184	4,293,693	713,698	5,899.06	Carbonate	1,017	1,046	296 to 996
184W105	184	4,306,176	713,991	6,007.30	Carbonate	1,135	1,160	416 to 1,114
184W502M	184	4,282,116	733,294	6,189.72	Carbonate	1,800	1,828	495 to 1,779
184W504M	184	4,293,712	713,647	5,900.11	Carbonate	1,020	1,040	309 to 999
184W506M	184	4,306,214	713,940	6,014.04	Carbonate	1,140	1,160	430 to 1,120
184W508M	184	4,281,309	724,071	6,056.19	Volcanic	1,160	1,180	376 to 1,140
SPR7005M	184	4,330,472	710,372	6,395.68	Carbonate	1,404	1,412	663 to 1,383
SPR7005X	184	4,330,507	710,357	6,397.56	Carbonate	1,350	1,395	669 to 1,330
SPR7006M	184	4,328,163	723,873	6,525.18	Carbonate	1,700	1,720	980 to 1,680
SPR7007M	184	4,303,147	727,976	6,017.73	Basin-Fill	1,020	1,040	300 to 1,000
SPR7007X	184	4,303,152	727,946	6,017.53	Basin-Fill	1,020	1,040	299 to 1,000
SPR7008M	184	4,334,703	722,865	5,704.86	Basin-Fill	946	960	226 to 926
SPR7008X	184	4,334,728	722,848	5,703.98	Basin-Fill	960	970	240 to 940
209M-1	209	4,168,066	677,323	5,097.30	Carbonate	1,616	1,616	1,274 to 1,616
CSVM-1	210	4,073,793	688,602	2,160.60	Carbonate	1,040	1,060	320 to 1,020
CSVM-2	210	4,059,370	685,625	2,572.74	Carbonate	1,400	1,425	720 to 1,380
CSVM-3	210	4,102,600	679,319	2,650.68	Carbonate	1,200	1,220	380 to 1,180
CSVM-4	210	4,095,971	688,086	2,842.38	Carbonate	1,600	1,605	800 to 1,580
CSVM-5	210	4,068,774	680,295	3,130.70	Carbonate	1,780	1,783	1,020 to 1,760
CSVM-6	210	4,078,333	686,453	2,251.66	Carbonate	1,180	1,200	420 to 1,160
UMVM-1	219	4,070,248	694,305	2,061.88	Carbonate	1,780	1,785	960 to 1,760

Table A-2
Water-Level Measurements at SNWA Wells

Well Name	HA Name	HA Number	Surface Elevation (ft amsl)	Measuring Point (ft)	Measuring Point Elevation (ft amsl)	Date	Time	Water Depth (ft bgs)	Water Elevation (ft amsl)
169M-7	Tikaboo Valley	169	4,290.93	1.39	4,292.32	10/21/2008	10:15	837.99	3,452.94
169W508M	Tikaboo Valley	169	4,796.01	1.45	4,797.46	10/22/2008	9:20	1,104.79	3,691.22
169W509M	Tikaboo Valley	169	5,157.81	1.55	5,159.36	10/22/2008	11:00	1,431.91	3,725.90
180W501M	Cave Valley	180	6,428.63	2.41	6,431.04	10/21/2008	11:49	1,053.43	5,375.20
180W902M	Cave Valley	180	5,984.89	1.19	5,986.08	10/21/2008	13:23	139.91	5,844.98
CAV6002M2	Cave Valley	180	5,982.81	2.10	5,984.91	10/21/2008	13:45	137.51	5,845.30
CAV6002X	Cave Valley	180	5,987.97	1.00	5,988.97	10/21/2008	14:07	142.50	5,845.47
181M-1	Dry Lake Valley	181	4,963.07	1.55	4,964.62	10/21/2008	10:32	675.63	4,287.44
181W909M	Dry Lake Valley	181	4,799.41	1.21	4,800.62	10/21/2008	11:31	497.02	4,302.39
182M-1	Delamar Valley	182	4,597.78	1.88	4,599.66	10/21/2008	14:49	827.18	3,770.60
182W906M	Delamar Valley	182	4,796.96	2.88	4,799.84	10/21/2008	13:45	1,316.19	3,480.77
184W101	Spring Valley	184	6,190.90	1.98	6,192.88	9/25/2008	11:20	482.13	5,708.77
184W103	Spring Valley	184	5,899.06	2.13	5,901.19	9/25/2008	9:23	97.93	5,801.13
184W105	Spring Valley	184	6,007.30	1.85	6,009.15	9/23/2008	16:58	208.69	5,798.61
184W502M	Spring Valley	184	6,189.72	1.97	6,191.69	9/25/2008	11:10	481.12	5,708.60
184W504M	Spring Valley	184	5,900.11	1.33	5,901.44	9/25/2008	9:20	99.77	5,800.34
184W506M	Spring Valley	184	6,014.04	2.40	6,016.44	9/23/2008	16:47	215.35	5,798.69
184W508M	Spring Valley	184	6,056.19	1.67	6,057.86	9/25/2008	10:25	276.69	5,779.50
SPR7005M	Spring Valley	184	6,395.68	2.80	6,398.48	9/24/2008	8:36	493.61	5,902.07
SPR7005X	Spring Valley	184	6,397.56	2.78	6,400.34	9/24/2008	8:26	495.51	5,902.05
SPR7006M	Spring Valley	184	6,525.18	2.68	6,527.86	9/24/2008	13:40	769.65	5,755.53
SPR7007M	Spring Valley	184	6,017.73	2.08	6,019.81	9/24/2008	16:05	151.85	5,865.88
SPR7007X	Spring Valley	184	6,017.53	2.90	6,020.43	9/24/2008	16:17	151.77	5,865.76
SPR7008M	Spring Valley	184	5,704.86	2.80	5,707.66	9/24/2008	13:08	14.15	5,690.71
SPR7008X	Spring Valley	184	5,703.98	2.11	5,706.09	9/24/2008	13:16	13.86	5,690.12
209M-1	Pahranagat Valley	209	5,097.30	1.17	5,098.47	10/21/2008	9:16	1,200.52	3,896.78
CSVM-1	Coyote Spring	210	2,160.60	---	2,160.60	10/10/2008	10:30	340.24	1,820.36
CSVM-2	Coyote Spring	210	2,572.74	---	2,572.74	10/9/2008	8:17	749.3	1,823.44
CSVM-3	Coyote Spring	210	2,650.68	---	2,650.68	10/9/2008	11:37	443.1	2,207.58
CSVM-4	Coyote Spring	210	2,842.38	---	2,842.38,	10/9/2008	10:35	967.81	1,874.57
CSVM-5	Coyote Spring	210	3,130.70	---	3,130.70	10/9/2008	9:10	1083.73	2,046.97
CSVM-6	Coyote Spring	210	2,251.66	---	2,251.66	10/10/2008	9:25	433.68	1,817.98
UMVM-1	Muddy River Springs Area	219	2,061.88	---	2,061.88	10/10/2008	11:14	245.6	1,816.28

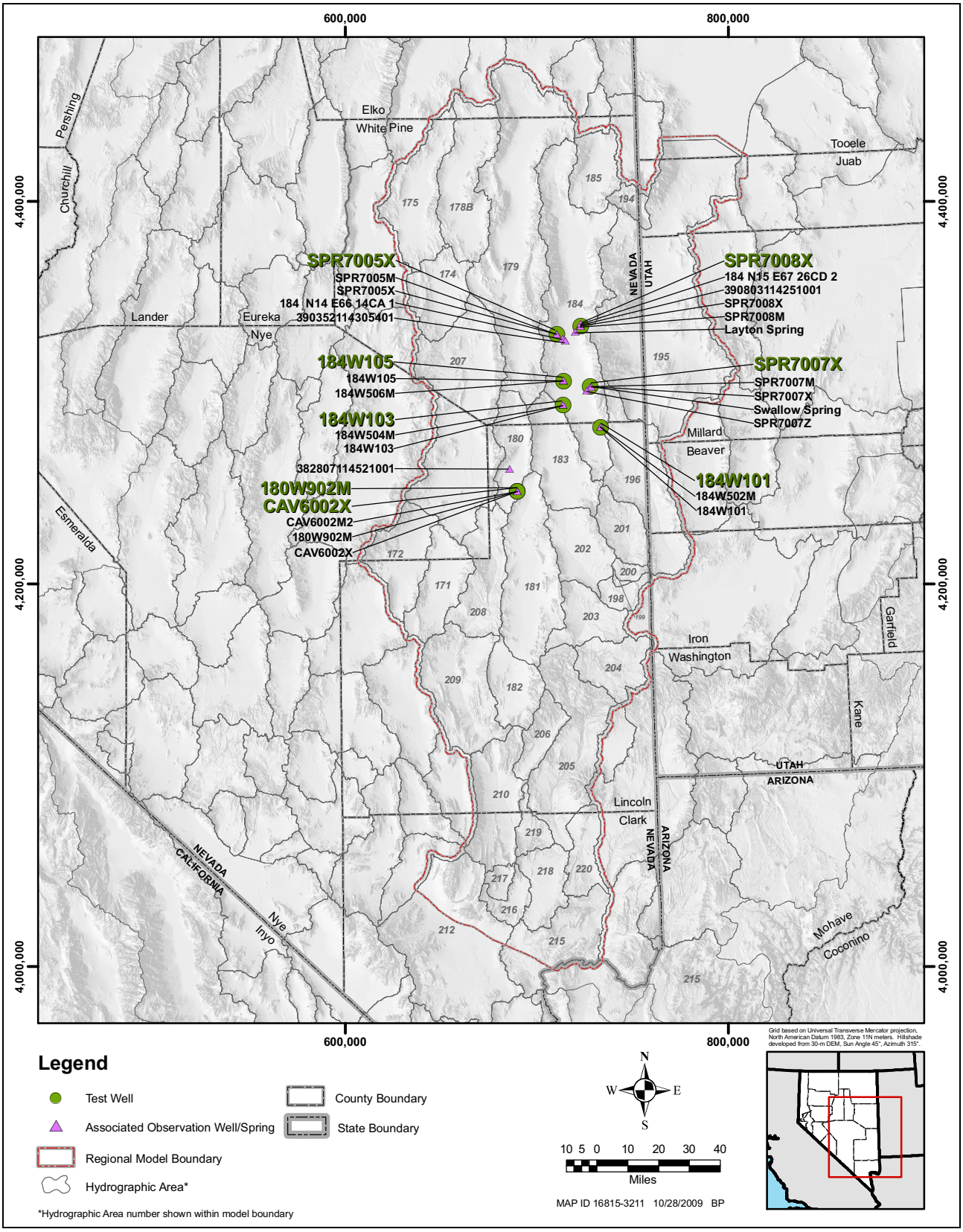


Figure A-2
Location of Wells Used in Aquifer Tests within the Project Basins and Vicinity

Table A-3
Aquifer-Test Data Summary for SNWA Wells
(Page 1 of 2)

Test Well Number	Associated Observation Well/Spring	Distance from Test Well (ft)	Specific Capacity (gpm/ft)	Constant-Rate Test Duration (hours)	Constant-Rate Test Flow Rate (gpm)	Step-Test Range (gpm)	Casing Diameter (in.)	Drill Depth (ft bgs)	Gravel Pack Interval (ft bgs)	Drawdown at end of Constant-Rate Test (ft)	Change in Spring Discharge
184W101	184W101	---	11.13	72	2,520	2,200 to 2,600	20	1,760	54 to 1,760	226.38	---
	184W502M	175	---				8	1,828	60 to 1,828[a]	21.12	---
	184W504M[b]	14 miles	---				---	---	---	0[c]	---
184W103	184W103	---	4.18	72	550	410 to 630	20	1,046	52 to 1,046	131.50	---
	184W504M	177	---				8	1,040	58 to 1,040[a]	3.92	---
	184W506M[b]	8 miles	---				---	---	---	0[c]	---
184W105	184W105	---	54.65	72	3,000	2,300 to 3,700	20	1,160	45 to 1,160	54.90	---
	184W506M	212	---				8	1,160	80 to 1,160[a]	4.63	---
	184W504M[b]	8 miles	---				---	--	---	0[c]	---
SPR7005X (184W111)	SPR7005X	---	111.1	120	3,000	2,000 to 3,800	20	1,395	509 to 1,350	39.82	---
	SPR7005M (184W512M)	129	---				8	1,412	452 to 1,406	2.88	---
	390352114305401	3.5 miles	---				2	160	Unknown (50 to 160)	0[c]	---
	184 N14 E66 14CA1	2.4 miles	---				8	372	50 to 372	0[c]	---
	184W506M	15 miles	---				8	1,160	80 to 1,160[a]	0[c]	---
SPR7007X (184W118)	SPR7007X	---	95.54	120	3,000	2,000 to 4,000	20	1,040	114 to 1,040	31.40	---
	SPR7007M (184W519M)	99	---				8	1,040	112 to 1,040	13.50	---
	390352114305401[b]	17 miles	---				2	160	Unknown (50 to 160)	0[c]	---
	Swallow Spring	2,300	---				---	---	---	---	(Discharge constant)[d]
	Minerva Spring Piezometer	1.7 miles	---				4	35	15 to 35	0[c]	---

Table A-3
Aquifer-Test Data Summary for SNWA Wells
(Page 2 of 2)

Test Well Number	Associated Observation Well/Spring	Distance from Test Well (ft)	Specific Capacity (gpm/ft)	Constant-Rate Test Duration (hours)	Constant-Rate Test Flow Rate (gpm)	Step-Test Range (gpm)	Casing Diameter (in.)	Drill Depth (ft bgs)	Gravel Pack Interval (ft bgs)	Drawdown at end of Constant-Rate Test (ft)	Change in Spring Discharge
SPR7008X (184W120)	SPR7008X	---	11.78	72	2,000	1,500 to 3,300	20	970	109 to 970	169.71	---
	SPR7008M (184W521M)	100	---				8	960	69 to 960	42.74	---
	390803114251001	376	---				2	200	Unknown (50 to 200)	0.38	---
	390352114305401[b]	---	---				2	160	Unknown (50 to 160)	0[c]	---
	Layton Spring	2.5 miles	---				---	---	---	---	(Discharge constant)[e]
	MX Flowing Well	3,900	---				2	Unknown	Unknown	---	(Discharge constant)[e]
CAV6002X (180W103)	CAV6002X	---	4.78	72	1,200	800 to 1,500	20	917	55 to 917	191.82	---
	CAV6002M2 (180W504M)	225	---				6	893	50 to 893	6.93	---
	180W902M	157	---				12	915	0 to 915	7.06	---
	382807114521001	8 miles	---				10	460	Unknown (50 to 460)	0[c]	---
180W902M	180W902M	---	82.36	72	1,100	---	12	915	0 to 915	7.06	---
	CAV6002X	157	---				20	917	55 to 917	191.82	---
	CAV6002M2 (180W504M)	114	---				6	893	50 to 893	6.93	---
	382807114521001	8 miles	---				10	460	Unknown (50 to 460)	0[c]	---
SPR7023I	SPR7023I	---	10.60	120	987	600 to 1,200	20	1,220	162 to 1,220	93.75	---
	184 N13 E67 22BA	1 mile	---				---	550	---	0[c]	---

[a]Interval from bottom of conductor casing to total depth (open borehole).
[b]Background well.
[c]Drawdown as a result of the pump test. Actual water-level fluctuations due to barometric and tidal influences.
[d]Flow measured with 3-in. and 6-in. Parshall flumes downstream of the north and south orifices, respectively.
[e]Flow measured volumetrically.
Note: These are preliminary data and are subject to change.

data are incorporated in a summarized ET data set provided in Appendix E. Also, the results of the 3-year data collection period (2005 to 2007) are presented in Devitt et al. (2008).

A.1.2.1 Objectives

Initially, SNWA's primary objective for the ET study was to refine previous estimates of groundwater ET using newer methodologies. Several objectives have been added as the ET study has progressed. These include (1) monitoring the variability in ET rates among different vegetation communities; (2) gaining an understanding of plant water uptake from groundwater sources versus surface-water sources; and (3) developing relationships between ET and vegetation indices that represent plant community health using remote-sensing applications.

A.1.2.2 Locations

ET-monitoring site locations were selected to represent a range of the phreatophytic areas located on the valley bottoms of selected basins within the study area (Figure A-3 and Table A-4). In 2005, two towers were rotated among six sites in Spring and White River valleys (three sites in Spring Valley and three sites in White River Valley). Rotating the towers revealed the variability among the basins and provided a robust data set for extrapolating to basin ET. It did not, however, provide continuous data sets for any of the ET-monitoring sites. In 2006, the towers remained stationary at one site in each of the valleys (SV1 and WRV2). Four additional towers were monitored in 2007 (Table A-4); one monitoring location from 2005 (SV3) was re-equipped, and three sites (SV2b, SNVl, and SNV2) were added.

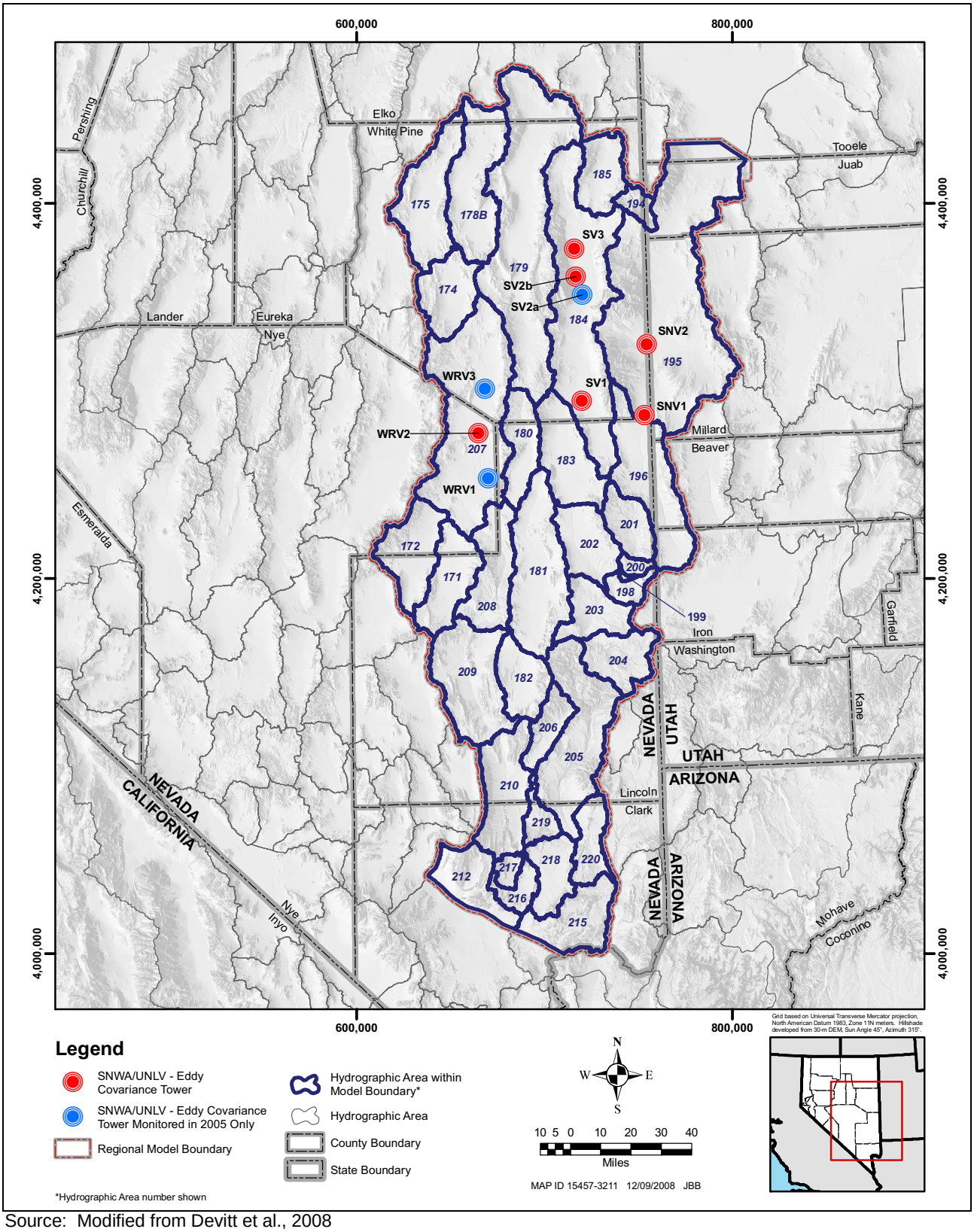
Species composition and percent cover within a 25 m × 25 m plot (size of Landsat satellite image pixel) at each site were evaluated by Devitt et a1. (2008). A brief description of the sites monitored between 2004 and 2007 is presented in Table A-4.

A.1.2.3 Data Collection Methods

Each ET site is equipped with an automated eddy covariance tower (ET towers), meteorological station, and groundwater monitor well for collection of ET, precipitation and PET data, and depth-to-water data, respectively. The ET towers are equipped with a 3D sonic anemometer and an infrared gas analyzer at a height of 1 m above average plant canopy height, with the exception of the pasture/grassland site (SV2b) where the height is 1.5 m above the grass. The towers are equipped with additional sensors to measure temperature, relative humidity, net radiation, rainfall, barometric pressure, saturated and actual vapor pressure, soil-heat flux, soil temperature, and volumetric water content. Continuous data are recorded on a l 0Hz interval (every l0th of a second) with data downloads occurring on a 2- to 3-week rotation. All sensors are calibrated according to the manufacturer's guidelines.

A.1.2.4 Data Reduction Methods

ET rates are based on using the l0Hz measurement data and incorporating a series of post-processing adjustments to produce 30-minute totals. An ET data quality assurance/quality control flagging



Source: Modified from Devitt et al., 2008

Figure A-3
ET-Monitoring Site Locations

Table A-4
ET-Monitoring Site Information

Station Name	UTM Northing Zone 11 (m)	UTM Easting Zone 11 (m)	Monitoring Period	Vegetation Type	Percent Cover	Depth to Water (ft bgs)
SV1	4,294,917	719,920	2005 to present[a]	Predominantly sagebrush, rabbitbrush, and greasewood, minor amounts of shadscale and buckwheat	27	15
SV2a	4,351,204	720,177	2004 to 2005[b]	Mixed grasses, greasewood, and rabbitbrush	62	shallow
SV2b	4,360,829	716,743	2007 to present	Irrigated pasture, with perennial grasses	100	shallow
SV3	4,375,912	715,857	2007 to present	Predominantly greasewood and rabbitbrush, minor amounts of shadscale and pickleweed	32	17
SNV1	4,287,266	753,182	2007 to present	Predominantly greasewood, minor amounts of shadscale and sagebrush	62	19
SNV2	4,325,090	754,601	2007 to present	Mixed community of rabbitbrush, greasewood, sagebrush, and shadscale	13	30
WRV1	4,253,557	670,230	2005[c]	Predominantly greasewood and sagebrush, minor amounts of buckwheat	62	32[d]
WRV2	4,277,445	665,017	2005 to present	Predominantly sagebrush and greasewood, minor amounts of shadscale and rabbitbrush	55	19
WRV3	4,301,044	668,300	2005[e]	Predominantly greasewood and rabbitbrush, minor amounts of sagebrush, shadscale, cactus, and grass	42	41[f]

[a]2005 data were collected from 3/31/2005 to 5/26/2005 and 8/18/2005 to 12/22/2005.
[b]Data were collected from 8/18/2004 to 2/15/2005 and 7/7/2005 to 8/18/2005.
[c]Data were collected from 4/1/2005 to 5/27/2005 and 8/19/2005 to 9/5/2005.
[d]Data from Moreo et al. (2007).
[e]Data were collected from 5/27/2005 to 7/17/2005.
[f]Depth to water calculated for the period of 2004 to 2006.

system checks for data spikes and other anomalies by running each 30-minute total through a series of nine tests. These nine tests include checks on signal resolution, meteorological range of the data (range of acceptable numbers for this field of data collection), sampling errors, stationarity (statistical parameters varying in time), and fulfillment of requirements for a well-defined turbulence (needed for the eddy covariance approach).

A series of gap-filling techniques are employed after the data are visually inspected for any measurement gaps. Data gaps can occur anywhere from the 30-minute totals up to the yearly totals. The gap-filling technique employed depends on the magnitude of the missing data. These techniques include (1) assigning a flat rate from previous literature or (2) using linear regression or an unbiased average of the available data surrounding the data gap.

A.2.0 REFERENCES

Devitt, D.A., Fenstermaker, L.K., Young, M.H., Conrad, B., Baghzouz, M., and Bird, B.M., 2008, Evapotranspiration estimates in north eastern Nevada basins: Las Vegas, University of Nevada Las Vegas, 231 p.

Moreo, M.T., Laczniak, R.J., and Stannard, D.I., 2007, Evapotranspiration rate measurements of vegetation typical of ground-water discharge areas in the Basin and Range Carbonate-Rock Aquifer System, White Pine County, Nevada, and adjacent areas in Nevada and Utah, September 2005–August 2006: U.S. Geological Survey Scientific Investigations Report 2007-5078, 48 p.

SNWA, see Southern Nevada Water Authority.

Southern Nevada Water Authority, 2008, Baseline characterization report for Clark, Lincoln, and White Pine Counties Groundwater Development Project: Southern Nevada Water Authority, Las Vegas, Nevada, 1146 p.

Appendix B

Additional Information in Support of the Simplified Hydrogeologic Framework

B.1.0 SIMPLIFIED HYDROGEOLOGIC FRAMEWORK DEVELOPMENT

This appendix contains information used to construct the simplified hydrogeologic framework. This includes a representation of the surface elevation as well as unit extent and structural contour maps for all RMUs (Figures B-1 through B-12).

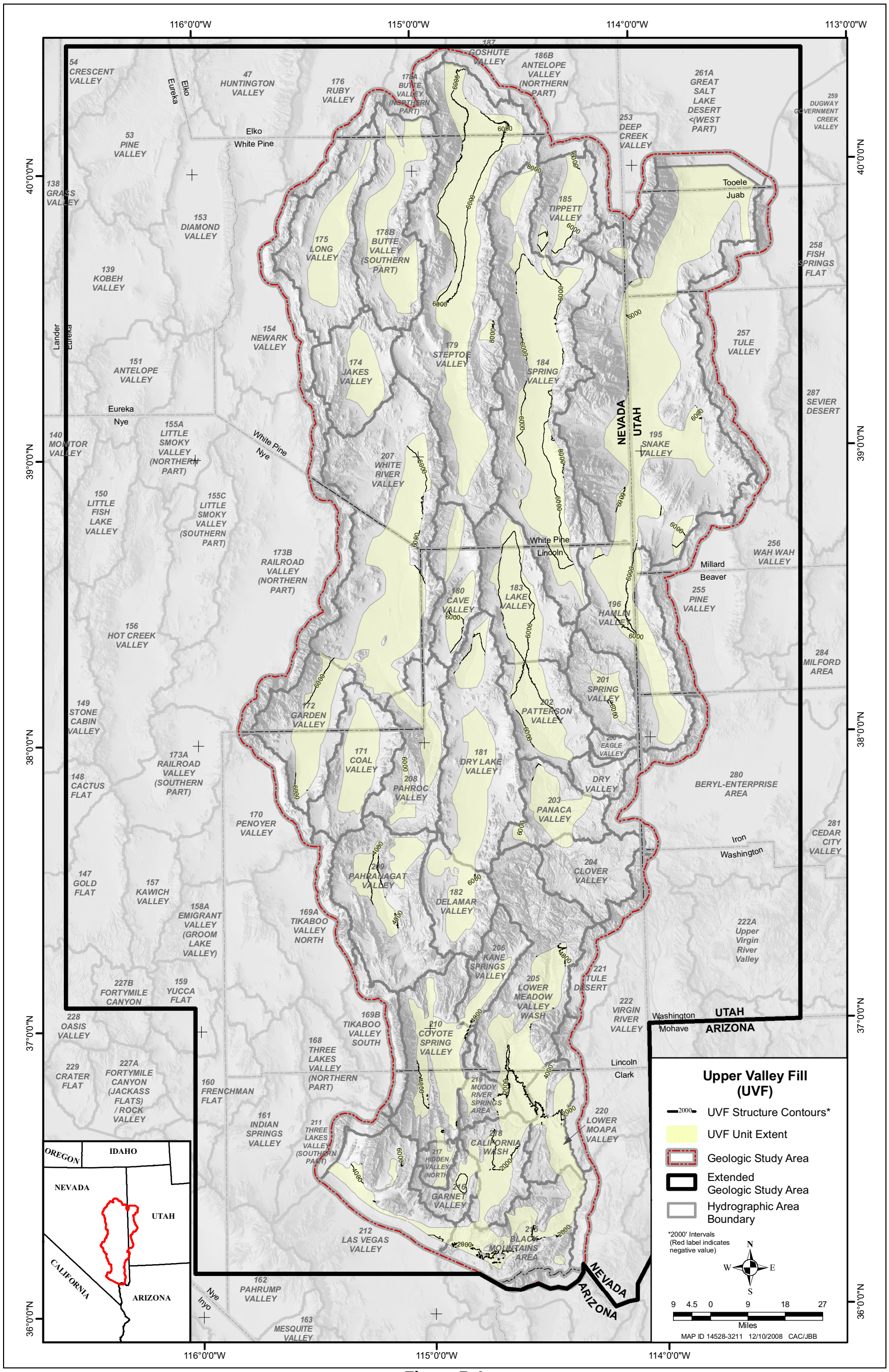


Figure B-1
Extent and Structural Contours of the Upper Valley Fill Regional Modeling Unit

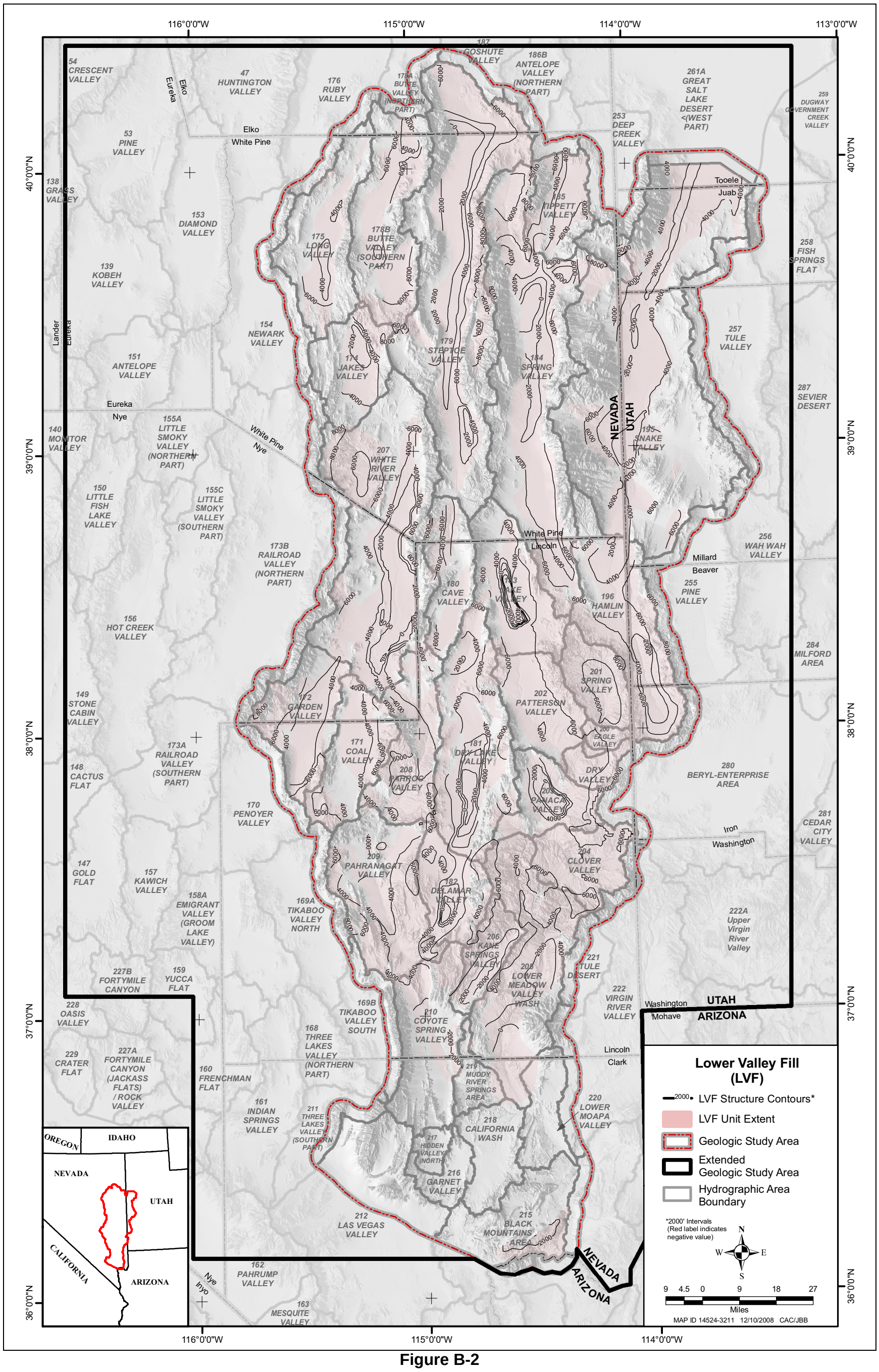


Figure B-2
Extent and Structural Contours of the Lower Valley Fill Regional Modeling Unit

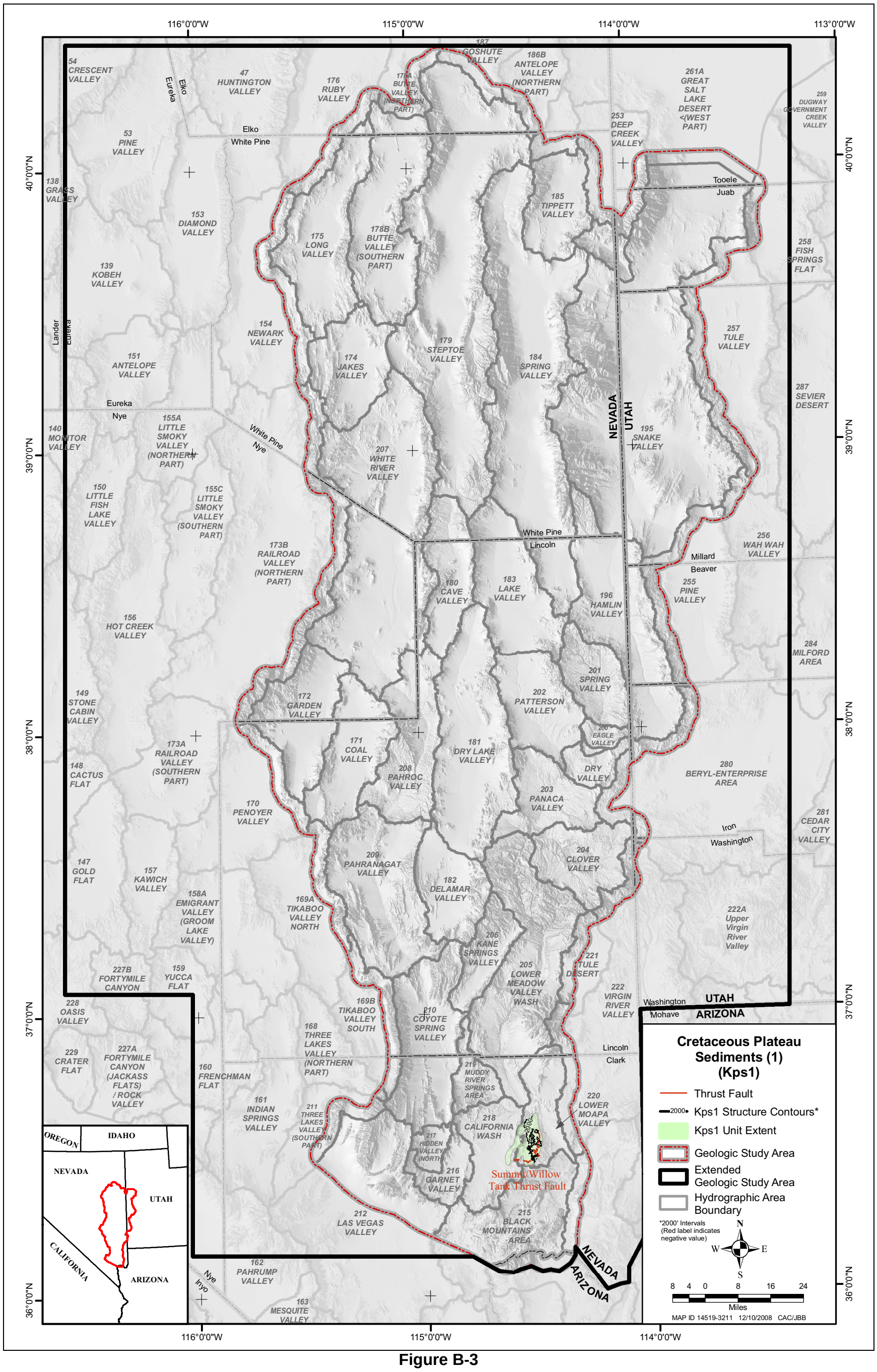


Figure B-3
Extent and Structural Contours of the Cretaceous Plateau Sediments (1) Regional Modeling Unit

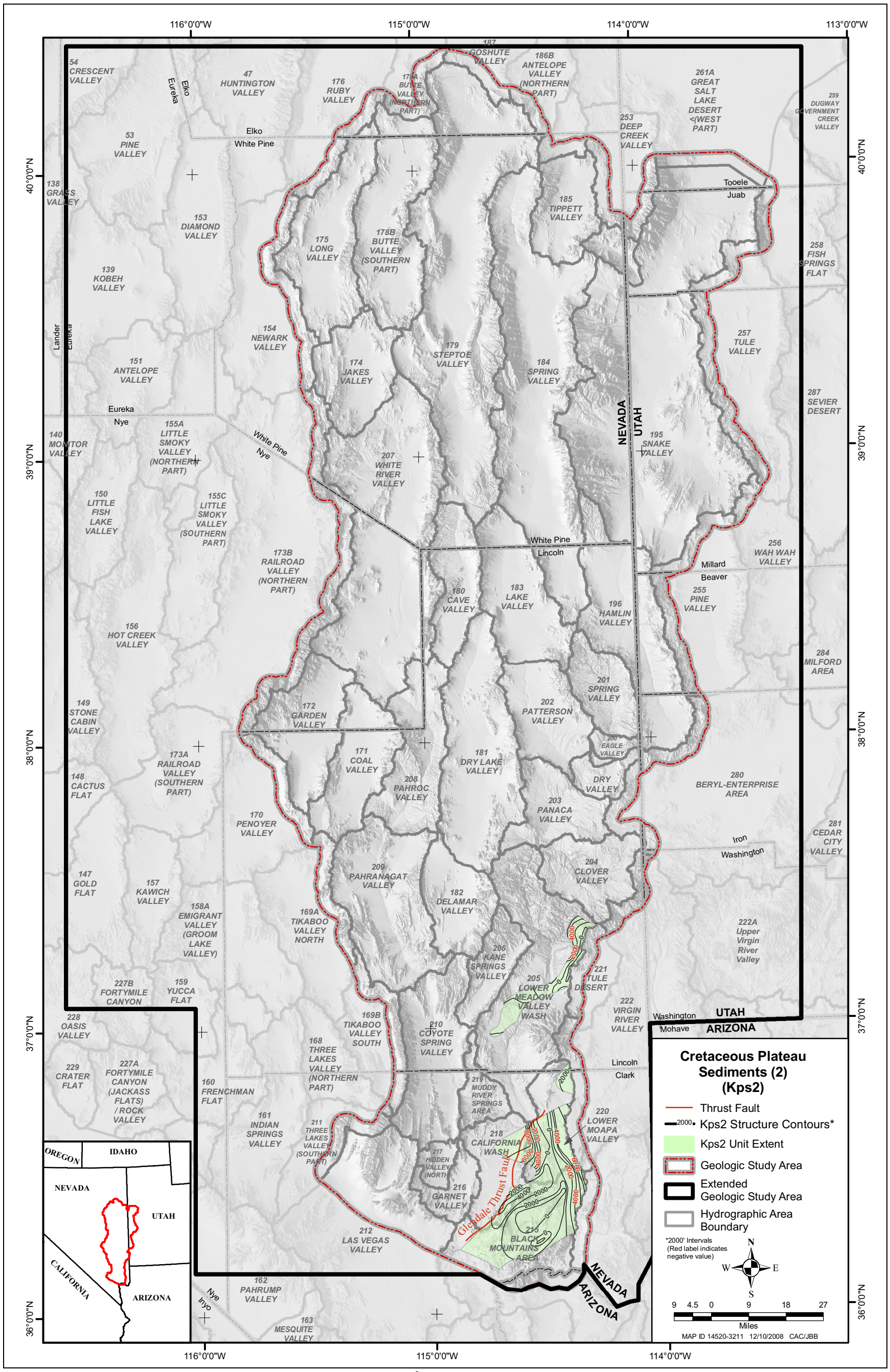


Figure B-4
Extent and Structural Contours of the Cretaceous Plateau Sediments (2) Regional Modeling Unit

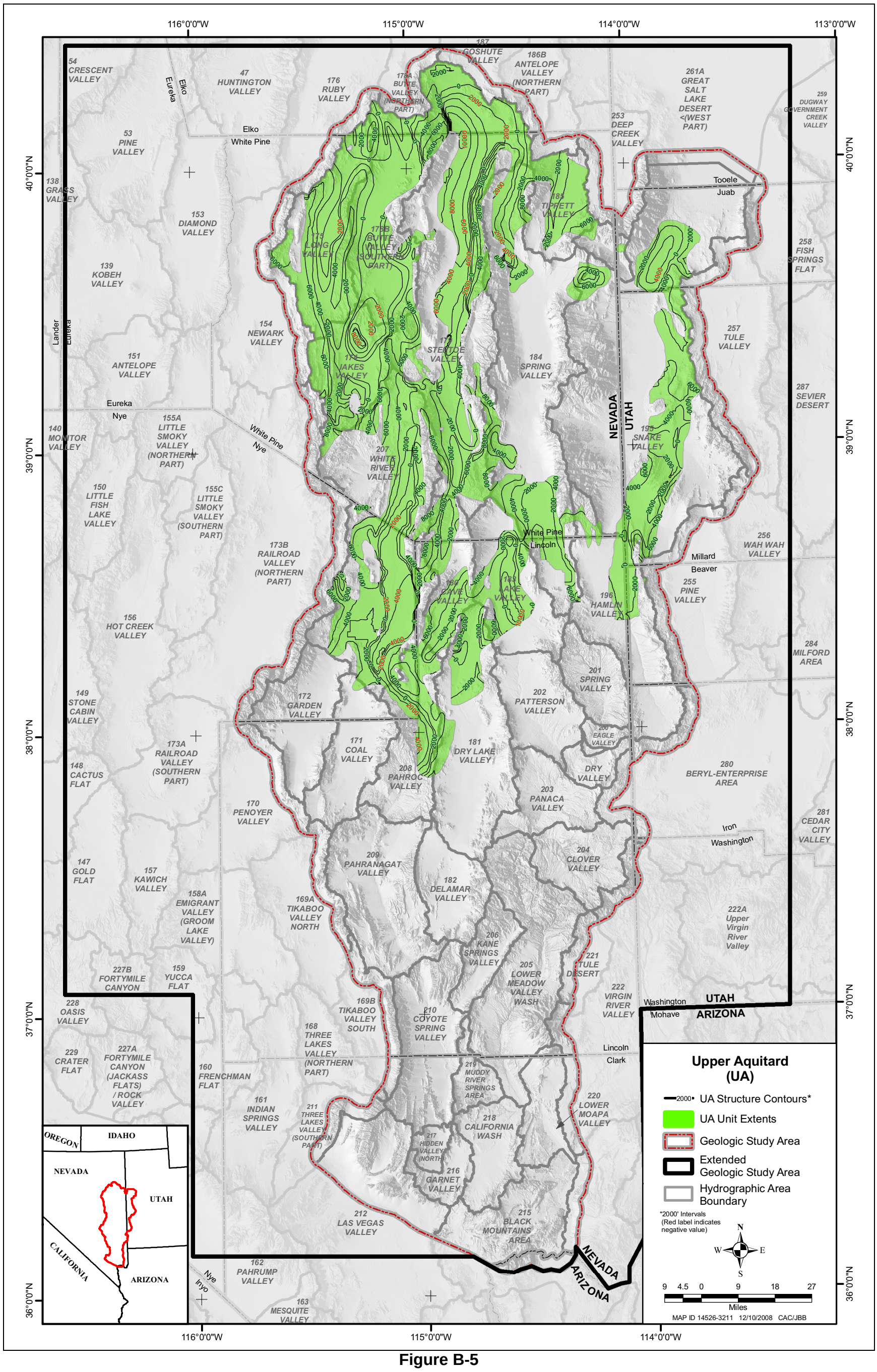


Figure B-5
Extent and Structural Contours of the Upper Aquitard Regional Modeling Unit

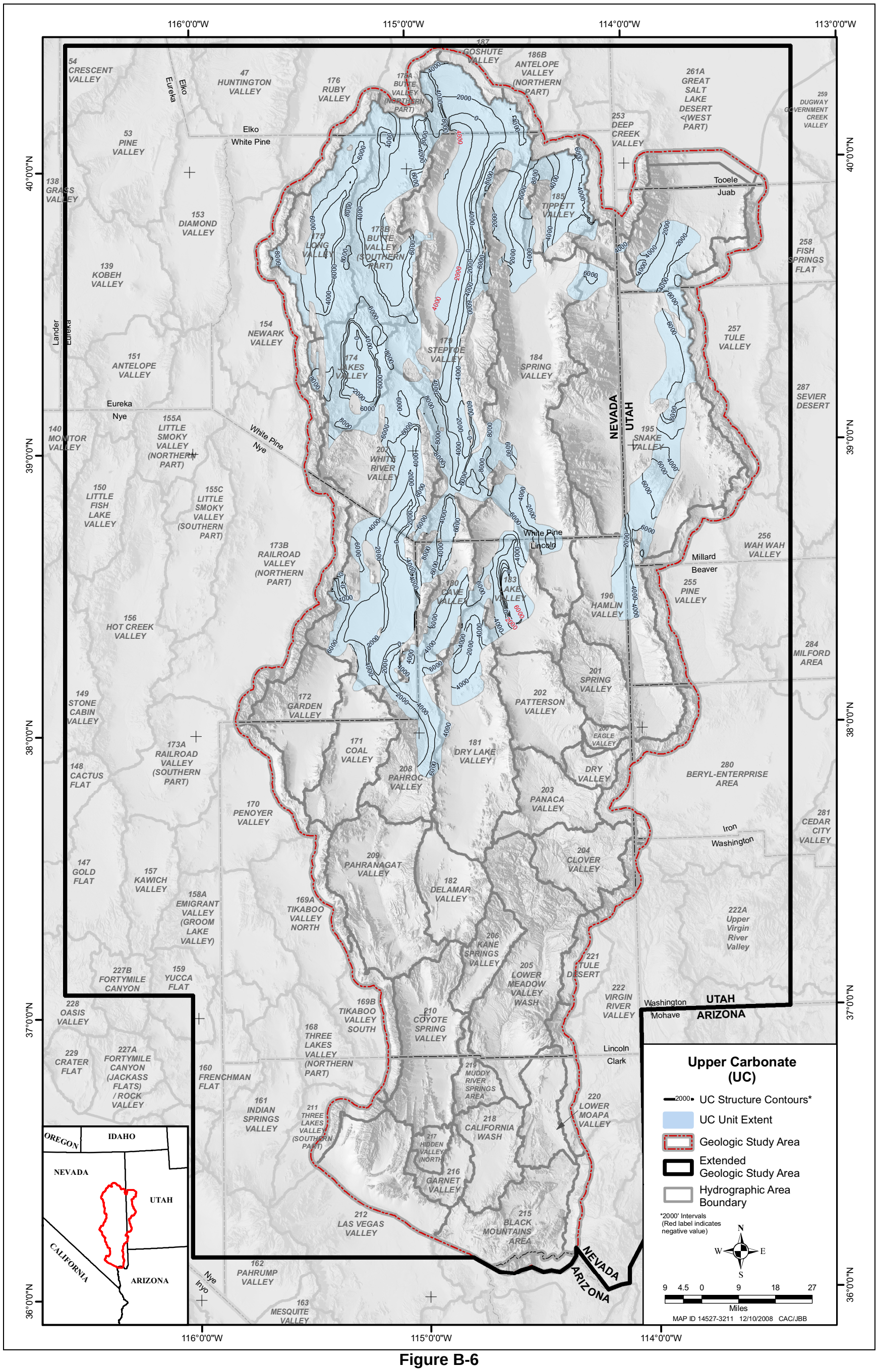


Figure B-6
Extent and Structural Contours of the Upper Carbonate Regional Modeling Unit

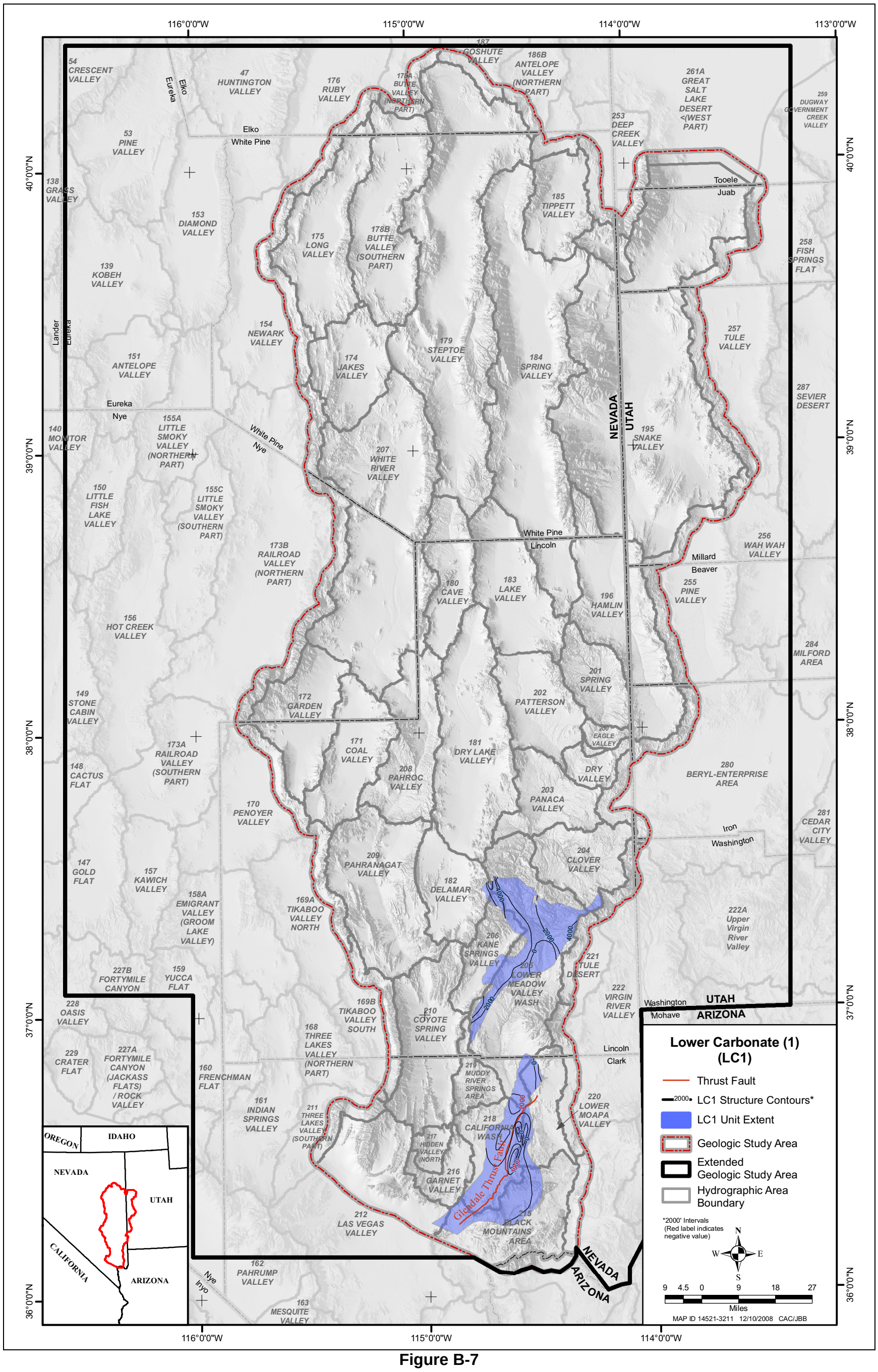


Figure B-7
Extent and Structural Contours of the Lower Carbonate (1) Regional Modeling Unit

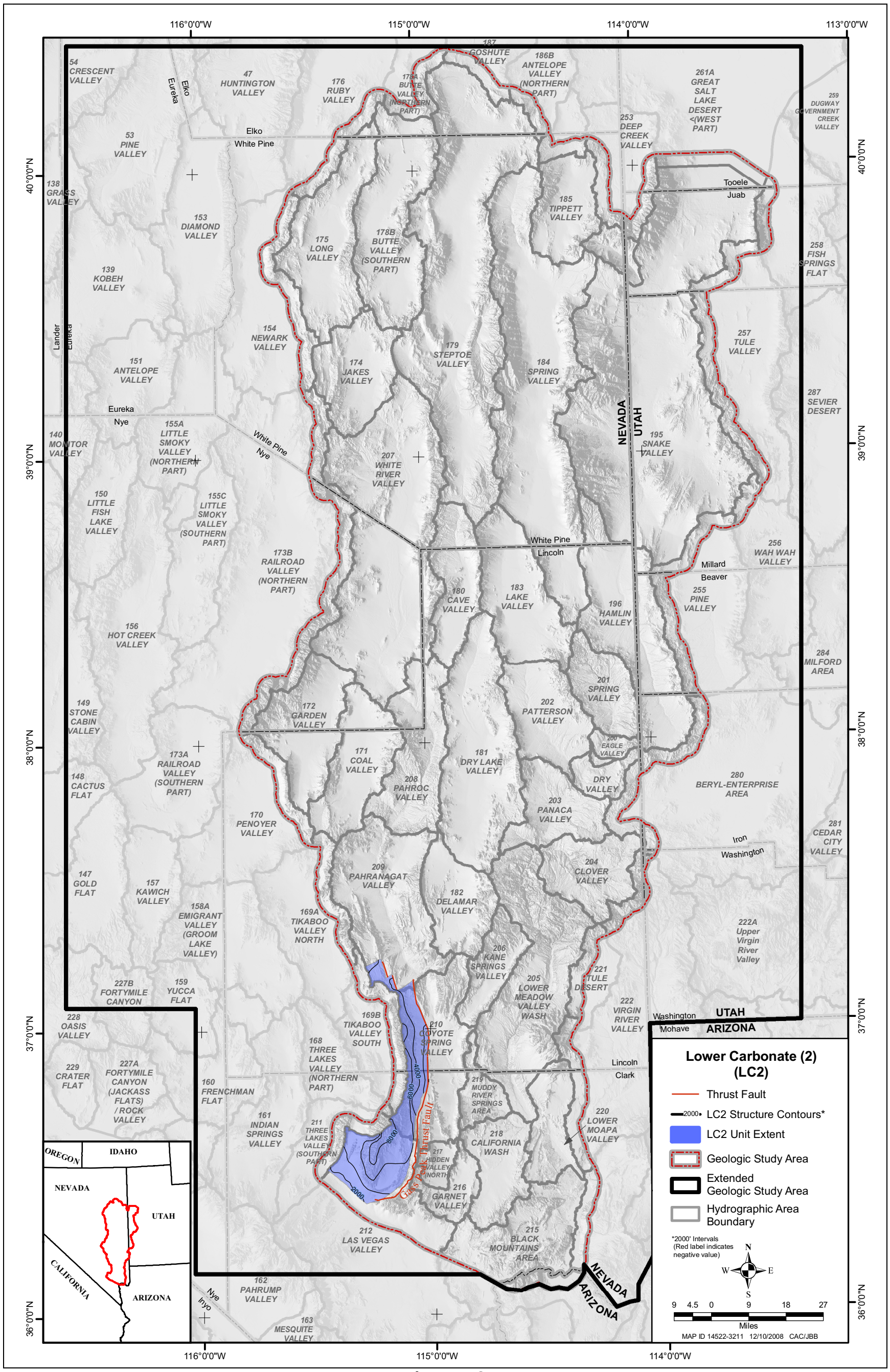


Figure B-8
Extent and Structural Contours of the Lower Carbonate (2) Regional Modeling Unit

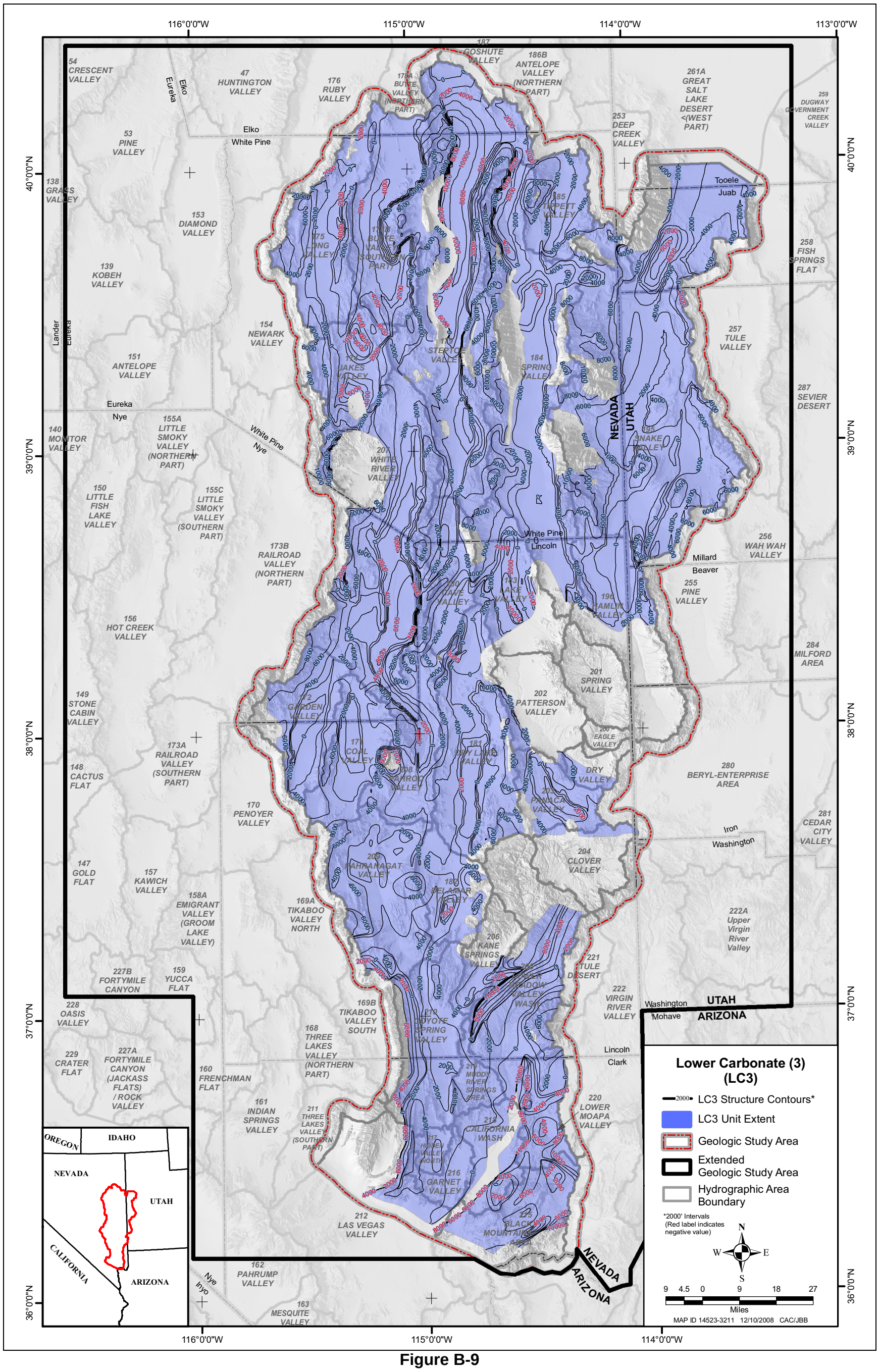


Figure B-9
Extent and Structural Contours of the Lower Carbonate (3) Regional Modeling Unit

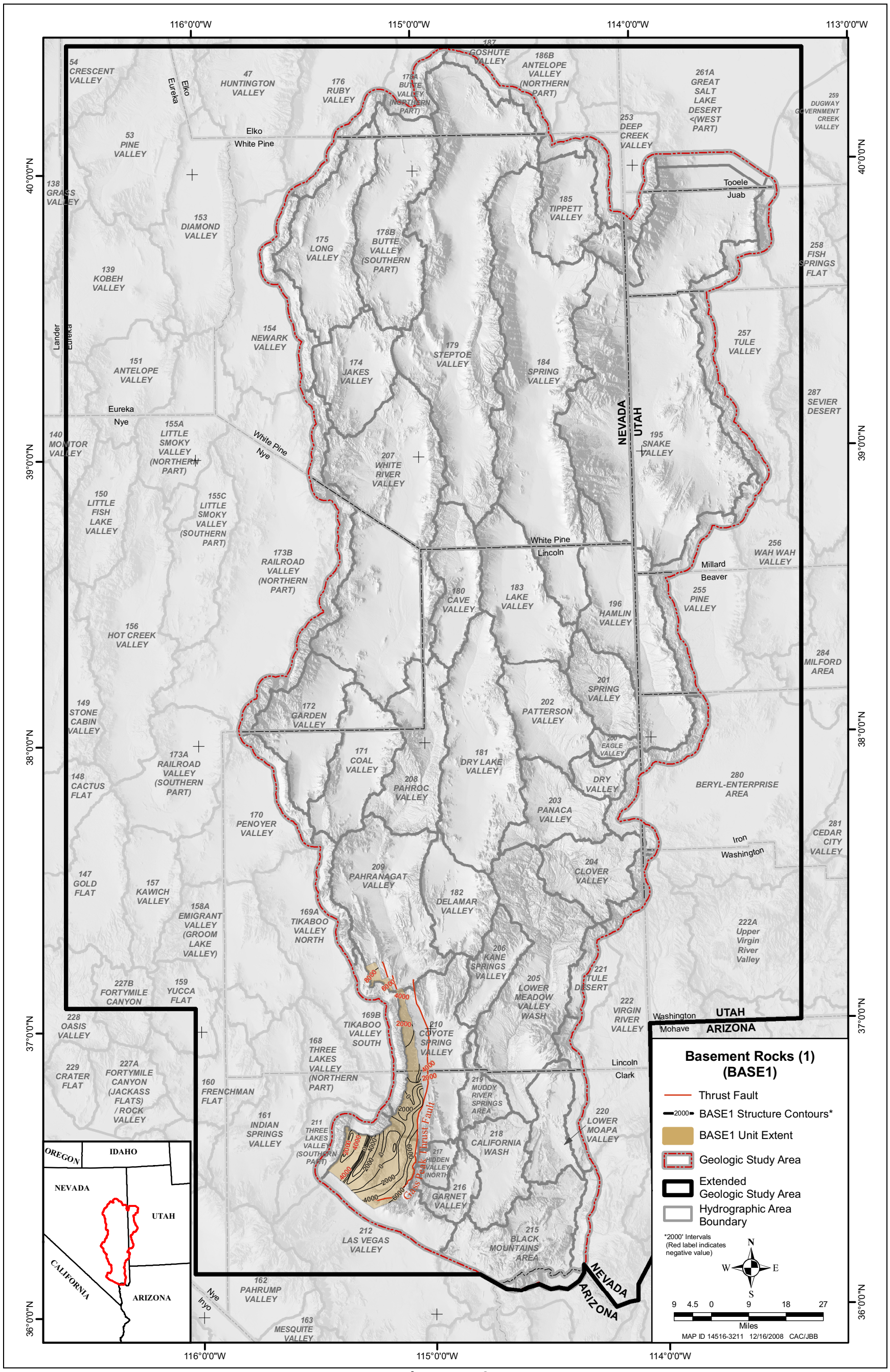


Figure B-10
Extent and Structural Contours of the Basement Rocks (1) Regional Modeling Unit

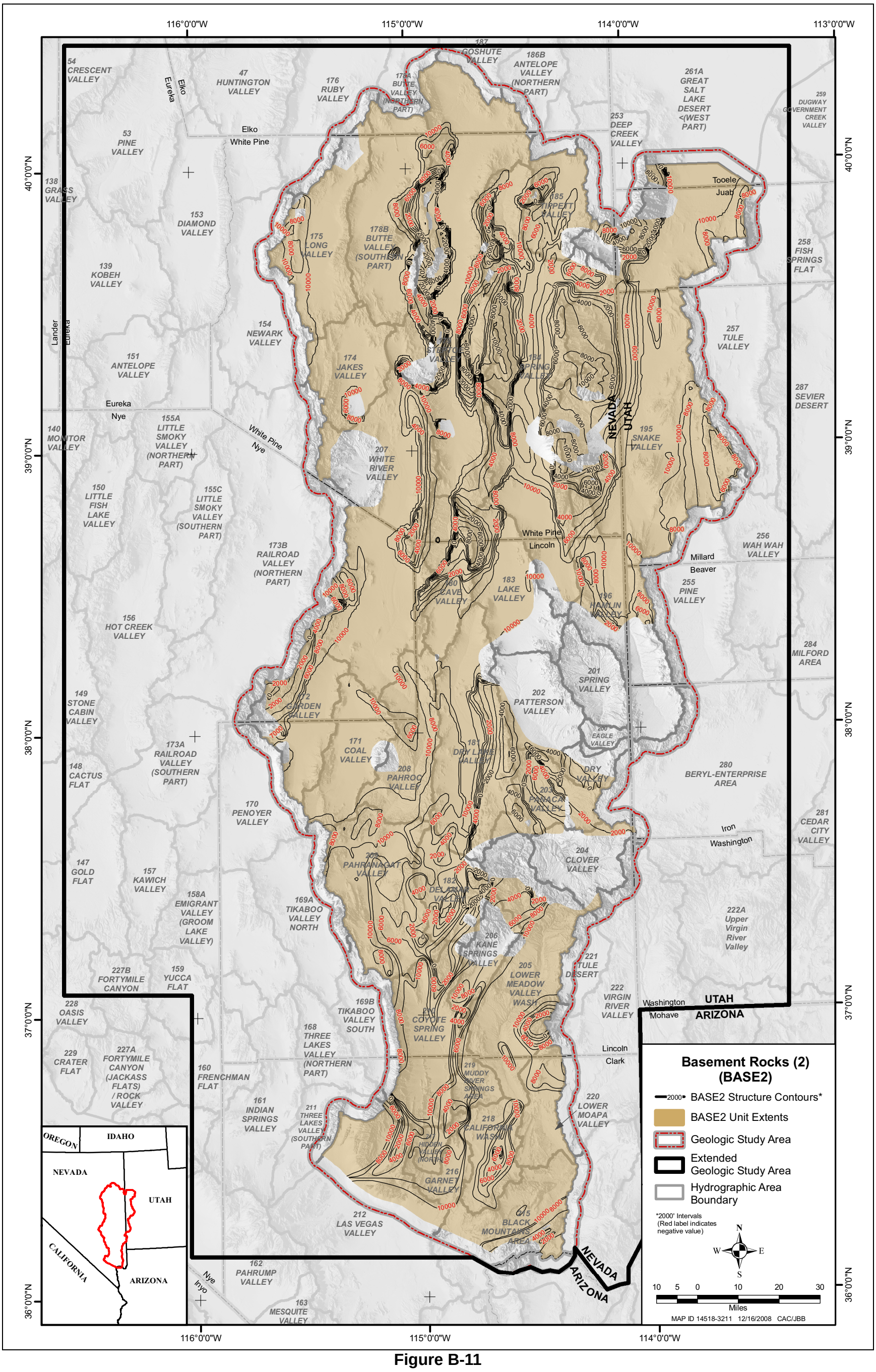


Figure B-11
Extent and Structural Contours of the Basement Rocks (2) Regional Modeling Unit

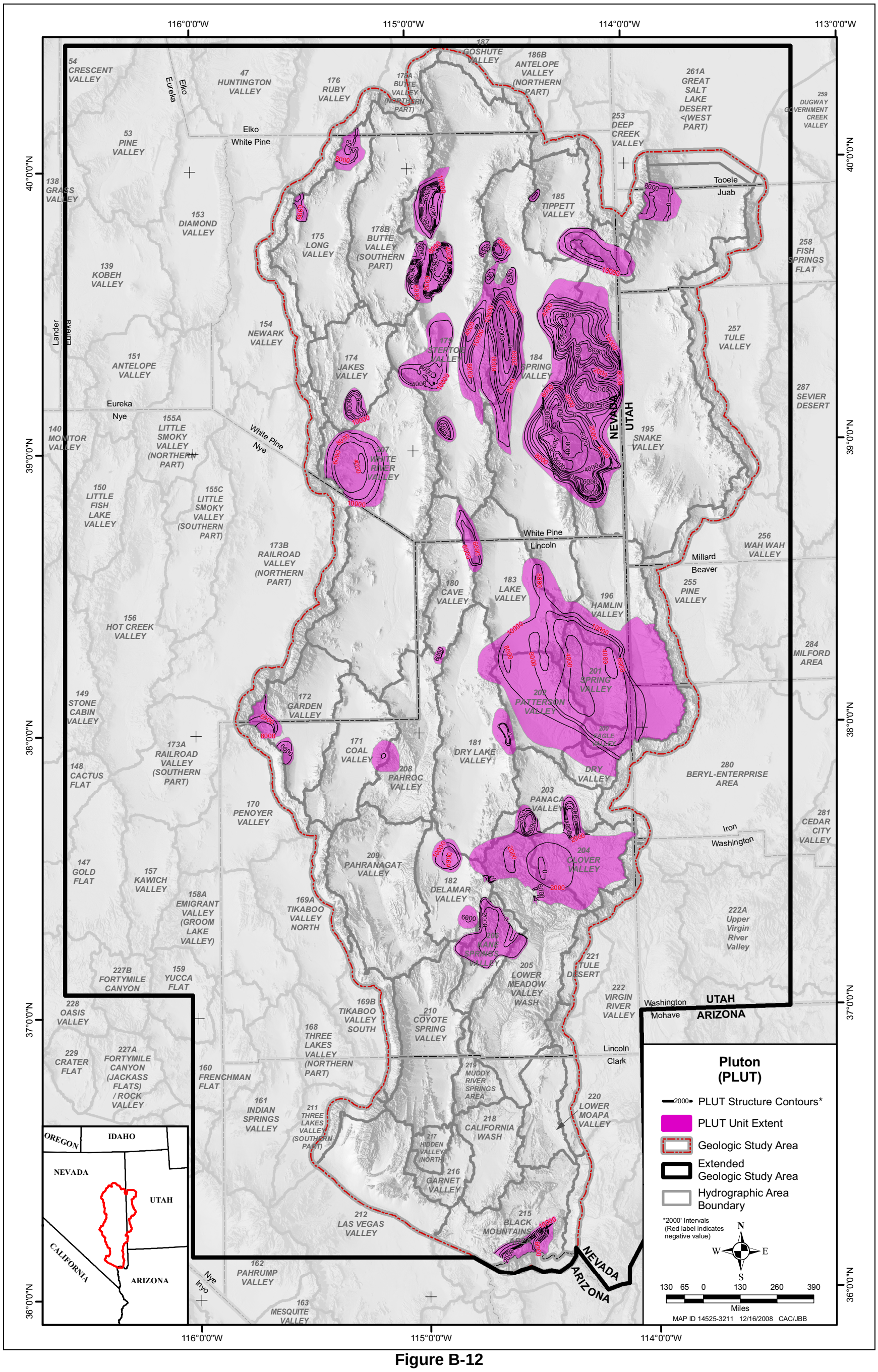


Figure B-12
Extent and Structural Contours of the Pluton Regional Modeling Unit

Appendix C

Hydraulic-Property Data Analysis

C.1.0 HYDRAULIC-PROPERTY DATA ANALYSIS

This appendix describes the data analysis efforts conducted to derive estimates of hydraulic properties for the RMUs of the study area. Descriptions of previous relevant studies, the technical approach, and the data analysis are presented in this appendix, followed by a summary. The data analysis is presented in two subsections: (1) reported aquifer-test data and (2) preliminary SNWA data.

C.1.1 Relevant Studies

The study area for the Project is largely unpopulated and therefore has not been extensively studied. This section contains a description of previous site-specific and regional studies that are relevant to this investigation, followed by a description of the ongoing investigations conducted by SNWA.

C.1.1.1 Previous Site-Specific Studies

Previous investigations conducted within the general study area are termed site-specific and are summarized below.

C.1.1.1.1 LVVWD Cooperative Water Project Studies

LVVWD published a series of reports in the early to mid 1990s in support of groundwater applications filed in eastern and central Nevada. The reports document the environmental setting and hydrology of select basins within the region.

C.1.1.1.2 MX Well Studies

In the late 1970s and early 1980s, hydrogeologic investigations were completed for the MX missile-siting program. The data collected from MX Well Tests under the USAF MX Missile-Siting Investigation–Water Resources Program are described in reports by Ertec Western, Inc. (1981 a through c) and Bunch and Harrill (1984). The area of investigation for this project extends over Nevada and Utah. A number of wells were constructed and tested in 1980 and 1981 when the project was stopped. Most tests were single-well constant-rate tests that were conducted in the valley-fill aquifer with a few tests conducted in the carbonate aquifer.

C.1.1.1.3 Drill-Stem Tests

McKay and Kepper (1988) compiled, reviewed, and analyzed drill-stem test (DST) data collected from oil and gas wells in Nevada. Most of the wildcat wells reviewed are in the Railroad Valley and White River flow systems. McKay and Kepper (1988) calculated transmissivities for 20 wells with

complete DST records for the carbonate aquifer. They found that DST transmissivity values were smaller than those derived from aquifer tests by as much as three orders of magnitude.

Since publication of McKay and Kepper (1988), 80 additional DSTs (1987 to 2003) have been conducted in Nevada. The data from these tests were not compiled or analyzed as part of this study.

C.1.1.1.4 White Pine Power Project

Leeds, Hill and Jewett, Inc., (1981b, 1983) describe well tests conducted as part of the White Pine Power Project. Aquifer-property data were derived from step-drawdown and pump tests. This study was conducted in three phases. Several wells were first installed and tested in the valley-fill and carbonate aquifers of Spring, Steptoe, and White River valleys. Then, a few more wells were installed and tested in Spring and Steptoe valleys.

C.1.1.1.5 NDWR Driller's Logs

The NDWR maintains an online database of driller's logs for many wells in Nevada (NDWR, 2004) and is a source of extensive information. In addition to location and well construction information, the driller's logs contain lithology and occasionally specific capacity data.

C.1.1.1.6 Other Site-Specific Studies

Other site-specific studies consist of reports on localized hydrological investigations of Coyote Spring Valley, Moapa Valley, Lower Meadow Valley Wash, and Garnet Valley. These reports include data derived from step-drawdown and constant-rate tests for wells completed in valley-fill, carbonate, and volcanic rocks.

C.1.1.2 Previous Regional Studies

For the most part, regional data were derived from studies associated with the Death Valley Flow System. This section briefly describes each of the regional studies.

C.1.1.2.1 Welch et al. (2008)

As part of BARCASS, Welch et al. (2008) derived estimates of hydraulic properties for their study area from the aquifer-test data set compiled by Belcher et al. (2001) for the DVFS. Welch et al. (2008) justified the use of DVFS data because of the lack of data specific to their study area and the similarity between rock types and HGUs within the DVFS.

Welch et al. (2008) grouped the horizontal hydraulic-conductivity data compiled by Belcher et al. (2001) by HGU and summarized the data statistically. They found that hydraulic-conductivity values for a given HGU vary by three to nine orders of magnitude and are affected by fracturing and chemical dissolution, at least for carbonate rocks.

C.1.1.2.2 Belcher et al. (2001)

Belcher et al. (2001) compiled an extensive aquifer-property data set from existing databases and the literature to support the USGS Death Valley Regional Flow System model (Belcher, 2004). Although most of the data compiled by Belcher et al. (2001) fall within the DVRFS model area, it also includes some data locations outside of the model boundary. The data set includes only "good quality" data as deemed by the authors of the report. The analyses performed by Belcher et al. (2001) included subdividing the carbonate aquifer based on rocks with extensive faulting, with or without karst development, and undisturbed rocks. The results of their analyses showed that faulted rocks had a geometric mean of the horizontal hydraulic conductivity of approximately 9.84 ft/day, whereas the undisturbed rocks had a geometric mean of 0.33 ft/day. The conclusion reached from this was that extensive faulting and karst development significantly increases the hydraulic continuity of the carbonate aquifers (Belcher et al., 2001).

C.1.1.2.3 NTS Studies

An aquifer-property data set was developed to support an earlier model of the regional groundwater flow model for the DVFS (IT, 1996), the NTS Regional Model (IT, 1997). This data set contains much of the regional data available at the time of the study, and each record in the data set was assigned a qualification flag.

In cooperation with the USGS, the Stoller-Navarro Joint Venture (SNJV) compiled raw slug-test data previously collected by the USGS for tests conducted on the NTS. SNJV analyzed the data for environmental restoration studies of the Pahute Mesa underground test area and published the results in a report discussing hydrologic data for Pahute Mesa (SNJV, 2004c).

Other NTS data are presented in hydrologic data-interpretation reports for wells or well clusters in the NTS and its vicinity conducted as part of the DOE Environmental Restoration Program (IT, 2002a through i; SNJV 2004a, b, d, and e).

C.1.1.2.4 Other Regional Studies

Other studies conducted within the region include data from the Nye County Early Warning Drilling Program (Questa Engineering, 1999a through c, 2000a and b, 2001, 2002a through c, and 2003). These studies include step-drawdown, constant-rate, and flow-logging tests for wells and multiple-well aquifer tests.

C.1.1.2.5 Ongoing SNWA Studies

As part of the Project, SNWA has been installing and testing several monitor and test wells within the study area (Appendix A). Aquifer tests have been conducted as part of the hydrologic data collection effort for some of these wells. A summary of the aquifer test results are presented in Section C.1.3.6.2.

C.1.2 Technical Approach

The role of aquifer properties, the types of data, and the objectives and approach for the hydraulic-property data analysis are described in this section.

C.1.2.1 Role of Aquifer Properties

Hydraulic properties include permeability and storage properties of geologic units. Permeability properties quantify the ability of fluids to flow through geologic media. Storage properties, as their name indicates, provide a measure of the storage capabilities of the geologic media.

In general, quantification of the permeability and storage properties of the geologic media is needed for several reasons: (1) it facilitates comparison of water-bearing geologic units; (2) it facilitates the identification of aquifers versus confining units; and (3) it is a requirement in flux calculations using simple analytical or complex numerical models of groundwater flow.

The aquifer-property data were used to support the development of a 3D numerical groundwater flow model by providing initial estimates and ranges of parameters. The numerical model was used to predict the potential effects of pumping from proposed production wells in the project basins (Figure 1-2).

C.1.2.2 Data Types

Data types of interest include (1) hydraulic properties, such as permeability and storage, derived directly from field or laboratory tests and (2) other types of data that may indirectly be used to estimate hydraulic properties or provide comparative estimates.

Permeability properties may be expressed as intrinsic permeability, hydraulic conductivity, or transmissivity. Intrinsic permeability is a measure of the ability of a geologic unit to transmit fluids under a hydraulic or potential gradient and is independent of the resident fluid properties (Fetter, 1988). This property is usually applied in the evaluation of oil and gas wells, where multiple fluids are usually present. Hydraulic conductivity is a measure of the ability of a geologic unit to transmit water and is a function of both the medium and the fluid (Fetter, 1988). Transmissivity is the rate at which water is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient and is a product of hydraulic conductivity and the thickness of the water-bearing geologic unit (Fetter, 1988). Hydraulic conductivity may vary with direction horizontally and vertically. Such variability is measured via anisotropy factors. Specific capacity is an expression of the productivity of a well that represents the well yield per unit of drawdown (Fetter, 1988) and may be used to derive estimates of transmissivity.

Storage properties include specific storage, storativity and specific yield. The storativity of an aquifer, also known as storage coefficient, is the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Fetter, 1988). Specific storage may be defined as the storativity per unit thickness. The specific yield is the ratio of water a

rock or soil will yield by gravity drainage to the volume of rock or soil. The retained portion is called specific retention (Fetter, 1988).

Other types of data that may be used to estimate hydraulic properties are texture and permeability indicator information. Lithologic logs may be used to develop models of the spatial variability of texture within geologic units. These models may, in turn, be used to derive estimates of hydraulic conductivity. Permeability indicators are useful for carbonate aquifers. Such factors include geomorphic landforms, groundwater-level fluctuations, and variability of groundwater chemistry, among other factors (Rovey, 1994). Permeability indicators will not be discussed any further in this report.

Therefore, the types of data that may be used to estimate hydraulic properties are:

- Hydraulic conductivity
- Anisotropy ratios
- Hydraulic-conductivity variation with depth
- Transmissivity
- Specific capacity
- Storage coefficient/specific storage
- Specific yield

Spatially, hydraulic conductivity is log-normally distributed (Freeze and Cherry, 1979). The spatial distribution of transmissivity also follows a log-normal probability distribution. Anisotropy ratios and storage properties were assumed to be normally distributed for this study.

C.1.2.3 Objectives

The primary objectives for the hydraulic-property assessment were to:

1. Analyze the reported aquifer-testing data available for the study area and vicinity to:

    - Derive a range of hydraulic conductivity for each RMU.
    - Estimate horizontal-to-vertical anisotropy factors.
    - Derive a range of specific-yield values for all RMUs under unconfined conditions.
    - Estimate the range of specific storage for all RMUs under confined conditions.
    - Derive a relationship of hydraulic conductivity with depth for each RMU (aquifer units only).

2. Present preliminary aquifer-property data derived from SNWA tests conducted in the project basins.

C.1.2.4 Approach

The approach for this analysis is to compile the available existing aquifer-property information for the region. Data are handled and used differently depending on the process used to derive them.

Reported data derived from previous field and laboratory tests were compiled and reduced to a unified structure, ultimately creating a database. The database could then be queried based on RMU and statistically analyzed to obtain estimates of the range of hydraulic conductivity, specific yield, and specific storage by RMU. For hydraulic conductivity, the statistics were performed on the Log_{10} of the *K* values.

The partial results of the ongoing SNWA field data collection activities within the study area are reported but not incorporated in the data analysis because they are preliminary. They are presented separately and are to be used only as additional guides in the interpretation of the hydraulic properties of the RMUs at the local scale.

C.1.3 Reported Testing Data

The types of tests, the sources of data, the data reduction, the quality evaluation, and the analysis of the reported testing data are described in this section.

C.1.3.1 Type of Tests

Types of tests conducted to derive measurements of aquifer hydraulic properties include those that estimate hydraulic properties directly and those that estimate hydraulic properties in a quantitative or qualitative manner using other related data.

Methods of direct aquifer-property measurement include:

- Specific-capacity tests
- Constant-rate pumping tests
- Slug tests
- Packer tests
- Step-drawdown tests
- Drill-stem tests
- Permeameter tests

Specific capacity is typically calculated from short-duration pumping tests conducted immediately following drilling and is occasionally reported on the driller's log as the pumping rate and the total drawdown. Specific capacity may then be calculated as the ratio of the pumping rate to total drawdown. Estimates of transmissivity may be derived from specific-capacity values.

Constant-rate tests are most commonly conducted to estimate transmissivity or hydraulic conductivity and storage properties (storage coefficient or specific yield). Tests may include a single well or multiple wells and usually consist of a pumping phase and a recovery phase. Note that estimates of storage properties that are representative of the tested portion of the aquifer may be obtained only from the time-drawdown data collected from observation wells.

The pumping well is typically pumped at a constant rate for a period ranging from several hours to several days. The pumping phase involves measuring changes in water levels in the pumping well

and observation wells (if any) while the well is being pumped. The recovery phase measures changes in water levels after pumping is stopped until the well recovers to pre-pumping conditions.

The resulting time-drawdown data are analyzed to derive estimates of transmissivity or hydraulic conductivity and storage properties if the test includes observation wells. The time-drawdown (or displacement) data are analyzed to derive estimates of transmissivity and storage properties.

Many methods are available for analyzing constant-rate test data in unconfined, confined, leaky, and fractured aquifers. These methods have been implemented in software packages, such as AQTESOLV. Analysis methods for constant-rate test data include Theis (1935), Theis residual drawdown (Theis, 1935), Cooper-Jacob (Cooper and Jacob, 1946), Hantush-Jacob (Hantush and Jacob, 1955), Hantush (1960, 1962), Papadopulos-Cooper (Papadopulos and Cooper, 1967), Neuman-Witherspoon (Neuman and Witherspoon, 1969), Neuman (1974), Streltsova (1974), and Moench (1984, 1985, 1993, 1996, 1997) methods.

Slug tests are usually conducted as single-well tests and provide estimates of hydraulic conductivity. During the process, a slug of water is either added to or removed from the well, and changes in water level are measured throughout the test. The resulting data are analyzed using one of the available data analysis methods. Confined-aquifer analysis methods include the Hvorslev (1951), Cooper et al. (1967), Bouwer and Rice (1976), and Hyder et al. (1994) methods. Unconfined-aquifer analysis methods include the Hvorslev (1951), Bouwer and Rice (1976), and Hyder et al. (1994) methods.

A slug test can also be conducted within a specific depth interval by isolating a section of the well using single or double packer(s). Changes in pressure are recorded using a transducer and converted to changes in hydraulic head or water level. These data are analyzed to derive estimates of transmissivity or hydraulic conductivity.

Step-drawdown tests are commonly conducted prior to constant-rate pumping tests. They are used to estimate well efficiency and optimal pumping rate. They are usually conducted with three to five consecutive short-duration pumped rates and provide estimates of the well's specific capacity, which can be used to derive an estimate of transmissivity. Step-drawdown-test data may be analyzed using the Theis (1935) step-test method.

DSTs are conducted to determine the potential of a producing oil or gas formation. The DST tool is placed on the bottom of the drill stem and lowered into the hole. Weight is applied to the tool to expand a hard rubber sealer (packer). To start the test, the tool ports are opened to the formation. A transducer records pressure versus time during pressure buildup. The time-pressure data may be analyzed to derive an estimate of transmissivity.

Permeameter tests are conducted on rock cores in the laboratory. A fluid (gas or liquid) is injected into the core at various pressures, and the differential pressure and flow rates are recorded. This information is then used in a Darcy's equation to calculate the permeability of the core sample. These tests provide small-scale estimates of permeability or hydraulic conductivity.

C.1.3.2 Data Sources

Data sources of aquifer-property data were subdivided into two main categories: (1) site-specific-testing data sources and (2) regional-testing data sources.

C.1.3.2.1 Site-Specific-Testing Data Sources

Site-specific-testing data sources are defined as reports or databases containing data for basins within the study area (Figure 1-1).

The main site-specific data sources cover more than one basin and are:

- MX Well tests (Ertec Western, Inc. reports, 1981 a through c; Bunch and Harrill, 1984)
- Driller's logs (NDWR, 2004; UDWR, 2005)
- Drill-stem tests (McKay and Kepper, 1988)
- White Pine Power Project well tests (Leeds, Hill, and Jewett, Inc., 1981a and b, 1983)

Other site-specific data sources cover a single basin located within the study area and are:

- Coyote Spring Valley (Berger et al., 1988; Johnson et al., 1998; Converse, 2002)
- Three Lakes Valley South (Converse, 1997, 1998a and b)
- Dry Lake Valley (SRK, 2001; Johnson, 2002)
- Meadow Valley (URS, 2001)
- Moapa Valley (Mifflin & Associates, 2001)
- Tule Desert (HydroSystems, 2002)

C.1.3.2.2 Regional-Testing Data Sources

Regional-testing data sources are defined as reports or databases containing data for regions including or located near the study area.

The main sources of regional data include:

- DVRFS Model data (Belcher et al., 2001)
- NTS Regional Model data (IT, 1996)
- Slug-test data (SNJV, 2004c)

Other sources of regional data are as follows:

- IT (2002 a through i)
- SNJV (2004a, b, d, and e)
- Questa Engineering (1999 a through c, 2000a and b, 2001, 2002a through c, 2003)
- Maurer et al. (2004)

C.1.3.3 Data Reduction

Data reduction for the hydraulic-property data set began with the calculation of hydraulic-conductivity estimates for the NDWR (2004) and UDWR (2005) specific-capacity data sets. All of the individual data sets were then formatted into the same fields of information, and all values were converted to a standard set of units. This formatting and standardization process included mapping the hydrogeologic or lithologic information to an RMU (Table 4-1). Formatting also involved the standardization of site names and the creation of a site-location table for unique locations. The individual data sets were then combined, and duplicate records were identified, flagged, and removed from the well-testing data set. Hydraulic conductivity was calculated when test interval thicknesses were available for transmissivity values. Finally, an aquifer-property database was constructed from the resulting location and property tables (SNWA, 2006). Figure C-1 shows the locations of aquifer-test data within the aquifer-property database.

C.1.3.4 Data-Quality Evaluation

The record documentation and the test type and scale were factors considered in the data-quality evaluation of each record of the combined data set as described in this section.

Record documentation includes the documentation of the test itself and the data analysis used to derive the aquifer properties. A data documentation evaluation flag was applied to each record in the well-testing data set. The levels of documentation are described below:

- Level 1: Data containing detailed information about how the properties were determined, including information on test type, dates of testing, pumping or injection rates, radius or interwell distances, transmissive intervals, lithologic or stratigraphic descriptions, analytical method, and source. This level also includes all of the data from Belcher et al. (2001).

- Level 2: Data containing all of the properties listed in Level 1 but missing the dates of testing.

- Level 3: Data containing most of the properties listed in Level 1 but missing multiple fields of relevant information, including dates, average pumping or injection rates, or radius or interwell distances.

- Level 4: Data missing information on analytical method, test types, or transmissive intervals. This level also includes NDWR and Utah Division of Water Rights Driller's Log information.

- Level 5: Data missing hydraulic-property values or the information required to calculate the values.

The type and scale of the test are extremely important when assessing the quality of a test for the intended purpose, especially for fractured HGUs. The following test types may be grouped according to their scales from largest to smallest: (1) multiple-well, constant-rate pumping tests; (2) single-well, constant-rate pumping tests; (3) specific-capacity and DSTs; (4) slug, packer, and step-drawdown tests; and (5) permeameter tests.

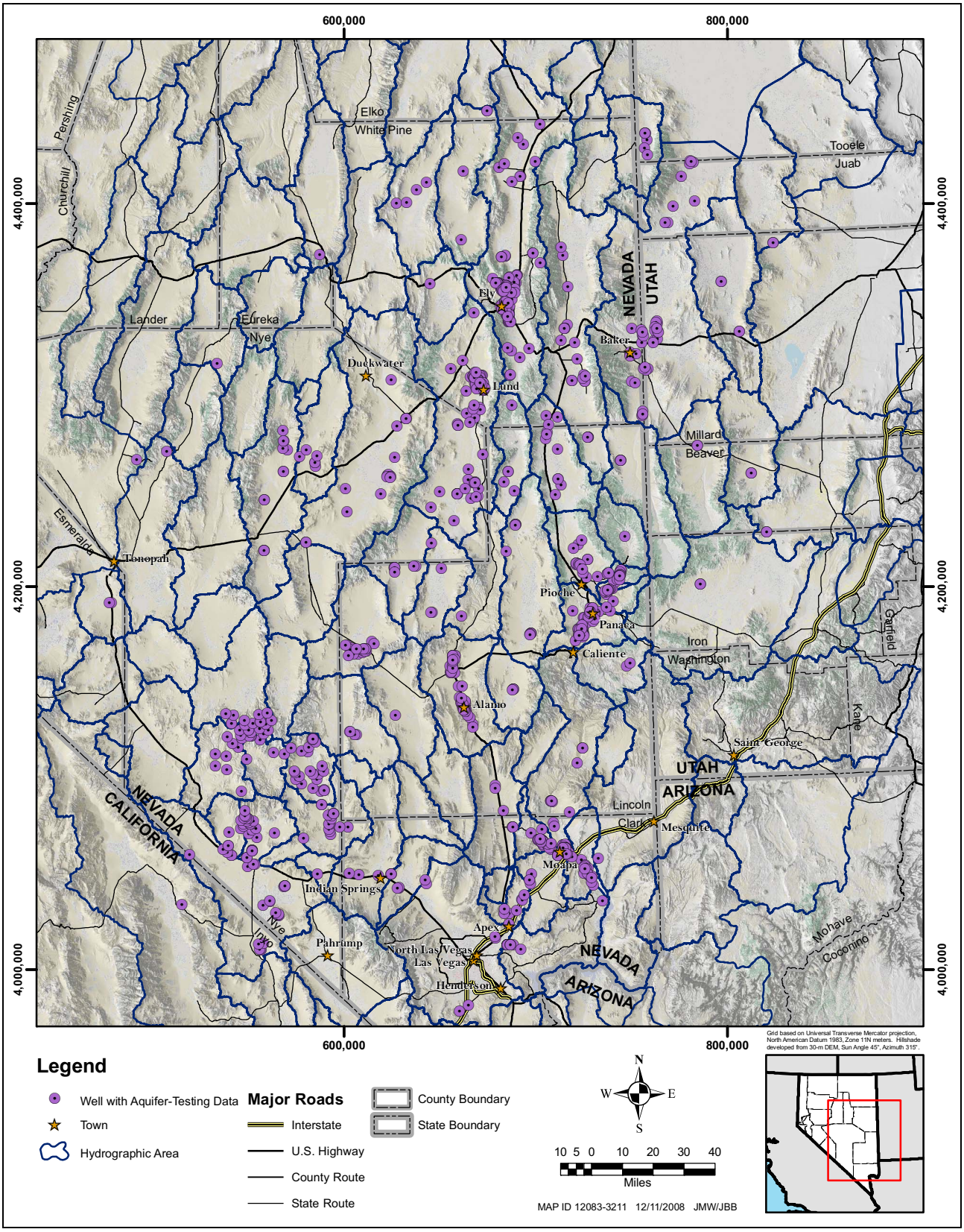


Figure C-1
Locations of Aquifer-Property Data

C.1.3.5 Reported Test Data Limitations

General data limitations include:

- Limited data in project basins
- Limited tests from deep wells
- Limited number of multiple-well tests
- Limited number of long-term pumping tests
- Assumed thickness of the open interval
- Analytical methods based on aquifer assumptions

In addition, a positive bias for the average hydraulic conductivity is often observed because many wells are screened preferentially across more productive zones (Belcher et al., 2002).

C.1.3.6 Data Analysis

The analysis of the reported testing data is subdivided into four parts: (1) analysis of lithologic data from driller's logs, (2) statistical analysis of hydraulic properties, (3) analysis of hydraulic conductivity with depth, and (4) analysis of hydraulic conductivity versus depth.

C.1.3.6.1 Analysis of Lithologic Data

An attempt was made to use the available lithologic data contained in driller's logs to derive a spatial distribution of hydraulic conductivity using a method that converts lithologic data into texture, which is then converted to hydraulic conductivity. Driller's logs for wells drilled in the UVF RMU and for which lithologic data are available are shown in Figure C-2.

This texture analysis method was used by Burrow et al. (2004) for the Modesto, California, area. As part of the Modesto study, approximately 3,500 well logs were compiled for an area of approximately 900 mi^2. Geostatistical methods were then applied to develop a spatial correlation model of the percentage of coarse-grained texture. This model was created by converting the lithologic information in driller's logs into a bivariate distribution of texture, where a value of 100 percent was assigned to coarse-grained lithologies and 0 percent was assigned to fine-grained lithologies. The 1-m data were then re-sampled, and a 3D kriged model was created to show the percentage of coarse-grained material. This model was then used as a surrogate for hydraulic conductivity and demonstrated that, in the Modesto area, the composition of alluvial materials is significantly heterogeneous, and therefore the hydraulic conductivities would be heterogeneous.

A similar methodology was attempted with 964 driller's logs within the northern groundwater project study area as part of this study. The results of this work indicated that there were not enough data within the study area for this method to be useful. The spatial distribution of data was not sufficient for contouring, and there was a general lack of data within the project basins. The other problem encountered was that the valley fill in many of the study area basins is several thousands of feet thick, while the wells are generally drilled to the water table or slightly below. This results in a deficiency

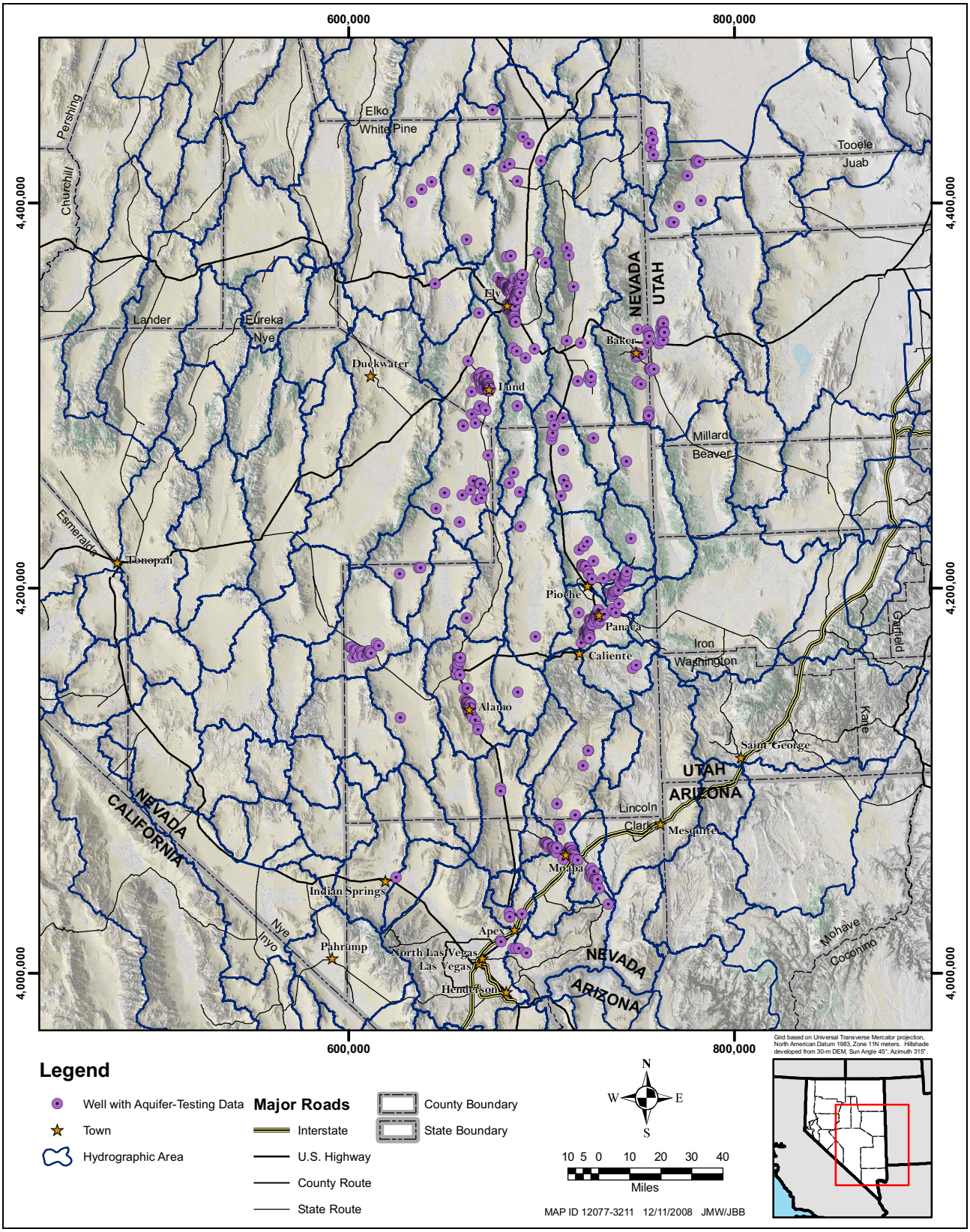


Figure C-2
Locations of Driller's Logs and Specific-Capacity Data for the UVF

of textural data for all but the uppermost alluvium. Therefore, this method was not used to determine hydraulic properties for this study.

C.1.3.6.2 Statistical Analysis of Hydraulic Properties

The data processing methodology and estimates of aquifer properties derived from the reported testing data are presented in this section. The data analysis does not include the preliminary results for the new SNWA monitor and test wells.

C.1.3.6.2.1 Methodology

Data analysis began with querying the aquifer-property database and extracting hydraulic-property information for all eight RMUs. The data were analyzed using two subsets of the data set, hydraulic conductivities and aquifer-storage properties, queried from the database:

The first subset was focused on hydraulic conductivity, as this property may be derived from all test types. However, this data subset was also used to derive estimates of other properties. The data were grouped by test type and quantity of available information. While duplicate records were removed before entry into the database, it was still possible to have multiple unique results for the same well interval. To keep these instances from creating a statistical bias, either a preferred value was accepted or the geometric mean of the values for the interval was calculated and applied. The data from Belcher et al. (2001) were considered to be high reliability and therefore were considered a preferred value. The higher weight applied to the Belcher et al. (2001) data stems from their re-analysis of tests before acceptance into their own data set. This processing reduced the data set to a set of records, each representing a single tested interval in a given well. Values of hydraulic conductivities were then transformed to Log_{10} values based on the assumption of a log-normal distribution for this property. Descriptive statistics, including the geometric means, standard deviations, minimum, and maximum, were calculated using the Log_{10} hydraulic-conductivity values for each RMU and test-type grouping. This reduced data set was also used to (1) conduct the analysis of the relationship of horizontal hydraulic conductivity with depth, (2) extract and summarize the few values of vertical anisotropy that are available, and (3) conduct a preliminary statistical analysis of the storativity and specific-yield data.

The estimates of storativity derived from the first data subset may not be representative of the aquifer units, as some of the records include estimates obtained from single-well aquifer tests. Aquifer-storage properties are most representative of the aquifer when they are derived from time-drawdown data collected from observation wells in multiple-well constant-rate aquifer tests. Thus, a second data subset was derived from the first subset. Because aquifer-storage properties are only needed for the aquifer RMUs, i.e., the UVF, LVF, and UC/LC RMUs, records for these RMUs corresponding to multiple-well constant-rate aquifer tests were extracted from the first data subset. This data subset was used to derive estimates of specific yield and specific storage. Because estimates of transmissivities in this data subset are also believed to be more representative of the tested aquifers, they were also statistically summarized from this data subset. Note that data records containing specific-yield values are identical in both data subsets because specific yield was only reported for observation wells.

C.1.3.6.2.2 Results

The results of the hydraulic-property data analysis are presented in this subsection. Statistics derived for horizontal hydraulic conductivity from the first data subset are presented in Table C-1 according to the type of test used to derive the estimates. The results of the analysis conducted using the second data subset are summarized in Table C-2. Analysis results for vertical anisotropy, specific yield, and storativity derived from the first data subset are presented by RMU in the following sections.

Table C-1
Hydraulic-Conductivity Estimates

Test Type	Log_{10} Hydraulic Conductivity (ft/day)				
	Mean	Standard Deviation	Minimum	Maximum	Number of Analyses
Upper Valley Fill (UVF RMU)					
Constant-Rate Test	1.07	1.15	-3.71	3.56	132
Specific-Capacity Driller's Logs	1.11	0.81	-1.76	3.35	850
Step-Drawdown\Swabbing Recovery	0.49	0.90	-3.51	1.59	26
Slug Test	-1.05	1.56	-3.69	1.47	19
Bailing	-0.45	0.08	-0.51	-0.39	2
Lower Valley Fill (LVF RMU)					
Constant-Rate Test	0.29	1.04	-2.62	2.53	136
Drill-Stem Tests	-1.99	0.62	-2.79	-1.46	5
Slug Test	-2.10	1.07	-6.31	1.11	958
Borehole Flow Logging	1.05	1.12	-1.67	2.93	28
Laboratory	-4.40	1.56	-6.61	-0.17	118
Intrusive Rock (PLUT RMU)					
All Test Types	-1.50	1.39	-2.73	0.67	7
Cretaceous to Triassic Siliciclastic Rock (Kps RMU)					
Drill-Stem Tests	-2.20	0.85	-3.20	-0.04	16
Mississippian Siliciclastic Rock (UA RMU)					
Constant-Rate Test	-1.24	1.52	-2.96	1.17	6
Drill-Stem Tests	-2.60	0.67	-3.07	-2.13	2
Slug Test	-1.16	0.95	-2.14	0.10	5
Borehole Flow Logging	-2.25	0.46	-3.07	-1.24	32
Carbonate Rock (UC/LC RMU)					
Constant-Rate Test	0.73	1.24	-1.56	3.50	89
Step-Drawdown\Swabbing Recovery	1.61	1.65	-1.00	3.71	7
Drill-Stem Tests	-1.13	1.65	-5.03	1.26	17
Slug Test	-0.17	1.08	-1.25	3.00	21
Bailing	-0.68	0.25	-0.86	-0.50	2
Borehole Flow Logging	2.39	0.59	1.38	3.63	22

Table C-2
Transmissivity, Specific-Yield, and Specific-Storage Values for Aquifer RMUs

RMU	Aquifer Property Name and Unit	Mean Value	Minimum Value	Maximum Value	Number of Data points
UVF	T (ft^2/d)	10,801	39	72,719	44
UVF	T (ft^2/d)[a]	5,039	39	72,719	44
UVF	Sy	0.0424	0.0004	0.2870	17
UVF	Ss (1/ft)	1.21E-04	1.72E-07	3.38E-03	36
LVF	T (ft^2/d)	8,711	43	34,432	11
LVF	T (ft^2/d)[a]	2,547	43	34,432	11
LVF	Sy	0.0023	0.0020	0.0030	3
LVF	Ss (1/ft)	6.75E-06	1.03E-07	3.44E-05	10
UC/LC	T (ft^2/d)	291,071	963	1,000,000	4
UC/LC	T (ft^2/d)[a]	48,809	963	1,000,000	4
UC/LC	Sy	0.0160	0.0012	0.0309	2
UC/LC	Ss (1/ft)	8.26E-06	4.67E-07	1.24E-05	3

[a]Values derived using Log_{10} values of transmissivity.

UVF RMU

Data available for the UVF RMU includes specific-capacity data and results of aquifer tests. Figure C-2 shows the distribution for driller's logs for which specific-capacity data are available, and Figure C-3 shows the distribution of all other test types in the UVF. Table C-1 contains a statistical summary for the horizontal hydraulic conductivity of the UVF. Table C-2 contains statistical summaries for the transmissivity, specific yield, and specific storage of the UVF.

Compared to the other RMUs, more site-specific hydraulic-property data are available for the UVF RMU. However, the available data (first data subset) are very spatially limited. Tested intervals for the constant-rate data include depths as great as 3,676 ft bgs; however, a majority of the tested depths were less than 1,000 ft deep. Based on 132 constant-rate tests, the mean *K* is 11.7 ft/day with a range of 0.0002 to 3,636 ft/day. Specific-yield estimates were available for 18 different wells or intervals for the UVF. Specific-yield estimates ranged from 0.0004 to 0.287 with an arithmetic mean of 0.043 after removing the suspect value of 0.0004. Belcher et al. (2001) removed the 0.0004 value from their statistics stating that the method used to derive it was not applicable. Storativity estimates were available for 58 different wells or intervals for the UVF and ranged from 1.04×10^{-15} to 0.7 with an arithmetic mean of 0.017. There are three tests in the UVF where the vertical anisotropy of hydraulic conductivity was measured. The vertical anisotropy factor, expressed as the horizontal-to-vertical hydraulic-conductivity ratio, ranges between 3 and 333.

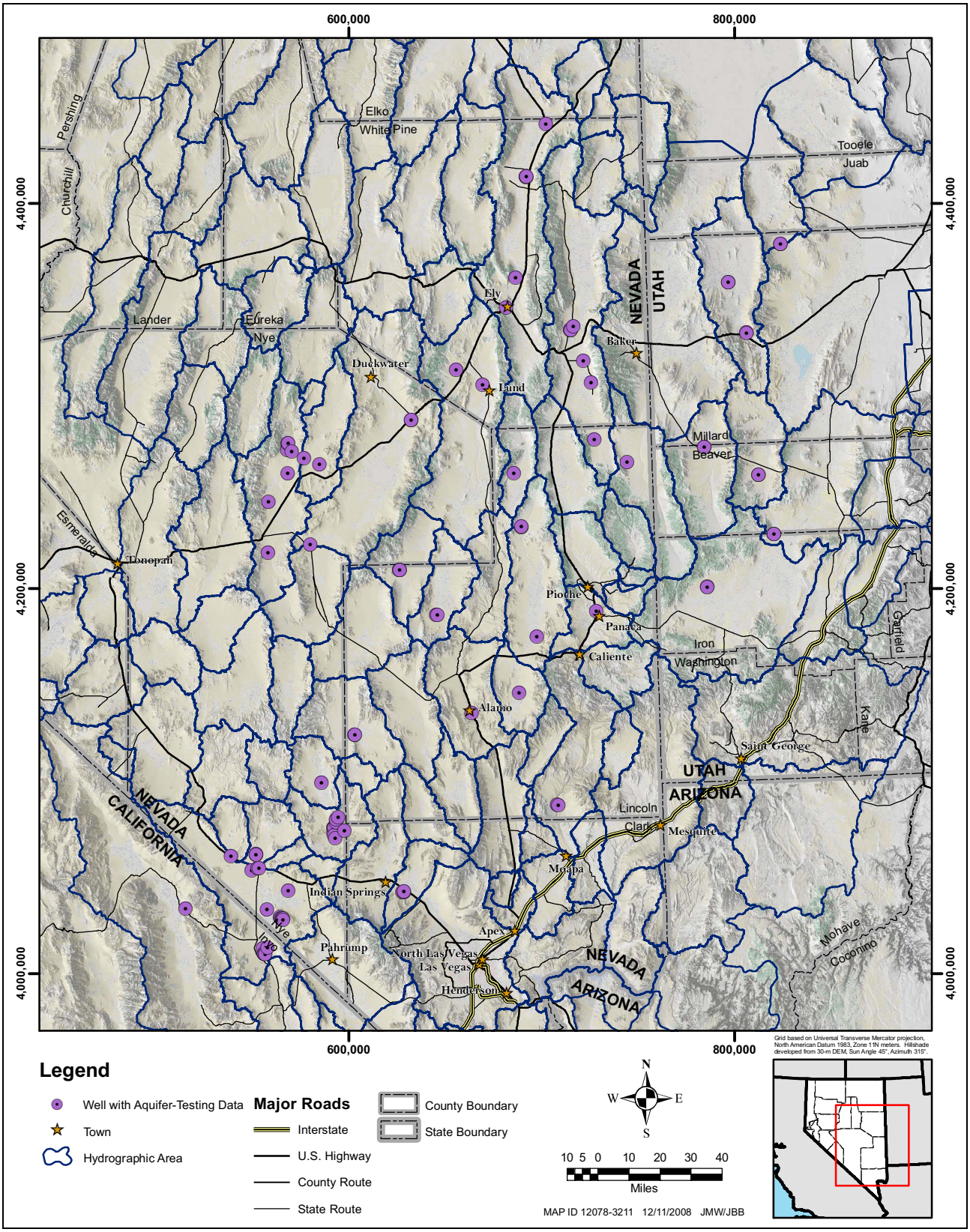


Figure C-3
Locations of Reported Aquifer-Property Data for the UVF

LVF RMU

Most of the LVF data locations are clustered around the NTS and Yucca Mountain, although some data are within Lincoln and northern Nye counties (Figure C-4). Table C-1 contains a statistical summary for the horizontal hydraulic conductivity of the LVF. Table C-2 contains statistical summaries for the transmissivity, specific yield, and specific storage of the LVF.

Tested intervals for the constant-rate test data include depths as great as 13,689 ft bgs. Analyses of constant-rate test data yielded a mean horizontal hydraulic conductivity of 1.95 ft/day and a range of 0.002 to 339 ft/day. Seven tests to measure the vertical-to-horizontal anisotropy within this RMU were conducted in two boreholes completed in the LVF. The anisotropy factors (horizontal-to-vertical hydraulic-conductivity ratios) range from 0.5 to 40. Specific-yield estimates were available for 10 intervals within two wells for the LVF. Specific-yield estimates ranged from 0.001 to 0.2 with an arithmetic mean of 0.032. Storativity estimates were available for 308 intervals within 35 wells for the LVF. Storativity estimates ranged from 0.00001 to 0.04 with an arithmetic mean of 0.000665.

PLUT RMU

Very few aquifer tests have been performed in this RMU, and the data in the aquifer-property database come from tests performed at the NTS and at well UCE-1 in northern Nye County. Table C-1 contains a statistical summary for the horizontal hydraulic conductivity of the PLUT. Because there are only seven measurements, they were all incorporated as a single statistical output. The derived mean horizontal hydraulic conductivity is 0.032 ft/day. No information is available for vertical anisotropy, specific yield, or specific storage for the PLUT.

Kps RMU

Table C-1 contains a statistical summary for the horizontal hydraulic conductivity of the Kps. Only one DST in Virgin River Valley (HA 222) was conducted for the Kps RMU (Figures B-3 and B-4, Appendix B). Sixteen other tests were conducted in south-central Utah in sedimentary rocks of the Colorado Plateau. The Colorado Plateau data should be transferable to the study area because both areas contain some of the same formations with similar lithologies. The mean value of horizontal hydraulic conductivity is 0.006 ft/day. No data are available for vertical anisotropy, specific yield, or storativity for the Kps.

UA RMU

Most of the aquifer-property data for the UA (Figure C-5) come from tests conducted on the NTS, with a few additional tests in northern Nye and White Pine counties. Table C-1 contains a statistical summary for the horizontal hydraulic conductivity of the UA. The mean value of horizontal hydraulic conductivity derived from these data is 0.058 ft/day. No information is available for conductivity anisotropy, specific yield, or storativity for the UA.

LC and UC RMUs

The LC and UC have the second greatest number of site-specific test information with aquifer test data in northern Nye, Lincoln, and White Pine counties and the southern part of the study area (Figure C-6). Table C-1 contains a statistical summary for the horizontal hydraulic conductivity of

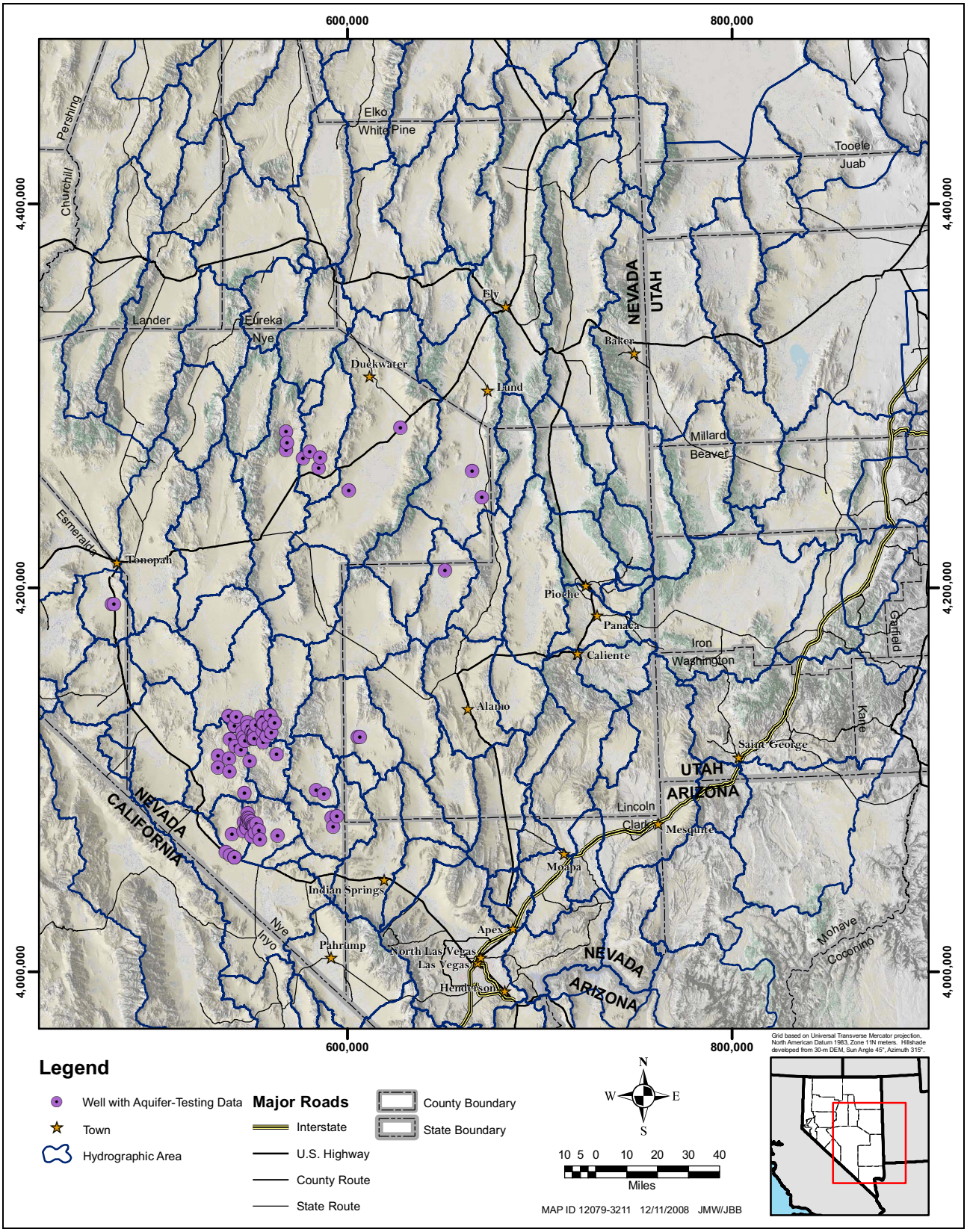


Figure C-4
Locations of Reported Aquifer-Property Data for the LVF

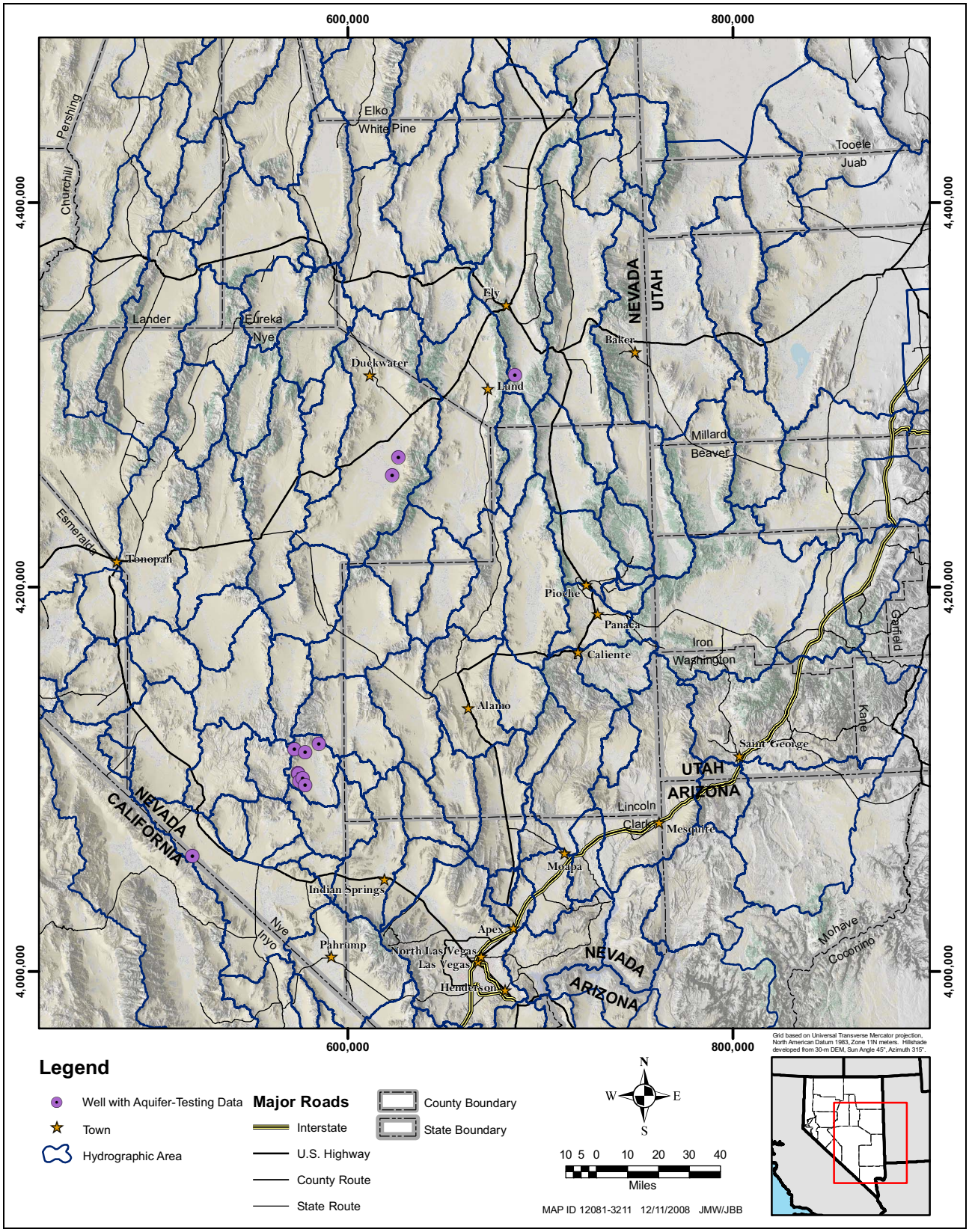


Figure C-5
Locations of Reported Hydraulic-Property Data for the UA

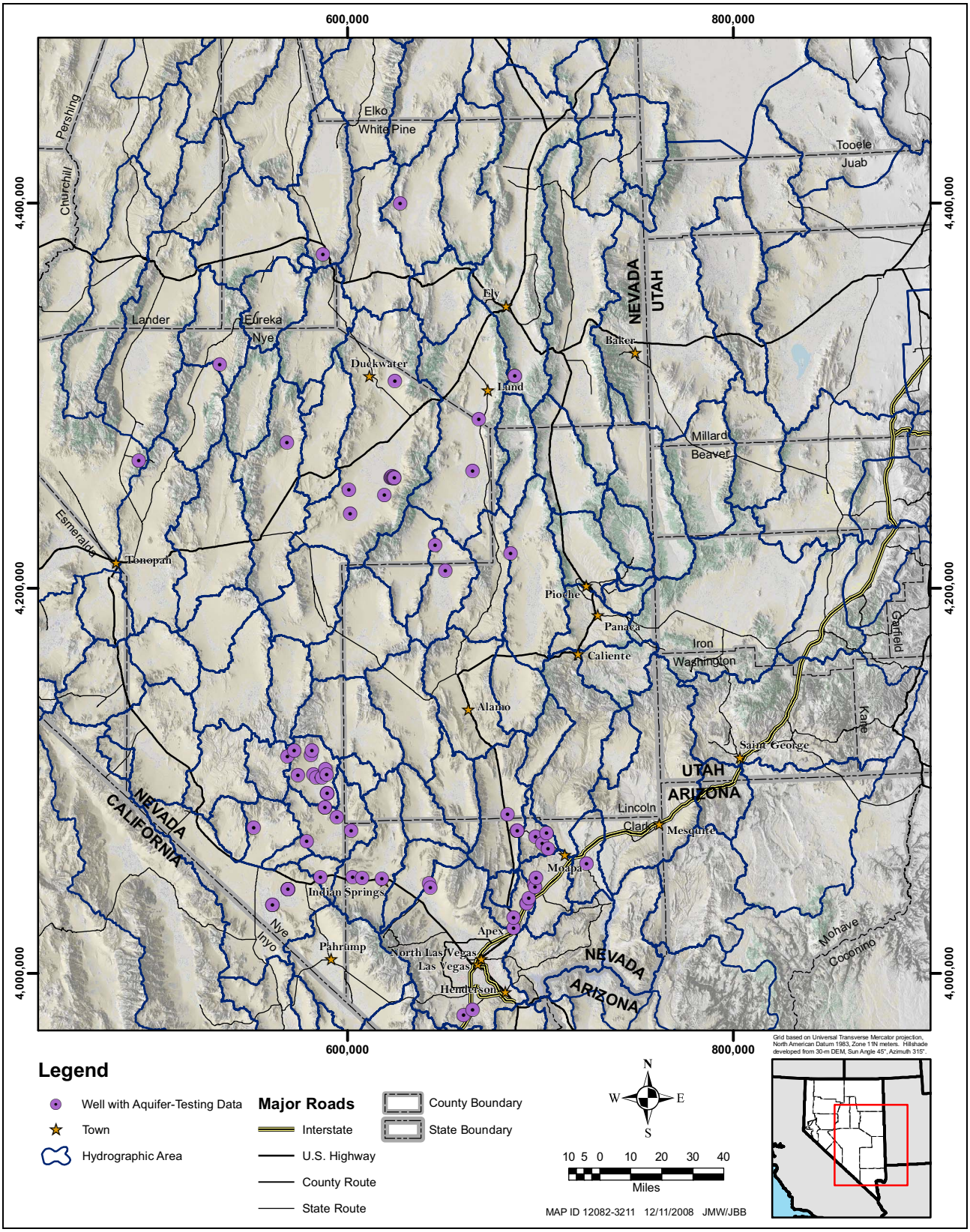


Figure C-6
Locations of Reported Aquifer-Property Data for the UC and LC

the LC and UC RMUs. Table C-2 contains statistical summaries for the transmissivity, specific yield, and specific storage of the UC and LC RMUs.

Tested intervals for the constant-rate data include depths as great as 5,923 ft bgs. The mean value of horizontal hydraulic conductivity derived from these data is 5.37 ft/day with a range of 0.028 to 3,158 ft/day. There are two tests in the carbonate rocks where the horizontal-to-vertical anisotropy was measured. These ratios range from 2 and 143. Specific-yield estimates were available for two wells in the UC and LC and were 0.001 and 0.031. There are 10 analyses of storativity for the UC and LC with a range of 1.7×10^{-9} to 8.14×10^{-3} and an arithmetic mean of 1.68×10^{-3}. The relatively large range of transmissivity listed in Table C-2 is probably more representative of faults, as the few data records were obtained from aquifer tests conducted in fault zones.

BASE RMU

No data exist in the aquifer-property database for the BASE unit.

C.1.3.6.3 Analysis of Hydraulic Conductivity with Depth

In theory, rock permeability decreases with depth resulting from the increasing pressure exerted by the overburden. In reality, many other factors also influence rock permeability. Nonetheless, as data are usually lacking for large depths, many studies attempted to define a relationship between permeability (or hydraulic conductivity) and depth. In this section, a literature review of selected studies is presented, followed by the analysis of the testing data versus depth.

C.1.3.6.3.1 Literature Review

The variability of permeability (or hydraulic conductivity) with depth has been studied for various reasons, including understanding the degassing of the Earth, locating and extracting oil, and modeling groundwater flow in the upper crust of the earth. Summaries of selected studies conducted by Ingebritsen and Manning (1999), Saar and Manga (2004), Bedinger et al. (1989), I T (1996, 1997), D'Agnese et al. (1997), Belcher et al. (2001), Belcher (2004), and SNJV (2008) are presented.

Some of the studies were performed using metric units. For consistency with the author's reports, the units will be left in the metric system. To convert from meters to feet, divide the value in meters by 0.3048 to obtain feet.

Ingebritsen and Manning (1999)

To understand the degassing of the Earth, Ingebritsen and Manning (1999) derived the following relationship between the permeability of the continental crust and depth, using geothermal data and calculated fluid flux during metamorphism:

$$\text{Log } k = 14\ 3.2 \text{ Log } z \qquad \text{(Eq. C-1)}$$

where,

k = Permeability (m^2)
z = Depth below ground surface (km)

At crustal depths greater than about 5 km, the relationship was mainly derived from data from prograde metamorphic systems. Therefore, the relationship is applicable to orogenic belts where the Earth's crust is undergoing thickening and/or heating.

Saar and Manga (2004)

Using data from the Oregon Cascades, Saar and Manga (2004) studied the decrease in permeability with depth. They used four methods, each of which is applicable to a different depth scale:

- For depths of less than 0.1 km, they used spring discharge models to estimate horizontal permeabilities.
- For depths of less than 1 km, they used simulations of coupled heat and groundwater flow to estimate horizontal and vertical permeabilities.
- For depths of less than 5 km, they derived estimates of vertical permeability from statistical investigations of earthquakes believed to be triggered by groundwater recharge.
- For depths of less than 15 km, they derived estimates of vertical permeability from considerations of magma intrusion rates and water devolatilization.

Saar and Manga (2004) found that for depths greater than 0.8 km, their results are similar to the power law relationship derived by Ingebritsen and Manning (1999) Equation C-1. However, for depths shallower than or equal to 0.8 km and up to 2 km, Saar and Manga (2004) defined the following relationship:

$$k = 5 \times 10^{-13} \times e^{(-z/0.25)} \qquad \text{(Eq. C-2)}$$

where,

k = Permeability (m^2)
z = Depth below ground surface (km)

Saar and Manga (2004) found that this relationship fits the data better than the relationship developed by Ingebritsen and Manning (1999). In addition, their relationship provided estimates of permeability for near-surface and zero depths. The two relationships, Equation C-1 and Equation C-2, are consistent at a depth of 0.8 km, yielding a smooth transition between the two.

Bedinger et al. (1989)

In support of high-level radioactive-waste isolation studies, Bedinger et al. (1989) evaluated the hydraulic properties of rocks in the Basin and Range Province. For crystalline rocks below the weathered horizon, they found that permeability data from a single borehole do not usually display a consistent decrease with depth. However, they reported that in larger data sets, permeability values collected at depths of less than 1,000 m display a decrease with depth. Furthermore, they reported that the decrease in permeability is apparently greater for depths above 300 m than for larger depths. Bedinger et al. (1989) also derived distributions of hydraulic conductivity for the HGUs present in the region. Their distribution of hydraulic conductivity accounts for variations in rock properties caused by depth and degree of faulting.

IT Corporation (1996 and 1997)

As part of the development of the NTS regional model, IT (1996, 1997) used the data available at the time to derive relationships between hydraulic conductivity and depth to help estimate the total depth of the flow system and the hydraulic conductivities of the deeper units. A relationship was developed for each of the major aquifers: the Alluvial Aquifer, the Volcanic Aquifer, and the Lower Carbonate Aquifer. The relationships represent the decreasing linear trends observed in the logarithm of hydraulic conductivity with increasing depth. The relationships, therefore, exhibit an exponential decrease of hydraulic conductivity with depth and are provided by the following equation:

$$K_{depth} = K_h(10^{-Dd}) \qquad \text{(Eq. C-3)}$$

where,

K_{depth} = Horizontal hydraulic conductivity at specified depth
K_h = Horizontal hydraulic conductivity at land surface
D = Decay coefficient (calculated from linear regression)
d = Depth from land surface

The rate of decrease of K with depth is controlled by the decay coefficient. The values of the decay coefficient for the three aquifers are provided in Table C-3.

Table C-3
Hydraulic-Conductivity Decay Coefficients with Depth

Aquifer	Mean Decay Coefficient (1/day)	Mean *K* at Land Surface (m/day)
Alluvial Aquifer	0.00563	21.18
Carbonate Aquifer	0.00102	6.76
Volcanic Aquifer	0.00256	7.75

Source: DOE (1997)

D'Agnese et al. (1997)

D'Agnese et al. (1997) developed a groundwater flow model for the DVFS. They used the findings of Bedinger et al. (1989) to incorporate a decrease in the hydraulic conductivity between depths of 300 to 1,000 m. Except in regional fault zones, they assumed that at depths greater than 1,000 m, permeability is probably representative of the rock matrix. At depths greater than 5,000 m, they assumed that faults and fractures are closed because of the overburden pressure (D'Agnese et al., 1997).

Belcher et al. (2001)

In support of the DVRFS model, Belcher et al. (2001) examined the relationship between hydraulic conductivity and depth for the HGUs of the Death Valley region. Similar to IT (1996), they found that the best correlation is provided by the log-transformed hydraulic-conductivity estimates versus the nontransformed depth values.

To evaluate the relative importance of HGUs and depth changes in the variations of hydraulic conductivity, they initially combined all data into a single data set. Using Analysis of Covariance (ANCOVA), they found that both depth and HGU are important factors at the same probability level of 0.025. Then they subdivided the data set by HGU and regressed each of the 15 data subsets separately (one for each HGU). Results from the ANCOVA showed a significant relationship between hydraulic conductivity and depth. The probability level was 0.025 for five of the HGUs, including the younger and older alluvial aquifers and the upper and lower carbonate aquifers. Belcher et al. (2001) observed that despite the relatively strong relationship with depth, hydraulic conductivity can greatly vary at any given depth. The variations are probably caused by factors other than depth, such as bedding, heterogeneity, or structural features. Belcher et al. (2001) also attributed some of the decreasing trend in hydraulic conductivity with depth to the process of deriving hydraulic conductivities from transmissivity values.

Belcher (2004)

Belcher (2004) developed the DVRFS model using MODFLOW-2000 where the K versus depth relationship was programmed into the hydrogeologic unit flow module of the program.

Several groundwater flow models developed by the DOE for the NTS and/or the Yucca Mountain Project used a hydraulic conductivity versus depth relationship of the form:

$$\text{Log } K = Ad + \text{Log } K_0 \qquad \text{(Eq. C-4)}$$

where,

K = Hydraulic conductivity at depth d
K_0 = Hydraulic conductivity projected to a reference surface
A = Depth-dependence coefficient, calculated from linear regression
d = Depth below the reference surface

SNJV (2008)

To address concerns about the apparent low correlation between hydraulic conductivity and depth previously derived from the available data (IT, 1996, 1997), SNJV (2008) developed an alternate method of data evaluation.

SNJV (2008) recognized that the variation of hydraulic conductivity within formations is due to two factors: natural variability and the effect of the overburden pressure (depth). The previous method (regression of $\text{Log}_{10}[K]$ versus depth) lumps the two factors to yield a measure of the overall variability. In the alternate method, after the regression is conducted, the derived equations are used to calculate hydraulic conductivity at the surface (K_0) for each data point. The resulting data set is then used to analyze the spatial variability of hydraulic conductivity.

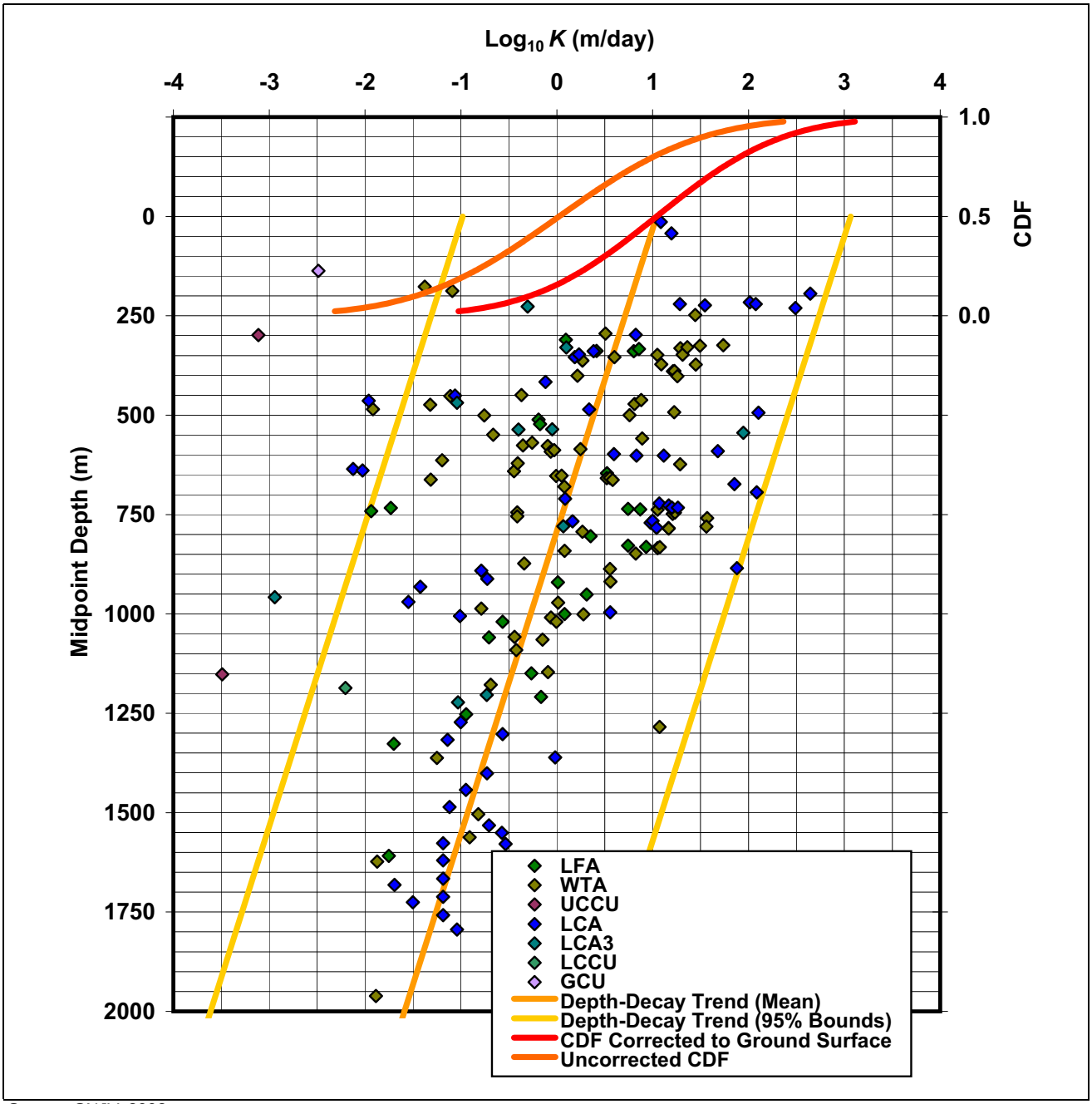
The HGUs were subdivided into two groups based on the effect of increasing overburden pressure on the formations:

- Brittle, fractured rocks
  - Granite Confining Unit (GCU)
  - Lava Flow Aquifer (LFA)
  - Lower Carbonate Aquifer (LCA/LCA3)
  - Lower Clastic Confining Unit (LCCU)
  - Upper Clastic Confining Unit (UCCU)
  - Welded Tuff Aquifer (WTA)
- Ductile, porous formations
  - Alluvial Aquifer (AA)
  - Older Alluvial Aquifer (OAA)
  - Playa Confining Unit (PCU)
  - Tuff-Confining Unit (TCU)

For the brittle group, the overburden pressure reduces fracture apertures. For the ductile group, the overburden pressure increases consolidation. The results of the linear regressions of $\text{Log}_{10}(K)$ versus depth, including the 95 percent confidence bounds, are shown on Figures C-7 and C-8. Both linear fits yielded the same correlation coefficient of -0.42. The probability distributions of all hydraulic conductivity values and of the hydraulic conductivity at the surface (K_0) are represented by cumulative density functions (CDFs) in Figures C-7 and C-8.

C.1.3.6.4 Analysis of Hydraulic Conductivity versus Depth

For this study, the relationship of hydraulic conductivity and depth was analyzed using the data within the aquifer-property database. The hydraulic-conductivity values were queried from the database and separated by RMU and test type. The hydraulic conductivities were then converted to Log_{10} and plotted against the midpoint of the depth interval they represent. Three plots were created to display the $\text{Log}_{10}(K)$ for the LC, LVF, and UVF RMUs (Figures C-9, C-10, and C-11). A linear trend line



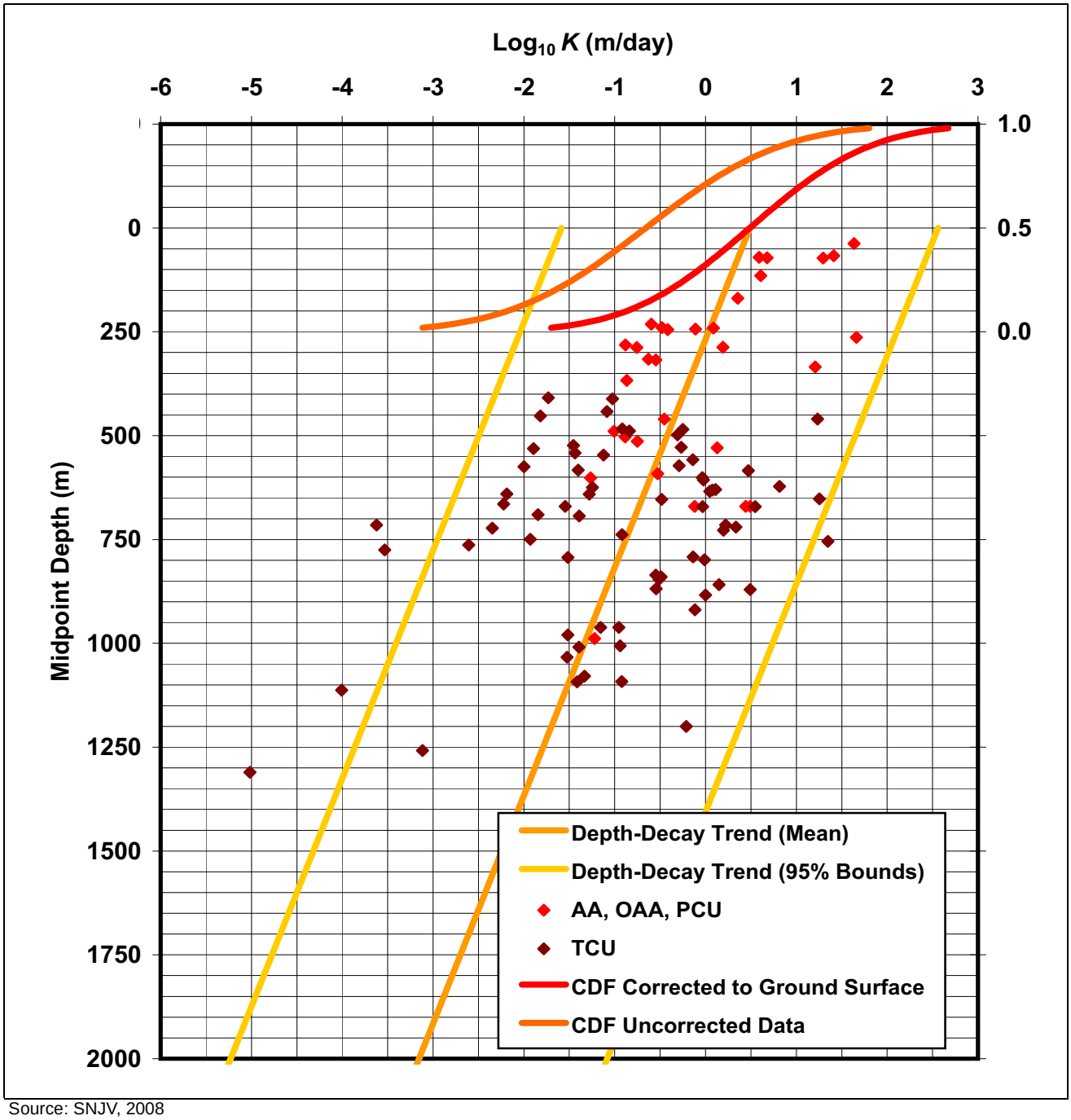
Source: SNJV, 2008

Notes:

1 - To convert from meters to feet, divide by 0.3048.

2 - To convert from Log_{10} *K* (m/day) to *K* (ft/day), extract *K* (m/day) as *K* (m/day) = 10^{value}, then divide *K* by 0.3048 to obtain *K* (ft/day).

Figure C-7
Depth Decay for Brittle Rocks



Source: SNJV, 2008

Notes:

1 - To convert from meters to feet, divide by 0.3048.

2 - To convert from Log_{10} *K* (m/day) to *K* (ft/day), extract *K* (m/day) as *K* (m/day) = 10^{value}, then divide *K* by 0.3048 to obtain *K* (ft/day).

Figure C-8
Depth Decay for Ductile Rocks

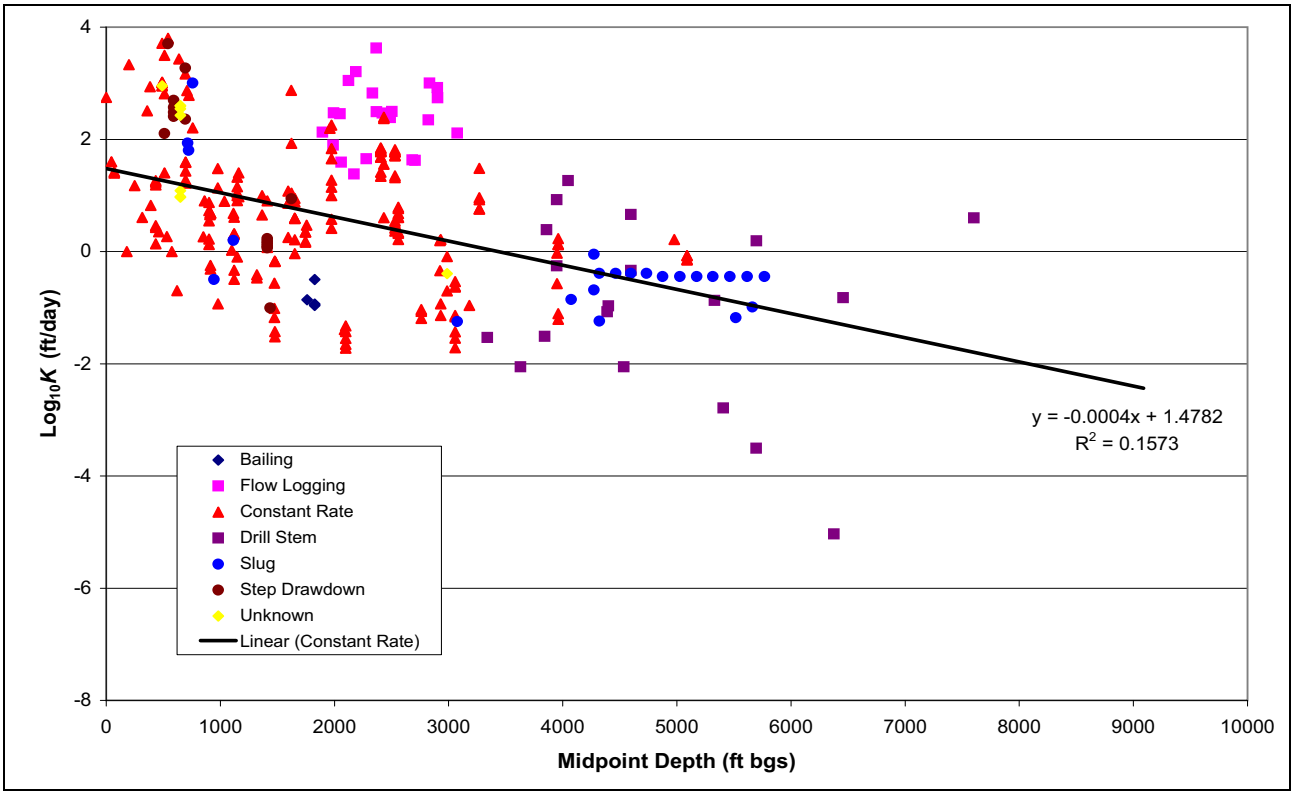


Figure C-9
Hydraulic Conductivity versus Depth for the LC

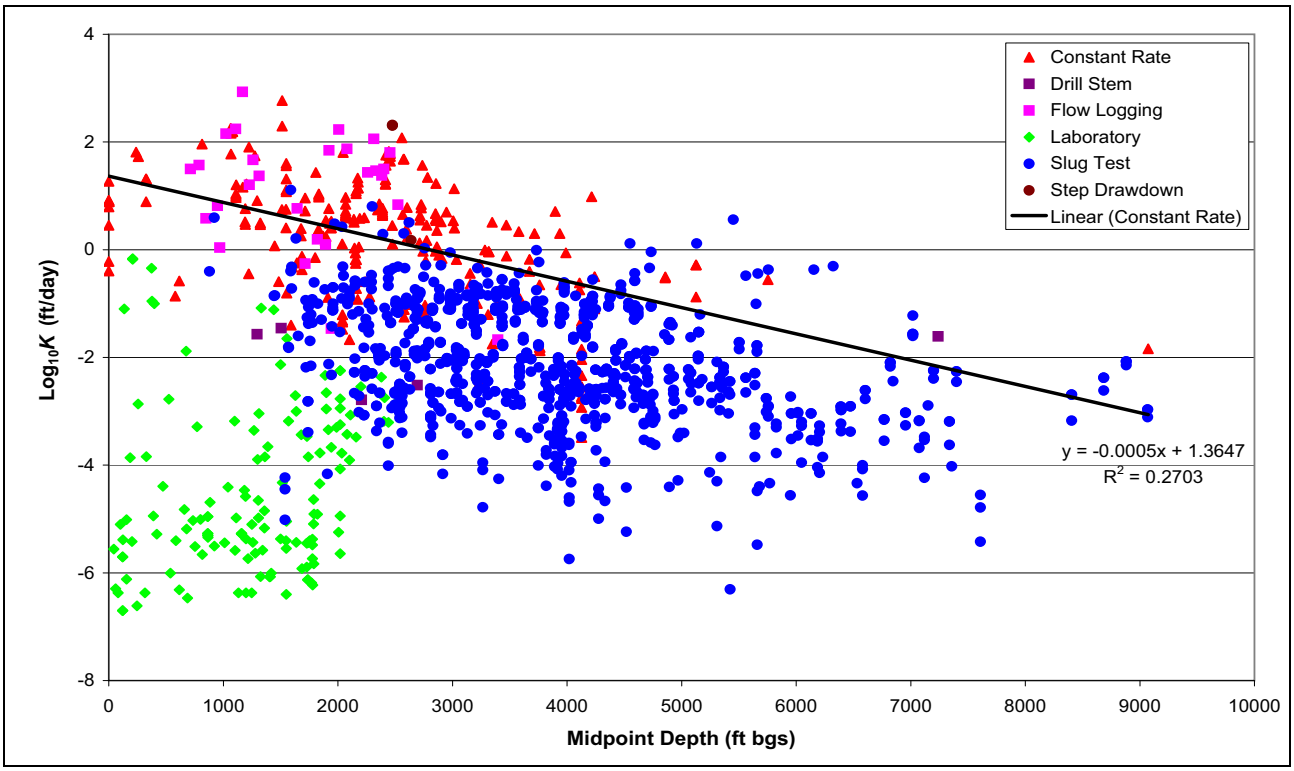


Figure C-10
Hydraulic Conductivity versus Depth for the LVF

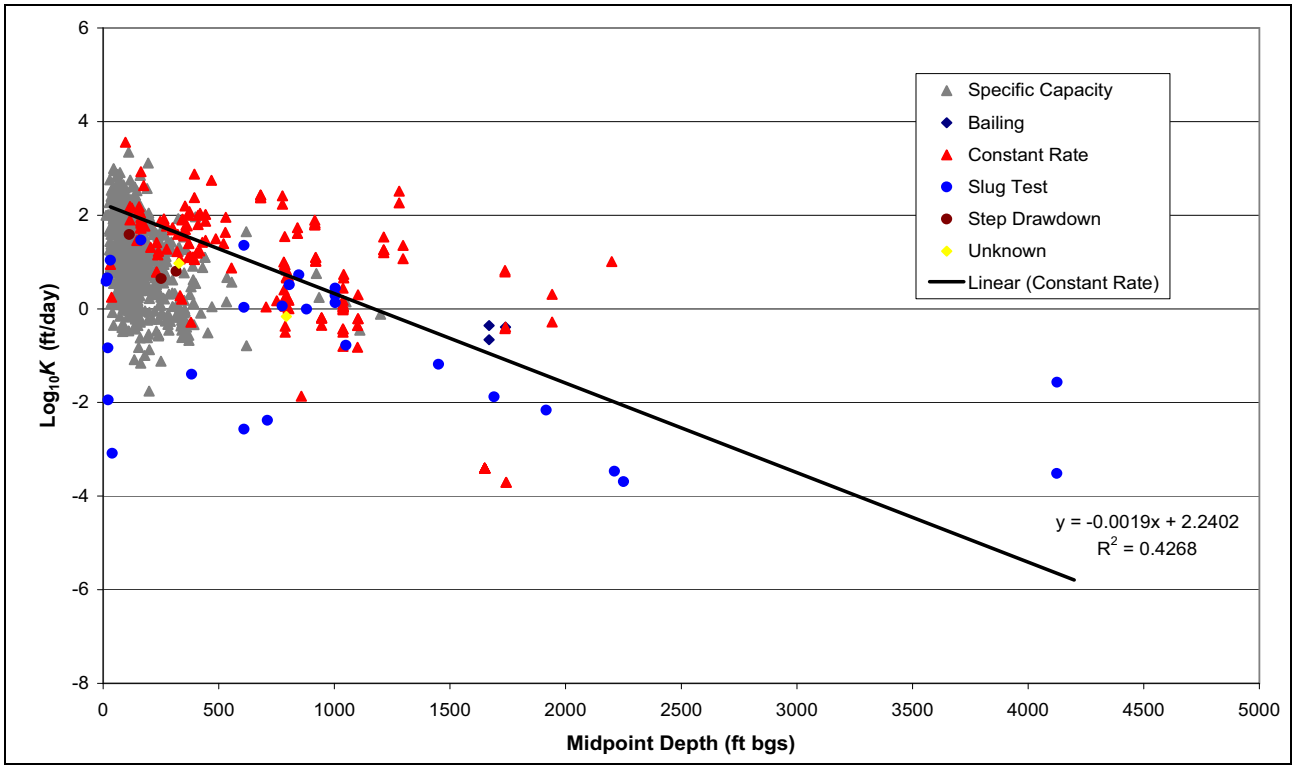


Figure C-11
Hydraulic Conductivity versus Depth for the UVF

was fitted to the constant-rate data for each of the RMUs, and the equation of the line was displayed on the plot. Each of the plots shows a decrease in *K* with depth, but with a large scatter in the data. The derived correlation coefficients between *K* and depth are 0.40 for the LC, 0.52 for the LVF, and 0.65 for the UVF. Although the results of this analysis show that some correlation exists between *K* and depth, the relationships are considered uncertain because of the large data scatter as well as the decrease in data with increasing depth.

C.1.4 Data from Ongoing SNWA Field Activities

This section contains a summary of the preliminary results obtained from aquifer testing at SNWA wells 184W101, 184W103, 184W105, SPR7005X, SPR7007X, SPR7008X, and SPR7023I. Results for CAV6002X are still pending. The location of each test site is presented in Figure A-1 (Appendix A). The carbonate-aquifer tests provided localized short-term results, which are consistent with increased formation hydraulic conductivity related to the fault structures and damage zones observed in carbonate aquifers compared with locations with limited fault influence in other areas.

C.1.4.1 Test Well 184W101 and Monitor Well 184W502M

An aquifer test was performed at Test Well 184W101 located in the southeast portion of Spring Valley approximately 14 mi southeast of Test Well 184W103. Test Well 184W101 was completed to a depth of approximately 1,760 ft bgs and has a static water level of approximately 470 ft bgs.

Hydrogeologic evaluation of the site indicated the presence of a fault structure, which was anticipated to be intersected by the test well.

Associated Monitor Well 184W502M, located approximately 175 ft from 184W101, was drilled first and encountered carbonates consisting of the Guilmette Formation and Simonson and Sevy dolomites. The borehole was initially planned to be terminated at approximately 1,300 ft bgs, but because the yield from the borehole above 1,300 ft bgs was very poor, the borehole was extended to 1,760 ft bgs. As a result, the borehole encountered the target fault structure with a higher density of open fractures, and the yield increased significantly.

A sustainable pumping rate of 2,520 gpm was maintained during the 72-hr constant-rate test. Drilling results, geophysical logs, and temperature data indicated that fractures associated with open fractures encountered between 1,300 and 1,700 ft bgs were the major source of well inflow.

Results from a 72-hr constant-rate and subsequent recovery aquifer test were evaluated using Barker Generalized Radial Flow Model (Barker GRFM) dual-porosity analysis and Cooper-Jacob analysis as the primary and secondary solutions, respectively. The primary solution indicated a composite optimal solution for hydraulic conductivity of approximately 7.6 to 8.0 ft/day using a saturated thickness over the length of the saturated interval of the borehole. However, considering the majority of inflow occurred from the zone consisting of the lower 20 percent of the well, an equivalent hydraulic conductivity would be approximately 40 ft/day over that interval of the borehole based on the Barker GRFM method. The secondary solution provided a wider range of hydraulic conductivities of 1.9 to 14 ft/day.

C.1.4.2 Test Well 184W103 and Monitor Well 184W504M

A 72-hr constant-rate and subsequent recovery aquifer test was performed at Test Well 184W103, located approximately 8 mi south of Test Well 184W105. This test well and associated monitor well are completed in the unconfined carbonate aquifer within the Arcturus Formation with drilled completion depths of 1,046 and 1,040 ft bgs, respectively. Static depth to water in these wells is approximately 100 ft bgs. Hydrogeologic reconnaissance and evaluation of this site indicated that the wells did not intersect significant fault structures and fractures were commonly clay filled. Results from the aquifer-test analysis using the Barker GRFM dual-porosity method and the Cooper-Jacob method as primary and secondary solutions, respectively, indicate a hydraulic conductivity of 5.0 to 12 ft/day.

C.1.4.3 Test Well 184W105 and Monitor Well 184W506M

Test well 184W105 and the associated monitor well 184W506M are completed in unconfined fractured carbonate, which was determined to be Pennsylvanian-Permian age limestone (Table C-4). Unsaturated Quaternary surface alluvium overlays the carbonate at this location to a depth of 15 to 35 ft bgs. Both wells were completed to a depth of 1,160 ft bgs, and the static depth to water at the site is approximately 214 ft bgs. The site location was selected after conducting a geologic reconnaissance of the area, including field mapping, review of geophysical and well log data, and

Table C-4
Summary of Preliminary Aquifer-Testing Results for SNWA Wells

Pumping Well	Observation Well(s)	Background Well(s)	Effective Saturated Thickness	Unit	Analytical Method	Hydraulic Conductivity	Fracture Hydraulic Conductivity	Matrix Hydraulic Conductivity	Transmissivity	Storativity or Specific Yield	Specific Storage (ft^{-1})	
	Distance From Pumping Well		(ft)			(ft/d)			(ft^2/d)		Fracture	Matrix
184W101	184W502M - 175 ft	184W504M - 14 mi	1,280	Carbonate	1	7.6 to 8.0	7.6 to 8.0	1.1E-05 to 6.5E-05	9,700 to 10,000	0.03	4.2E-05 to 6.9E-07	3.9E-06 to 4.5E-06
					2	1.9 to 14	---	---	2,500 to 18,000	0.03	---	---
184W103	184W504M - 177 ft	184W506M - 8 mi	943		1	12	12	2.5E-05	11,000	0.018	7.7E-07	1.9E-05
					2	5.0	---	---	4,700	---	---	---
184W105	184W506M - 212 ft	184W504M - 8 mi	946		1	61 to 64	61 to 64	4.8E-04 to 6.3E-03	57,000 to 61,000	9.5E-03	1.3E-07 to 1.5E-07	1.0E-05
					2	56 to 58	---	---	53,000 to 55,000	2.1E-04	---	---
SPR7005X	SPR7005M - 129 ft	184W506M - 15 mi	856		1	---	2,700	1.8E-03	2,300,000[a] Open Fracture Fault	0.035	1.0E-06	4.1E-05
					2	35 to 48	---	---	30,000 to 41,000	---	---	---
SPR7007X	SPR7007M - 99 ft	390352114305401 - 17 mi	883	Alluvium	3, 4, 5	33 to 38	---	---	29,000 to 34,000	0.01 to 0.07	---	---
SPR7008X	SPR7008M - 100 ft	390352114305401 - 7 mi	800		5	4.2 to 5.9	---	---	3,300 to 4,700	0.2	---	---
SPR7023I	---	184 N13 E67 22BA	900		2, 3'	8.2 to 9.9	---	---	7,900 to 8,900	---	---	---

1 Barker GRFM dual porosity
2 Cooper Jacob
3 Theis
3' Theis Recovery
4 Neuman
5 Moench

[a]Transmissivity calculated for the fracture only. Not representative of the formation.

evaluating surface structural features using aerial photography. Regional data and geologic mapping in the vicinity indicate the presence of faulting and related structures at the site.

The wells are located near several structures and are likely situated in the fault damage zone. A fault is visible with a strike of N42W approximately 500 ft northwest of the site along with an associated secondary north-south to N10W trending fault dipping 30 to 62 E. The northwest structures trend almost directly toward the wells. The test and monitor wells are believed to be located along the strike and within the damage zone of this exposed fault. This fault zone is estimated to be less than 500 ft wide at the surface and is part of a larger fault complex. An additional east-west fault trends through the hills west of the well site and is inferred to pass just north of Monitor Well 184W506M.

Significant fracture zones were identified using downhole geophysical methods at depths ranging from 790 to 850 ft bgs for Test Well 184W105, with less pronounced fracture zones identified in the range of 200 to 300 ft and 600 to 700 ft. Fracture zones were defined in Monitor Well 184W506M at depths of 200 to 300 ft and 480 to 880 ft.

A constant discharge rate of 3,000 gpm was used for the 72-hr test. The constant rate and subsequent recovery data were evaluated using Barker GRFM dual-porosity analysis as the primary solution and Cooper-Jacob analysis as the secondary solution. Results indicate an optimal solution for hydraulic conductivity of approximately 56 to 64 ft/day.

C.1.4.4 Test Well SPR7005X and Monitor Well SPR7005M

A 120-hr constant-rate aquifer test was performed at Test Well SPR7005X located at Cooper Canyon in Spring Valley. The pumping rate during the constant-rate test was 3,000 gpm. This well was sited based upon geologic reconnaissance and surface geophysics indicating the presence of faulting in Middle Cambrian limestone and dolomite. It was completed, along with associated Monitor Well SPR7005M, within a distinctive fault structure. Specific capacity of the test well was greater than 111 gpm/ft of drawdown at the end of the 120-hr test. Data are currently being analyzed. However, the hydraulic conductivity is expected to be at the higher range of the other carbonate aquifer tests performed in Spring Valley.

These results, while local, are consistent with higher hydraulic conductivities associated with fault structures compared to nonfaulted areas. Preliminary aquifer-property values reflect a composite value over the length of the communication interval between the aquifer and the well. Property values would vary within discrete vertical zones depending upon the fracture density and zone characteristics (Table C-4).

C.1.4.5 Test Well SPR7007X and Monitor Well SPR7007M

Test well SPR7007X is located approximately 100 ft north of Monitor Well SPR7007M. These wells are completed in Quaternary-Tertiary alluvium at depths of 1,040 ft bgs, and their static depth to water is approximately 156 ft bgs. Preliminary analysis using the Theis Recovery, Neuman Unconfined Solution, and Moench 1997 models indicate the hydraulic conductivity would range from 33 to 38 ft/day.

C.1.4.6 Test Well SPR7008X and Monitor Well SPR7008M

A 72-hr constant-rate test was performed on Test Well SPR7008X with a target discharge rate of 2,000 gpm. This well and associated Monitor Well SPR7008M were completed in the alluvial aquifer at a total depth of 970 and 960 ft bgs, respectively. The static depth to water at these wells is approximately 13 and 14 ft bgs, respectively. Moench confined and unconfined with leaky confining layers methods were used to evaluate the possible connection between the aquifer test interval, presumably a confined aquifer, and an upper unconfined aquifer. Preliminary results indicate a hydraulic conductivity of the test interval of 4.2 to 5.9 ft/day.

C.1.4.7 Irrigation Well SPR7023I

Irrigation Well SPR7023I is completed in the unconfined alluvial aquifer with a drilled depth of 1,200 ft bgs. The static water level is approximately 302 ft bgs. A 120-hr constant-rate pumping test was conducted at this well. The time-drawdown data were analyzed using the Cooper-Jacob straight-line and Theis recovery methods. These analyses indicate a hydraulic-conductivity range of 8.2 to 9.9 ft/day.

C.1.4.8 Summary

Estimates of aquifer properties are an essential component of the development of a conceptual groundwater flow model. These estimates served as the initial estimates used to constrain the hydraulic properties in the numerical groundwater flow model.

Data used in this report were obtained from many site-specific and regional reports and synthesized into a single aquifer-property database. The data were then queried from the database according to one of the eight RMUs that were developed as part of the hydrogeologic conceptual model for the study area. The data were then statistically analyzed by RMU to obtain estimates of aquifer properties, including hydraulic conductivity, storativity, and specific yield. The range in values provides a measure of the uncertainty in the property.

The relationship of hydraulic conductivity with depth was also analyzed as part of this study. Many previous investigators have shown a relationship between hydraulic conductivity and depth. In general, hydraulic conductivity decreases with depth as a result of confining pressures, sealing fractures and faults, and compressing sedimentary units. This study showed there was a trend of decreasing hydraulic conductivity with increasing depth in the UVF, LVF, and LC RMUs. Uncertainty in the use of this application stems from the large data scatter as well as the decrease in available data with increasing depth.

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Appendix D

Precipitation Station Data

D.1.0 PRECIPITATION STATION DATA

Precipitation station data were compiled and the period of record mean annual value was derived for each station. Data were compiled from the following sources:

- NDWR
- USGS
- Western Regional Climate Center (WRCC)
- National Climatic Data Center (NCDC)
- NRCS - SNOwpack TELemetry (SNOTEL).

Precipitation stations selected from these sources included stations qualified as climate normals by the NCDC. The average annual precipitation as reported by WRCC was used for these stations. Other stations, except for the Sheep Peak and Hayford Peak stations, have more than 20 "non-zero" years of reported annual precipitation (i.e., years in which the reported annual precipitation was greater than zero). Summary data for the stations located within and near the WRFS are listed in Table D-1.

Table D-1
Precipitation Station Information
(Page 1 of 2)

Station No.	Station Name	UTM Northing[a] (m)	UTM Easting[a] (m)	Altitude (ft amsl)	Annual Precipitation			Period of Record	Period of Record (Number of Years)	NCDC Normal	Source
					Mean (in.)	Min (in.)	Max (in.)				
1	Connors Pass	4,323,835	703,315	7,732	14.72	2.90	26.30	1954 to 2005	52	No	NDWR
2	Current Creek	4,298,199	649,245	5,999	13.71	6.00	24.49	1954 to 2005	52	No	NDWR
3	Robinson Summit	4,365,136	665,201	7,800	14.05	0.55	27.30	1954 to 2005	52	No	NDWR
4	Schellbourne Pass	4,409,348	702,800	7,100	13.67	0.00	26.80	1954 to 2005	52	No	NDWR
5	Wilson Creek Summit	4,254,601	730,436	7,200	17.51	6.50	33.00	1954 to 2005	52	No	NDWR
6	Berry Creek	4,354,622	705,390	9,100	27.35	19.00	40.80	1981 to 2005	25	No	NRCS (SNOTEL)
7	Ward Mountain	4,333,562	677,114	9,200	24.22	13.30	38.80	1981 to 2005	25	No	NRCS (SNOTEL)
8	Cave Mountain	4,337,547	706,108	10,650	20.41	12.00	32.16	1984 to 2005	22	No	USGS
9	Cherry Creek Range	4,443,655	680,594	9,700	15.67	9.00	26.25	1984 to 2005	22	No	USGS
10	Hayford Peak	4,058,445	660,853	9,840	15.75	7.25	29.00	1986 to 2003	18	No	USGS
11	Mt. Washingon	4,309,377	732,764	10,440	26.13	12.00	46.00	1984 to 2005	22	No	USGS
12	Mt. Wilson	4,236,086	728,118	9,200	19.68	0.00	47.00	1984 to 2005	22	No	USGS
13	Sheep Peak	4,050,080	656,908	9,600	15.10	3.00	28.25	1986 to 2003	18	No	USGS
14	Unnamed Peak NW of Mt. Moriah	4,355,941	737,695	9,300	16.72	0.00	28.50	1984 to 2005	22	No	USGS
15	Adaven	4,219,700	624,110	6,250	12.73	4.42	23.64	1928 to 1982	55	No	WRCC
16	Caliente	4,166,179	719,105	4,400	9.10	1.84	18.73	1928 to 2007	80	30 yr	WRCC
17	Callao	4,421,801	780,345	4,330	5.80	0.94	10.59	1948 to 2007	60	30 yr	WRCC
18	Callville Bay	4,002,962	703,844	1,270	5.37	3.18	11.85	1989 to 2007	19	10 yr	WRCC
19	Desert Game Range	4,038,794	646,235	2,920	4.51	0.69	14.78	1948 to 2007	60	No	WRCC
20	Echo Bay	4,022,206	733,343	1,250	5.73	3.35	12.96	1989 to 2007	19	10 yr	WRCC
21	Elgin	4,136,549	718,409	3,420	12.23	3.72	24.98	1951 to 2007	57	10 yr	WRCC
22	Ely WBO	4,350,044	685,372	6,250	9.56	4.22	16.16	1897 to 2007	111	No	WRCC
23	Eskdale	4,334,515	763,613	4,980	6.39	3.18	12.57	1966 to 2007	42	30 yr	WRCC

Table D-1
Precipitation Station Information
(Page 2 of 2)

Station No.	Station Name	UTM Northing[a] (m)	UTM Easting[a] (m)	Altitude (ft amsl)	Annual Precipitation			Period of Record	Period of Record (Number of Years)	NCDC Normal	Source
					Mean (in.)	Min (in.)	Max (in.)				
24	Fish Springs Refuge	4,415,084	808,023	4,340	7.89	3.89	12.64	1960 to 2007	48	30 yr	WRCC
25	Garrison	4,313,196	757,384	5,260	7.61	4.59	14.69	1951 to 1990	40	10 yr	WRCC
26	Geyser Range	4,282,815	706,113	6,020	8.67	1.65	15.49	1948 to 2002	55	No	WRCC
27	Great Basin National Park	4,320,446	740,673	6,830	13.27	7.37	21.20	1948 to 2007	60	10 yr	WRCC
28	Hiko	4,157,377	657,455	3,940	7.08	1.45	13.68	1989 to 2007	19	10 yr	WRCC
29	Key Pittman WMA	4,164,774	657,315	3,950	7.94	4.64	11.94	1964 to 1989	26	No	WRCC
30	Lages	4,436,011	702,945	5,960	8.20	4.83	13.20	1984 to 2007	24	10 yr	WRCC
31	Lake Valley Steward	4,243,927	705,365	6,350	15.69	9.39	28.29	1971 to 1998	28	No	WRCC
32	Logandale	4,049,785	726,628	1,410	5.14	3.23	9.81	1968 to 1992	25	No	WRCC
33	Lund, Nevada	4,302,024	673,483	5,570	10.20	4.99	18.83	1957 to 2007	51	30 yr	WRCC
34	Mcgill	4,363,530	691,944	6,300	8.81	3.76	16.21	1914 to 2007	94	30 yr	WRCC
35	Overton	4,047,975	728,168	1,290	4.40	0.71	8.94	1948 to 2007	60	No	WRCC
36	Pahranagat Wildlife Refuge	4,126,112	666,918	3,400	6.28	2.23	11.54	1964 to 2007	44	30 yr	WRCC
37	Partoun	4,391,336	767,708	4,780	6.68	2.03	12.21	1950 to 2007	58	30 yr	WRCC
38	Pioche	4,201,109	724,042	6,180	13.20	3.81	27.29	1948 to 2006	59	30 yr	WRCC
39	Ruth	4,350,154	673,938	6,840	12.04	6.68	19.46	1958 to 2007	50	10 yr	WRCC
40	Shoshone 5 N	4,311,105	725,336	5,930	9.65	5.48	14.56	1988 to 2007	20	10 yr	WRCC
41	Spring Valley State Park	4,212,891	747,440	5,950	12.17	5.05	23.48	1974 to 2007	34	10 yr	WRCC
42	Sunnyside	4,254,266	672,777	5,300	9.38	5.73	17.11	1948 to 2007	60	30 yr	WRCC
43	Valley of Fire State Park	4,034,875	722,534	2,000	6.55	1.66	16.90	1972 to 2007	36	30 yr	WRCC

[a]North American Datum of 1983 (NAD83), Zone 11

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Appendix E

ET Rates and Related Information

E.1.0 ET RATES AND RELATED INFORMATION

This appendix contains detailed information in support of the estimates of groundwater ET volume calculations. The information consists of the following:

- Observed ET rates
- Rooting depths of phreatophytic plants
- PET data and spatial distribution

E.1.1 Observed ET Rates

A literature survey for annual ET rates measured in the study area and vicinity was conducted, and the rates were compiled into the data set presented in Table E-1.

E.1.2 Rooting Depths of Phreatophytic Plants

The roots of phreatophytes in arid climates are extensive, covering a greater diameter and depth compared to those of plants in wetter climates. Because arid plants depend on their ability to tap groundwater for survival, the roots can exploit the soil/medium at greater depths to reach the water table (Lewis and Burghy, 1964). Therefore, understanding rooting depths of phreatophytes in arid climates would increase understanding of the extinction depth of groundwater ET.

Table E-2 lists rooting depths for different plants found in arid environments similar to that of the study area. The rooting depth information was obtained from different studies conducted in the southwestern United States or in similar environments. The rooting depths of phreatophytic plants extend from just below the ground surface to depths greater than 100 ft. SNWA field personnel have found plant roots hanging on a water-level logger during a routine monitor well run. The average depth to water at that particular well is about 18.6 ft. The well is surrounded by greasewood and rabbitbrush; therefore, it could be assumed that the roots could be from one of these phreatophytes. During a study performed in the southwestern United States, it was found that mesquite roots protruded to extreme depths, as deep as 175 ft (Phillips, 1963). This represents the maximum rooting depth found in the literature review.

Within a given phreatophytic area of reasonably homogeneous conditions, the maximum rooting depths correspond to the extinction depths of groundwater ET in that area. Groundwater ET is believed to decrease with increasing depth to water and reaches zero at the extinction depth (Shah et al., 2007). However, extinction depths are also influenced by other physical characteristics. Soil characteristics can have an impact on the maximum rooting depth. For instance, a phreatophyte in a sandy clay soil can have a greater extinction depth than in sandy loam (Shah et al., 2007). Conventionally, it was believed that the relationship between the extinction depth and groundwater

Table E-1
Summary of Reported ET Rates
(Page 1 of 7)

Report	Location	ET Unit Description	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Groundwater ET (ft/yr)
Lee (1912)	Independence area of Owens Valley, CA	Alfalfa	---	4.3	---	---
		Bare soil (Tank 1)	5.7 to 5.9	3.33	---	---
		Saltgrass (Tanks 2-7)	0.1 to 6.0	0.66 to 3.59	---	---
White (1932)	Escalante Valley, UT	Greasewood	1.3 to 3.3	0.99 to 2.1[a]	0.13 to 0.37[a]	---
		Alfalfa	2.3 to 3.3	1.92 to 2.16[a]	0.13 to 0.43[a]	---
		Saltgrass	0.92 to 2.3	0.76 to 1.88[a]	0.01 to 0.37[a]	---
Maxey and Eakin (1949)	White River Valley, NV	Native phreatophytes	---	---	---	0.8
		Cultivated plants	---	---	---	1.25
Gatewood et al. (1950)	Safford Valley, AZ	Saltcedar	3.13 to 7.79	3.3 to 8.6	0.0 to 0.22	---
		Cottonwood	5.01 to 6.86	3.4 to 8.7	0.0 to 0.22	---
		Baccharis	1.66 to 6.09	2.9 to 7.1	0.0 to 0.22	---
Eakin (1961)	Long Valley, NV	Mixed rabbitbrush and greasewood	10 to 40	---	---	0.2
Eakin (1962)	Cave Valley, NV	Main drainage channel	---	---	---	---
Eakin (1963a)	Dry Lake/Delamar valleys, NV	No phreatophytes, discharge from springs	---	---	---	---
Eakin (1963b)	Garden/Coal valleys, NV	Along stream channels and spring areas	---	---	---	---
Eakin (1963c)	Pahranagat/Pahroc valleys, NV	Phreatophytes, agriculture, and lakes	---	---	---	1.0 to 4.8
Rush and Eakin (1963)	Lake Valley, NV	Saltgrass and wetland meadow	<5	---	---	1.5
		Saltgrass and moderately wet meadow	<5	---	---	1.25
		Saltgrass and dry meadow	5 to 20	---	---	0.5
		Greasewood	20 to 25	---	---	0.25
		Greasewood and rabbitbrush mixed with big sage	25 to 50	---	---	0.1
Rush (1964)	Clover Valley, NV	Dry meadow	5 to 10	---	---	0.5
		Rabbitbrush	10 to 25	---	---	0.2
	Dry Valley, NV	Rabbitbrush and big sage	15 to 40	---	---	0.1
	Eagle Valley, NV	Dry meadow	---	---	---	0.5
		Rabbitbrush and big sage	10 to 15	---	---	0.3
	Lower Meadow Valley, NV	Saltbush	20 to 60	---	---	0.1
		Greasewood and rabbitbrush	20 to 50	---	---	0.1
		Greasewood, rabbitbrush, and creosote bush	---	---	---	0.1
		Cottonwood, willow, and saltcedar	0 to 5	---	---	3.0
	Panaca Valley, NV	Greasewood and rabbitbrush	10 to 20	---	---	0.1
		Rabbitbrush	15 to 25	---	---	0.2
	Patterson Valley, NV	Greasewood and rabbitbrush	20 to 30	---	---	0.1
	Rose Valley, NV	Rabbitbrush and big sage	20 to 25	---	---	0.1

Table E-1
Summary of Reported ET Rates
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Report	Location	ET Unit Description	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Groundwater ET (ft/yr)
Rush (1964) cont.	Spring Valley, NV	Rabbitbrush	5 to 25	---	---	0.1
		Wetland meadow (very wet meadow and dry meadow)	0 to 10	---	---	0.5 to 1.5
Eakin (1964)	Coyote Spring, NV	Not delineated	---	---	---	---
	Kane Spring, NV	Not delineated	---	---	---	---
	Muddy River Springs, NV	Springs area	---	---	---	---
Rush and Kazmi (1965)	Spring Valley, NV	Wetland meadow and saltgrass	0 to 5	---	---	1.5
		Saltgrass, rabbitbrush, and moderately wet meadow	0 to 10	---	---	1.0
		Greasewood, saltgrass, meadow grass, and swamp cedar	5 to 15	---	---	0.5
		Greasewood and rabbitbrush	10 to 50	---	---	0.2
		Bare soil and sparse vegetation	5 to 15	---	---	0.1
		Cottonwood, willow, and wildrose	0 to 5	---	---	2.0
Hood and Rush (1965)	Snake Valley, NV and UT	Wetland meadow	0 to 5	---	---	1.75
		Meadow grass and rabbitbrush	2 to 10	---	---	0.5
		Greasewood and rabbitbrush	10 to 50	---	---	0.2
		Playas (flooded part of year)	0 to 15	---	---	0.75
		Playas (rarely flooded, but shallow water table)	0 to 30	---	---	0.1
Eakin (1966)	Jakes Valley, NV	Not delineated	---	---	---	---
Eakin et al. (1967)	Steptoe Valley, NV	Wetland meadow and saltgrass, including lowland spring areas	0	---	---	1.5
		Saltgrass, rabbitbrush, greasewood, and Goshute Lake playa	<10	---	---	0.5
		Greasewood, rabbitbrush, and saltgrass	<20	---	---	0.3
		Saltgrass, rabbitbrush, and greasewood	<12	---	---	0.1
Glancy (1968)	S. Butte Valley, NV	Open water	---	---	---	3.5
		Saltgrass	0 to 10	---	---	0.5
		Rabbitbrush and greasewood	10 to 35	---	---	0.2
		Greasewood	30 to 50+	---	---	0.1
Rush (1968)	Hidden Valley, NV	None	---	---	---	---
	Garnet Valley, NV	None	---	---	---	---
	California Wash Area, NV	Saltbush, saltgrass, saltcedar, mesquite, and cottonwood	2 to 50	---	---	1
	Lower Moapa Valley, NV	Saltbush, saltgrass, saltcedar, mesquite, cottonwood, and tules	2 to 50	---	---	2
	Black Mountains Area, NV	Tules, mesquite (Las Vegas Wash and Rogers Spring)	0 to 5	---	---	6
	Gold Butte Area, NV	Cottonwood, willow, grass, and tules near small springs	0 to 10	---	---	---
	Greasewood Basin, NV	Cottonwood, willow, grass, and tules near small springs	0 to 10	---	---	---

Table E-1
Summary of Reported ET Rates
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Report	Location	ET Unit Description	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Groundwater ET (ft/yr)
Robinson (1970)	Humboldt River Valley, NV	Greasewood	5.0 to 7.8	1.14 to 1.81[a]	0.14 to 0.44[a]	---
		Rabbitbrush	5.0 to 6.2	1.07 to 2.19[a]	0.14 to 0.44[a]	---
		Bare soil	1.9 to 4.0	0.36 to 1.00[a]	0.14 to 0.44[a]	---
		Willow	3.5 to 5.8	2.07 to 3.94[a]	0.14 to 0.44[a]	---
		Wild Rose	4.2 to 6.1	1.23 to 2.13[a]	0.14 to 0.44[a]	---
Harrill (1971)	Tippet Valley, NV	No phreatophytes	>50	---	---	---
	Pilot Creek, NV	Greasewood, shadscale, and rabbitbrush	80 to 100	---	---	---
	Great Salt Lake Desert, UT	Playas (saltbrush)	80 to 100	---	---	---
		Bare soil on playas	<10	---	---	0.1
	Northern Antelope Valley, NV	Valley Floor (patches of greasewood)	80 to 100	---	---	---
Duell (1990)	Owens Valley, CA	Alkali meadow (sacaton and thistle)	10 to 15	2.71	---	---
		Alkali meadow (saltgrass, sacaton, and rabbitbrush)	7 to 9	2.05	---	---
		Alkali meadow (Nevada saltbush, sacaton, and rabbitbrush)	5 to 7	2.69	---	---
		Desert sink scrub (rabbitbrush, sacaton, and ephedra)	10 to 11	1.99	---	---
		Desert sink scrub (saltgrass and greasewood)	8 to 9	1.26	0.52	---
		Rabbitbrush meadow (saltgrass and rabbitbrush)	10 to 11	1.55	0.49	---
		Rush and sedge meadow (saltgrass, sacaton, and rush)	≤4	3.24	0.26	---
Malek et al. (1990)	Utah West Desert, UT	Pilot Valley playa, often salt covered	0 to 1	0.75	0.42	---
Carman (1993)	Smith Creek Valley and Carson Desert, NV	Soda Lake (greasewood)	25 to 30	0.59	0.49 to 0.66	---
		Smith Creek (rabbitbrush)	10 to 15	1.05	0.66 to 0.98	---
Nichols (1994) from Nichols (2000)	Northern Great Basin, NV	Smoke Creek desert (greasewood, salt brush, and sagebrush)	8.9	---	---	0.82[a]
		Smith Creek Valley (greasewood and rabbitbrush)	5.9	---	---	1.2[a]
		Railroad Valley (greasewood and salt brush)	5.9	---	---	0.2[a]
Lower Colorado River Accounting System (LCRAS) (BOR, 1997; 1998; 1999; 2000a,b; 2001; 2002; 2004a,b; 2005; 2007) Fort Mohave Reservation	Lower Colorado River, AZ	Marsh (cattail, bulrush, and phragmites [bamboo])	---	5.93	---	---
		Desert vegetation	---	1.34	---	---
		Barren (≤10% vegetation)	---	1.66	---	---
		Saltcedar (11 to 60%), arrowweed (≤25%)	---	4.36	---	---
		Saltcedar (61 to 100%), arrowweed (≤25%)	---	5.12	---	---
		Saltcedar (11 to 60%), mesquite (11 to 60%), arrowweed (≤25%)	---	5.45	---	---
		Saltcedar (≤75%), arrowweed (≥25%)	---	5.29	---	---
		Saltcedar (15 to 45%), mesquite (15 to 45%), arrowweed (20 to 40%)	---	5.43	---	---
		Screwbean/honey mesquite (11 to 60%), arrowweed (≤25%)	---	3.99	---	---
		Screwbean/honey mesquite (61 to 100%), arrowweed (≤25%)	---	4.99	---	---
		Mesquite (21 to 60%), arrowweed (31 to 60%), saltcedar (≤20%)	---	4.76	---	---

Table E-1
Summary of Reported ET Rates
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Report	Location	ET Unit Description	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Groundwater ET (ft/yr)
LCRAS - cont.	Lower Colorado River, AZ	Arrowweed (51 to 100%), trees (≤10%)	---	4.69	---	---
		Cottonwood and willow trees (61 to 100%)	---	4.96	---	---
		Low vegetation (phreatophyte vegetation >10% to ≤30%)	---	4.29	---	---
		Moist soil unit (flooded in winter and irrigated in summer)	---	5.03	---	---
		Seasonal wetland (flooded in winter and not irrigated in summer)	---	3.65	---	---
Nichols et al. (1997) from Nichols (2000)	Ash Meadows, NV	Ash Meadows 1 (salt grass)	1.6	---	---	2.45
		Ash Meadows 2 (salt grass and wiregrass)	0	---	---	2.52
Czarnecki (1997)	Franklin Lake Playa, CA	Seepweed, greasewood, and saltgrass (sparse)	<10	1.2 to 1.3	<0.16	---
Devitt et al. (1998)	Virgin River, NV	Riparian (mostly tamarix)	---	2.5 to 4.8		---
Laczniak et al. (1999)	Ash Meadows, NV	Open water body	---	8.6	0.21 to 0.35	---
		Submerged aquatic vegetation (shallow part of open water areas, includes sparse emergent vegetation)	---	8.6	0.21 to 0.35	---
		Dense grassland vegetation (grasses, short rushes, and trees)	---	3.5	0.21 to 0.35	---
		Sparse grassland vegetation (grasses)	---	1.3	0.21 to 0.35	---
		Moist bare soil (grasses)	---	2.6	0.21 to 0.35	---
		Dense wetland vegetation (reedy and rushy marsh plants)	---	3.9	0.21 to 0.35	---
		Dense meadow vegetation (trees, grasses, and shrubs)	---	3.4	0.21 to 0.35	---
Nichols (2000)	16 valleys in Great Basin, NV	Open water	---	---	---	---
		Playa / bare soil	---	---	---	0.15
		<10% plant cover	---	---	---	0.29 to 0.41
		10 to <20% plant cover	---	---	---	1.28 to 1.35
		20 to <35% plant cover	---	---	---	2.14 to 2.15
		35 to <50% plant cover	---	---	---	2.50 to 2.51
		≥50% plant cover	---	---	---	2.58
Laczniak et al. (2001)[b]	Death Valley Regional Flow System, primarily Ash Meadows and Oasis Valley, NV	Open water	0	8.4 to 8.8	---	---
		Submerged aquatic vegetation (shallow part of open water areas, includes sparse emergent vegetation)	0	8.1 to 8.5	---	---
		Sparse grassland vegetation (grasses and very low density shrubs)	few to 12	0.6 to 2.3	---	---
		Sparse woodland vegetation (mesquite)	10 to 40	0.7 to 1.8	---	---
		Dense meadow / forested vegetation (trees, grasses, and shrubs)	few to 20	3.0 to 4.0	---	---
		Sparse to moderate density shrubland vegetation (greasewood, rabbitbrush, wolfberry, and seepweed)	5 to 20	0.7 to 2.5	---	---
		Dense wetland vegetation (reedy and rushy marsh plants)	0	3.7 to 4.3	---	---
		Dense to moderate density grassland vegetation (saltgrass and/or short rushes with occasional tree or shrub)	< 5	2.5 to 3.7	---	---

Table E-1
Summary of Reported ET Rates
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Report	Location	ET Unit Description	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Groundwater ET (ft/yr)
Laczniak et al. (2001)[b] - cont.	Death Valley Regional Flow System, primarily Ash Meadows and Oasis Valley, NV	Moist bare soil (very sparse grasses)	< 5	2.2 to 3.0	---	---
		Open playa (bare soil)	5 to 40	0.1 to 0.7	---	---
Berger et al. (2001)	Ruby Lake National Wildlife Refuge Area, Ruby Valley, NV	Open water (submerged aquatic vegetation)	---	5.31[a]	0.65[a]	---
		Greasewood, rabbitbrush, wildrye, sagebrush (sparse to moderate)	17	1.33[a]	0.65[a]	0.68[a]
		Rabbitbrush, wildrye, greasewood, sagebrush (moderate)	5	1.33[a]	0.65[a]	0.68[a]
		Rabbitbrush, wildrye, greasewood, and sagebrush (moderate)	10	1.33[a]	0.65[a]	0.68[a]
		Saltgrass, rabbitbrush, wildrye, and greasewood (moderate)	<5	1.33[a]	0.65[a]	0.68[a]
		Desert shrub upland (moderate sagebrush and rabbitbrush)	>80	0.99[a]	0.65[a]	0.34[a]
		Bulrush marsh (moderate to dense bulrush and cattails)	1 to 3	4.19[a]	0.65[a]	3.54[a]
		Meadow (dense mixed sedges, rushes, and grasses)	<2	3.19[a]	0.65[a]	2.54[a]
		Saltgrass, rabbitbrush, wildrye, and greasewood (moderate)	<5	1.32[a]	0.65[a]	0.67[a]
		Grasslands	---	2.36[a]	0.65[a]	1.71[a]
		Playa/bare soil	---	0.80[a]	0.65[a]	0.15[a]
Reiner et al. (2002)[c]	Oasis Valley and Ash Meadows, NV	Open water body	---	8.6	0.50	8.1
		Submerged and sparse aquatic vegetation (shallow part of open water areas, includes sparse emergent vegetation)	0	8.6	0.50	8.1
		Dense wetland vegetation (Reedy and rushy marsh plants)	0	3.9	0.50	3.4
		Dense meadow and woodland vegetation (trees, grasses, shrubs)	0 to 20	3.3	0.50	2.8
		Moderate density to dense grassland (grasses, short rushes, occasional scattered trees.)	<10	3.2	0.50	2.7
		Sparse to moderate density grassland (grasses)	few to 10	2.0	0.50	1.5
		Moist bare soil (grasses)	≤5	2.6	0.50	2.1
		Sparse to moderate density shrubs (greasewood, rabbitbrush, and wolf-berry)	5 to 20	1.2	0.50	0.7
Harrington & Steinwand (2003, 2004)	Owens Valley, CA	Nevada saltbush scrub	13 to 14	0.59	0.35	0.25
		Rabbitbrush scrub	>16	0.31	0.11	0.19
		Nevada saltbush meadow	6.9 to 7.9	0.71 to 1.06	0.10 to 0.30	0.61 to 0.76
		Desert sink scrub	>13	0.49 to 0.80	0.10 to 0.50	0.31 to 0.38
		Rabbitbrush meadow	8.5 to 11	1.68	0.23	1.44
		Alkali meadow (sacaton, saltgrass, and wildrye)	6.6 to 11	1.37 to 2.25	0.11 to 0.99	0.87 to 2.18
DeMeo et al. (2003)	Death Valley, CA	Bare-soil playa	≤10	0.21 to 0.37	0.06 to 0.35	0.01 to 0.15
		Low density vegetation (salt grass, pickleweed, and shrub mesquite)	5 to 20	0.60	0.06	0.54
		Moderate density vegetation (grasses, arrowweed, mesquite, and pickleweed)	2 to 20	2.0	0.23	1.8

Table E-1
Summary of Reported ET Rates
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Report	Location	ET Unit Description	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Groundwater ET (ft/yr)
DeMeo et al. (2003) - cont.	Death Valley, CA	High density vegetation (Mesquite Flat)	≤20	2.9	0.16	2.7
		High density vegetation (Mesquite Flat and mixed grasses)	≤20	3.9	0.25	3.6
		Salt to encrusted playa	≤5	0.17 to 0.39	0.04 to 0.28	-1.40 to 0.13
Maurer et al. (2006)	Carson Valley and Douglas County, NV, and Alpine County, CA	Rabbitbrush and greasewood	3 to 5	1.9	---	---
		Flood-irrigated alfalfa	3 to 6	3.1	---	---
		Flood-irrigated pasture	2 to 5	3.2	---	---
		Flood-irrigated pasture	3 to 4	2.8	---	---
		Flood-irrigated alfalfa	40	3.0	---	---
		Non-irrigated pasture	6 to 7	1.7	---	---
		Bitterbrush and sage	60	1.5	---	---
		Flood-irrigated pasture	0 to 2	4.4	---	---
Cooper et al. (2006)	San Luis Valley, CO	Rush and saltgrass	3.0	1.34	0.60	0.74
		Greasewood and rabbitbrush	8.2	0.91	0.63	0.28
Laczniak et al. (2006)	Death Valley, CA	Saltgrass, grass, yerba mansa, arrowweed, desert baccharis, mesquite	0 to 15	2.28 to 2.68	0.05 to 0.49	2.1 to 2.3
Westenburg et al. (2006a)	Lake Mead, AZ and NV	Open water - Water Barge Cove	---	7.0	0.28 to 0.34[d]	---
		Open water - Sentinel Island	---	7.5	0.28 to 0.34[d]	---
		Open water - Virgin Basin	---	7.6	0.28 to 0.34[d]	---
		Open water - Overton Arm	---	6.8	0.28 to 0.34[d]	---
Westenburg et al. (2006b)	Topock Wash, Havasu area, Lower Colorado River, AZ	High density saltcedar - 2002	8	3.80	0.03	3.77
		Medium density (mesquite, saltcedar, saltgrass, arrowweed, baccharis, rush) - 2002	4 to 8	2.85	0.03	2.82
		Low to medium density arrowweed - 2002	8	2.87	0.03	2.84
		Barren soil - 2002	---	0.96	0.03	0.93
		High density saltcedar (saltcedar) - 2003	8	3.56	0.43	3.13
		Medium density (mesquite, saltcedar, saltgrass, arrowweed, baccharis, rush) - 2003	4 to 8	2.61	0.43	2.18
		Low to medium density arrowweed - 2003	8	2.65	0.43	2.21
		Barren soil - 2003	---	0.87	0.43	0.44
		High density saltcedar (saltcedar) - 2004	8	3.59	0.57	3.02
		Medium density (mesquite, saltcedar, saltgrass, arrowweed, baccharis, rush) - 2004	4 to 8	2.63	0.57	2.06
		Low to medium density arrowweed (arrowweed) - 2004	8	2.71	0.57	2.14
		Barren soil - 2004	---	0.88	0.57	0.31

Table E-1
Summary of Reported ET Rates
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Report	Location	ET Unit Description	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Groundwater ET (ft/yr)
Moreo et al. (2007)	Snake, Spring, and White River valleys, NV	Moderate density desert shrubland (greasewood)	17.16	0.836	0.52	0.32
		Sparse desert shrubland (greasewood and rabbitbrush)	9.78	0.835	0.72	0.12
		Moderate density desert shrubland (greasewood and rabbitbrush)	7.24	1.01	0.76	0.24
		Grassland/Meadowland (mixed grasses/meadow)	3.89	2.25	0.66	1.58
		Dense desert shrubland (greasewood)	32.39	1.06	0.74	0.32
		Moderate density desert shrubland (greasewood)	23.58	1.02	0.95	0.06
SNWA Project data	Snake, Spring, and White River valleys, NV	High density monotypic stand of greasewood (SNV1-2007)	19.31	1.65	0.37	1.28
		Moderate density monotypic stand of greasewood (SNV2-2007)	30.47	0.64	0.16	0.48
		Mixed shrubland; low density greasewood, sagebrush, rabbitbrush, shadscale, horsebrush (SV1-2006)	15.20	0.79	0.51	0.28
		Mixed shrubland; low density greasewood, sagebrush, rabbitbrush, shadscale, horsebrush (SV1-2007)	15.32	0.62	0.42	0.20
		Irrigated pasture/grassland; dense perennial grasses (SV2b-2007)	shallow	3.56	0.35	3.21
		Mixed shrubland; moderate density greasewood, rabbitbrush, shadscale (SV3-2007)	17.38	0.80	0.27	0.53
		Mixed shrubland; moderate density greasewood, sagebrush, rabbitbrush, shadscale, budsage (WRV2-2006)	18.95	1.38	0.87	0.51
		Mixed shrubland; moderate density greasewood, sagebrush, rabbitbrush, shadscale, budsage (WRV2-2007)	18.85	0.68	0.45	0.23
Devitt et al. (2008)	Snake, Spring, and White River valleys, NV	High density monotypic stand of greasewood (SNV1-2007)	19.31	1.64	0.12[a]	---
		Moderate density monotypic stand of greasewood (SNV2-2007)	30.47	0.70	0.04[a]	---
		Mixed shrubland; low density greasewood, sagebrush, rabbitbrush, shadscale, horsebrush (SV1-2006)	15.20	0.79	0.16[a]	---
		Mixed shrubland; low density greasewood, sagebrush, rabbitbrush, shadscale, horsebrush (SV1-2007)	15.32	0.66	0.11[a]	---
		Irrigated pasture/grassland; dense perennial grasses (SV2b-2007)	shallow	4.10	0.12[a]	---
		Mixed shrubland; moderate density greasewood, rabbitbrush, shadscale (SV3-2007)	17.38	0.89	0.10[a]	---
		Mixed shrubland; moderate density greasewood, sagebrush, rabbitbrush, shadscale, budsage (WRV2-2006)	18.95	1.39	0.24[a]	---
		Mixed shrubland; moderate density greasewood, sagebrush, rabbitbrush, shadscale, budsage (WRV2-2007)	18.85	0.90	0.20[a]	---

[a]Rates reflect growing season or less.
[b]Laczniak et al. (2001) rely on rates from previously published literature.
[c]Reiner et al. (2002) include data reported by Laczniak et al. (1999) for Ash Meadows.
[d]Average annual precipitation (1961 to 1990) measured at McCarran Airport, Las Vegas, NV (0.34 ft) and Overton, NV (0.28 ft) from DRI (Westenburg et al., 2006a).

Table E-2
Rooting Depths of Plants of the Southwestern United States

Plant	Rooting Depth (ft bgs)	Source
Alfalfa	12	Weaver (1926)
Alkali sacaton	25	Meinzer (1927)
Arrowweed	25	Meinzer (1927)
Big sage	5.9	Canadell et al. (1996)
Cottonwood	30	Robinson (1958)
Giant wildrye	≥12	Meinzer (1927)
Greasewood	60	Robinson (1958)
Mesquite	50	Meinzer (1927)
Mesquite	175	Phillips (1963); Canadell et al. (1996)
Pickleweed	≥20	Meinzer (1927)
Rabbitbrush	35	Mower and Nace (1957)
Rushes and sedges	A few feet	Meinzer (1927)
Saltbrush	62	Robinson (1958)
Saltcedar	11.8	Canadell et al. (1996)
Saltgrass	12	Meinzer (1927)
Wolfberry	30	USFS (2008)

ET is linear, but as mentioned above, different soil characteristics with different phreatophytes could generate different relationships. For example, Shah et al. (2007) found an exponential decline of groundwater ET with increasing depth to water.

E.1.3 PET Data and Spatial Distribution

A PET regression model was derived using estimates of PET reported in McCurdy and Albright (2004). McCurdy and Albright (2004) calculated PET for existing meteorological stations within the study area and vicinity using the Kimberly-Penman method (Wright, 1982) and the Hargreaves-Samani (Hargreaves and Samani, 1985) equation. The PET spatial distribution was derived from a multiple linear regression model of PET rates versus the latitude and altitude of the location where PET was measured. The regression model is expressed by the following equation:

$$PET = 104.3531 - 0.82922734Y - 0.004186006Z \qquad \text{(Eq. E-1)}$$

where,

PET = Potential ET rate (in./yr)
Y = Latitude (NAD, 1983)
Z = Altitude (ft amsl) (North American Vertical Datum of 1988)

Using GIS-gridding operations, the spatial distribution of PET was derived by applying Equation E-1 to a 100-m resolution DEM based on the USGS 30-m DEM (USGS, 2006). The meteorological station locations and their estimated PET values are depicted in Figure E-1 with the resultant PET distribution derived for the study area.

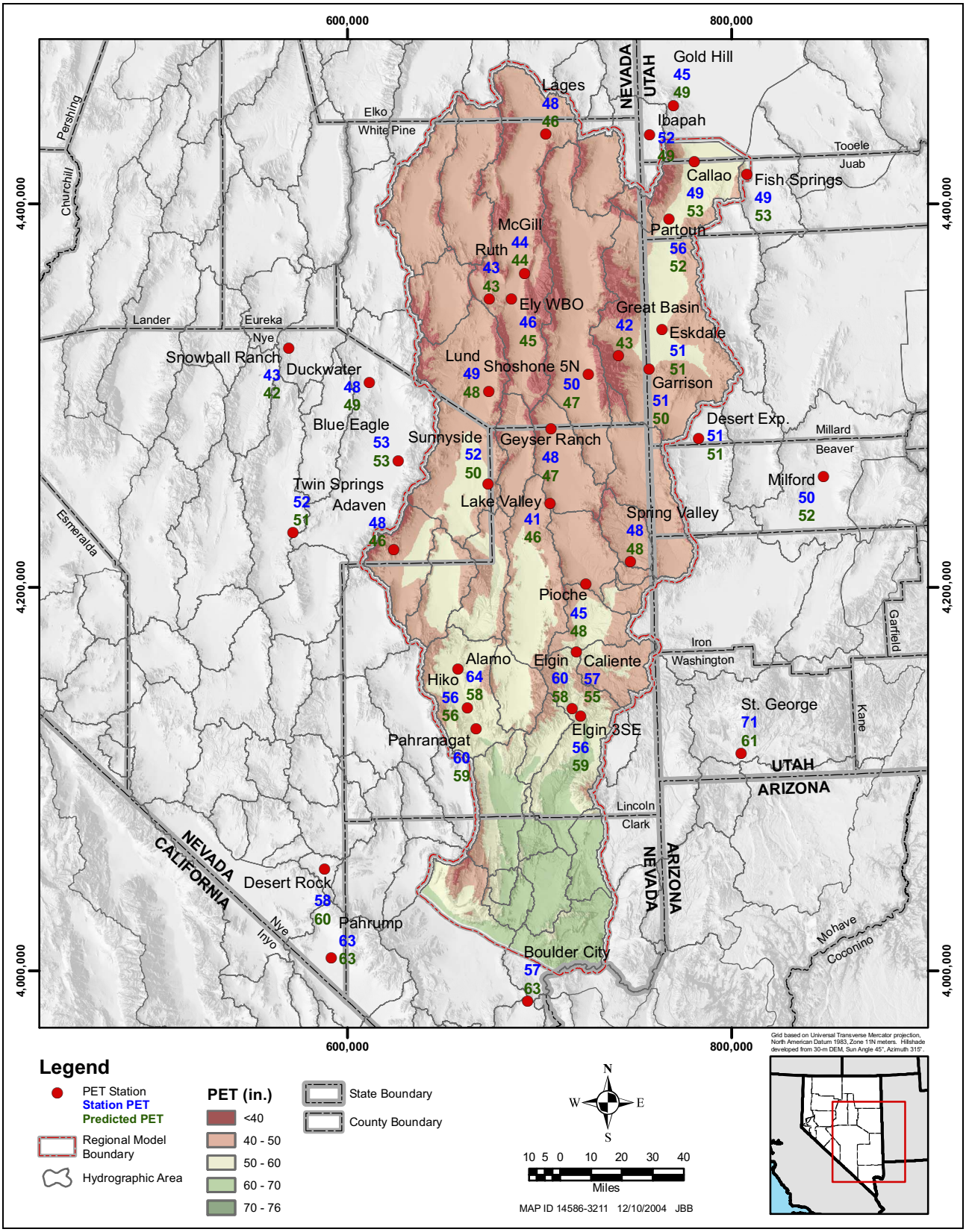

Figure E-1
Distribution of PET within the Flow System of the Study Area

E.2.0 REFERENCES

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Appendix F

Details of Groundwater ET Estimates

F.1.0 DETAILS OF GROUNDWATER ET ESTIMATES

This appendix contains additional information in support of the groundwater ET estimates. This information consists of the details associated with the deterministic and stochastic groundwater ET estimates.

F.1.1 Deterministic Groundwater ET Estimates

Deterministic groundwater ET estimates were made for the entire study area using Method 1. Deterministic estimates were also made by Welch et al. (2008) for BARCASS using Method 2. The final estimates used in this study are a combination of Method 1 for the southern basins of the study area and Method 2 for the northern basins.

F.1.1.1 Method 1 Estimates

This section details the groundwater ET estimates derived by Method 1 and explains how the ET rates were selected, adjusted, and used in the calculations.

The literature ET rates presented in Appendix E were reviewed to select the most appropriate rates for each of the five ET-unit classes defined for this analysis. The rates selected for each class (Table F-1) were based on the similarities between the vegetation types and climate and the availability of supporting data, such as site coordinates, precipitation, and depth to water.

The selected literature ET rates were adjusted for use in the study area. The adjustment consisted of scaling the observed ET rates by the PET ratio (PET of ET area/PET at ET observation station). These adjusted rates were consistently applied to the study area with the following exceptions:

- ET rates for the medium-vegetation class in White River and Cave valleys were not scaled by the PET ratio. The average of the two basin-specific measured rates was used instead.
- Because the ET rate observed for the medium vegetation in Spring Valley was too low as compared to most of the medium vegetation that actually occurs in Spring Valley, this rate was not used. Instead, the mean value for dense desert shrubland derived for BARCASS, 1.24 ft/yr, was used.
- The basin-specific ET rate measured for bare soil in Snake Valley was used for that category without any scaling by PET.

Using the ET rates described above, the ET areas, and the 800-m PRISM precipitation grid presented in Section 5.0, the groundwater ET volumes were calculated using GIS tools. The calculations were

Table F-1
Method 1 - ET and PET Rates Used in the Derivation of Groundwater ET Estimates (Limited Station Data)

ET-Unit Class	Selected ET Site	Description of Selected ET Site	Total ET or Evaporation Rate (ft/yr)	Source	PET Rate Extracted from PET Grid (ft/yr)
Open Water	Peterson Reservoir	Open water supplied by spring discharge	8.60	Reiner et al. (2002)	5.42
Wetland/Meadow	SPV-3	Wetland/meadow land cover surrounding riparian corridors throughout the project area	2.25	Moreo et al. (2007)	4.00
Dense Meadow/ Riparian	Springdale and Carson Meadow	Area dominated by dense meadow and woodland vegetation, primarily trees, meadow and marsh grasses, or mixed trees, shrubs, and grasses; trees, desert ash and cottonwood, with some desert willow and mesquite; water table typically ranging from above land surface to about 20 ft bgs; soil wet to dry	3.30[a]	Reiner et al. (2002)	4.84
Medium-Density Phreatophytes	WRV-1, WRV-2, and SPV-2	Medium-density phreatophytes, greasewood and shrubs, such as sagebrush	1.03[b]	Moreo et al. (2007)	4.13
Bare Soil/ Low-Density Phreatophytes	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[c]	Welch et al. (2008)	4.11

[a]Average ET rate from Springdale and Carson Meadow
[b]Average ET rate from WRV-1, WRV-2 and SPV-2
[c]Average of the area-weighted average annual ET for the sparse and moderately dense shrubland ET Units reported by Welch et al. (2008)

made following the 800-m PRISM grid and consisted of first subtracting the precipitation rate from the assigned ET rate, and second, multiplying the resulting groundwater ET rate by the area. For grid cells where the precipitation rates were larger than the ET rate, the difference was assumed to be zero. Thus, the corresponding groundwater ET volume was calculated as zero. The groundwater ET volumes calculated for the grid cells were then grouped by ET class for each basin where groundwater ET occurs. Table F-2 provides the results of these calculations. The table contains the scaled ET rates, the precipitation rates, and the groundwater ET areas.

The following are column-by-column descriptions of the information contained in Table F-2.

- HA Number: Hydrographic area number
- HA Name: Hydrographic area name
- ET Class Number: Class of groundwater ET within potential groundwater ET area
- Category 1 ET Area (acres): Area of groundwater ET categorized as likely using main groundwater system
- Category 2 ET Area (acres): Area of groundwater ET categorized as using uncertain groundwater system (may have partial or complete connection with main groundwater system
- Category 3 ET Area (acres): Area of groundwater ET categorized as likely using local groundwater system
- Total ET Area (acres): Total area of groundwater ET for categories 1, 2, and 3
- Scaled ET Rate (ft/yr): Total ET rates scaled by PET ratio
- Avg. Annual Precipitation PRISMV2 (ft/yr): Average precipitation rate for ET class within given basin derived from 800-m PRISM grid
- Category 1 Groundwater ET Volume (afy): Volume of groundwater ET calculated as (ET Rate – PRISMV2) × Category 1 ET area
- Category 2 Groundwater ET Volume (afy): Volume of groundwater ET calculated as (ET Rate – PRISMV2) × Category 2 ET area
- Category 3 Groundwater ET Volume (afy): Volume of groundwater ET calculated as (ET Rate – PRISMV2) × Category 3 ET area
- Total Groundwater ET Volume (afy): Total volume of groundwater ET (sum of Categories 1, 2, and 3)

Table F-2
Method 1 - Scaled ET Rates and Volumes of Groundwater ET by ET Class
(Page 1 of 4)

HA Number	HA Name	ET Class	ET Area Category 1 (acres)	ET Area Category 2 (acres)	ET Area Category 3 (acres)	ET Area Total (acres)	Scaled ET Rate (ft/yr)	Avg. Annual Precipitation PRISMV2 (ft/yr)	Groundwater ET Volume Category 1 (afy)	Groundwater ET Volume Category 2 (afy)	Groundwater ET Volume Category 3 (afy)	Groundwater ET Volume Total (afy)
178B	Butte Valley South	1	2	0	0	2	5.95	0.96	10	0	0	10
		2	10,970	0	0	10,970	1.00	0.94	658	0	0	658
		3	38,321	0	0	38,321	1.16	0.94	8,431	0	0	8,431
		4	1,839	0	0	1,839	2.11	0.92	2,188	0	0	2,188
178B Total			**51,132**	**0**	**0**	**51,132**			**11,287**	**0**	**0**	**11,287**
179	Steptoe Valley	1	129	0	4	133	6.07	0.83	676	0	21	697
		2	64,501	7	61	64,569	1.00	0.70	19,350	2	18	19,370
		3	51,050	171	846	52,067	1.19	0.73	23,483	79	389	23,951
		4	42,231	1,069	3,452	46,752	2.15	0.73	59,968	1,518	4,902	66,388
179 Total			**157,911**	**1,247**	**4,363**	**163,521**			**103,477**	**1,599**	**5,330**	**110,406**
GVFS Total			**209,043**	**1,247**	**4,363**	**214,653**			**114,764**	**1,599**	**5,330**	**121,693**
184	Spring Valley	1	278	0	0	278	6.36	0.72	1,568	0	0	1,568
		2	76,568	22	244	76,834	1.00	0.75	19,142	6	61	19,209
		3	68,916	62	272	69,250	1.24	0.80	30,323	27	120	30,470
		4	14,183	0	104	14,287	2.25	0.79	20,707	0	152	20,859
		6	11,505	0	0	11,505	0.71	0.79	0	0	0	0
184 Total			**171,450**	**84**	**620**	**172,154**			**71,740**	**33**	**333**	**72,106**
185	Tippett Valley	2	7,554	0	5	7,559	1.00	0.78	1,662	0	1	1,663
		3	88	0	8	96	1.23	0.80	38	0	3	41
		4	130	0	34	164	2.22	0.80	185	0	48	233
185 Total			**7,772**	**0**	**47**	**7,819**			**1,885**	**0**	**52**	**1,937**
194	Pleasant Valley	2	0	0	325	325	0.78	0.92	0	0	0	0
		3	0	0	1,213	1,213	1.19	0.98	0	0	255	255
		4	0	0	608	608	2.15	0.99	0	0	705	705
194 Total			**0**	**0**	**2,146**	**2,146**			**0**	**0**	**960**	**960**
195	Snake Valley	1	336	0	2	338	6.75	0.71	2,029	0	12	2,041
		2	199,934	302	524	200,760	0.87	0.59	55,982	85	147	56,214
		3	18,855	688	667	20,210	1.32	0.69	11,879	433	420	12,732
		4	30,026	1,267	1,211	32,504	2.39	0.64	52,546	2,217	2,119	56,882
		6	58,009	0	0	58,009	0.71	0.55	9,281	0	0	9,281
195 Total			**307,160**	**2,257**	**2,404**	**311,821**			**131,717**	**2,735**	**2,698**	**137,150**

Table F-2
Method 1 - Scaled ET Rates and Volumes of Groundwater ET by ET Class
(Page 2 of 4)

HA Number	HA Name	ET Class	ET Area Category 1 (acres)	ET Area Category 2 (acres)	ET Area Category 3 (acres)	ET Area Total (acres)	Scaled ET Rate (ft/yr)	Avg. Annual Precipitation PRISMV2 (ft/yr)	Groundwater ET Volume Category 1 (afy)	Groundwater ET Volume Category 2 (afy)	Groundwater ET Volume Category 3 (afy)	Groundwater ET Volume Total (afy)
196	Hamlin Valley	1	0	0	0	0	6.45	0.73	0	0	0	0
		2	743	146	7	896	0.83	0.79	30	6	0	36
		3	1,918	293	117	2,328	1.26	0.77	940	144	57	1,141
		4	204	0	0	204	2.28	0.73	316	0	0	316
196 Total			**2,865**	**439**	**124**	**3,428**			**1,286**	**150**	**57**	**1,493**
GSLDFS Total			**489,247**	**2,780**	**5,341**	**497,368**			**206,628**	**2,918**	**4,100**	**213,646**
183	Lake Valley	1	58	0	0	58	6.26	0.86	313	0	0	313
		2	22,592	0	0	22,592	0.80	0.90	0	0	0	0
		3	21,112	0	0	21,112	0.98	0.91	1,478	0	0	1,478
		4	3,683	0	0	3,683	2.21	0.86	4,972	0	0	4,972
183 Total			**47,445**	**0**	**0**	**47,445**			**6,763**	**0**	**0**	**6,763**
198	Dry Valley	1	33	0	0	33	6.68	1.08	185	0	0	185
		2	82	0	0	82	1.00	1.08	0	0	0	0
		3	1,182	0	0	1,182	2.87	1.07	2,128	0	0	2,128
		4	771	0	0	771	2.87	1.07	1,388	0	0	1,388
198 Total			**2,068**	**0**	**0**	**2,068**			**3,701**	**0**	**0**	**3,701**
199	Rose Valley	2	0	0	0	0	1.00	1.12	0	0	0	0
		3	89	0	0	89	2.83	1.10	154	0	0	154
		4	255	0	0	255	2.83	1.10	441	0	0	441
199 Total			**344**	**0**	**0**	**344**			**595**	**0**	**0**	**595**
200	Eagle Valley	2	3	0	0	3	1.00	1.14	0	0	0	0
		3	154	0	0	154	2.79	1.14	254	0	0	254
		4	477	0	0	477	2.79	1.15	782	0	0	782
200 Total			**634**	**0**	**0**	**634**			**1,036**	**0**	**0**	**1,036**
201	Spring Valley	1	52	0	0	52	6.28	1.15	267	0	0	267
		2	7	3	0	10	1.00	1.14	0	0	0	0
		3	603	25	2	630	2.70	1.12	953	40	3	996
		4	1,528	52	77	1,657	2.70	1.10	2,445	83	123	2,651
201 Total			**2,190**	**80**	**79**	**2,349**			**3,665**	**123**	**126**	**3,914**
202	Patterson Valley	3	771	0	0	771	2.81	1.06	1,349	0	0	1,349
202 Total			**771**	**0**	**0**	**771**			**1,349**	**0**	**0**	**1,349**

Table F-2
Method 1 - Scaled ET Rates and Volumes of Groundwater ET by ET Class
(Page 3 of 4)

HA Number	HA Name	ET Class	ET Area Category 1 (acres)	ET Area Category 2 (acres)	ET Area Category 3 (acres)	ET Area Total (acres)	Scaled ET Rate (ft/yr)	Avg. Annual Precipitation PRISMV2 (ft/yr)	Groundwater ET Volume Category 1 (afy)	Groundwater ET Volume Category 2 (afy)	Groundwater ET Volume Category 3 (afy)	Groundwater ET Volume Total (afy)
203	Panaca Valley	2	343	0	0	343	1.00	0.86	48	0	0	48
		3	3,537	0	0	3,537	3.03	0.88	7,605	0	0	7,605
		4	5,224	0	0	5,224	3.03	0.88	11,232	0	0	11,232
203 Total			**9,104**	**0**	**0**	**9,104**			**18,885**	**0**	**0**	**18,885**
204	Clover Valley	2	36	0	150	186	1.00	1.36	0	0	0	0
		3	136	0	1,641	1,777	2.90	1.42	201	0	2,429	2,630
		4	359	0	1,188	1,547	2.90	1.21	607	0	2,008	2,615
204 Total			**531**	**0**	**2,979**	**3,510**			**808**	**0**	**4,437**	**5,245**
205	Lower Meadow Valley Wash	1	0	0	0	0	8.43	0.45	0	0	0	0
		2	528	0	0	528	1.00	0.48	275	0	0	275
		3	1,264	0	0	1,264	3.62	0.60	3,817	0	0	3,817
		4	6,024	0	0	6,024	3.62	0.67	17,771	0	0	17,771
205 Total			**7,816**	**0**	**0**	**7,816**			**21,863**	**0**	**0**	**21,863**
MVFS Total			**70,903**	**80**	**3,058**	**74,041**			**58,665**	**123**	**4,563**	**63,351**
172	Garden Valley	2	12	0	9	21	1.00	0.92	1	0	1	2
		3	483	0	69	552	2.82	0.94	908	0	130	1,038
		4	129	0	247	376	2.82	1.07	226	0	432	658
172 Total			**624**	**0**	**325**	**949**			**1,135**	**0**	**563**	**1,698**
174	Jakes Valley	1	0	0	0	0	5.72	1.07	0	0	0	0
		2	0	0	4	4	1.00	1.06	0	0	0	0
		3	0	0	621	621	1.12	1.03	0	0	56	56
		4	0	0	346	346	2.02	1.05	0	0	336	336
174 Total			**0**	**0**	**971**	**971**			**0**	**0**	**392**	**392**
175	Long Valley	2	6,727	13	0	6,740	1.00	0.95	336	1	0	337
		3	10,167	557	0	10,724	1.18	0.95	2,338	128	0	2,466
		4	131	0	0	131	2.14	0.95	156	0	0	156
175 Total			**17,025**	**570**	**0**	**17,595**			**2,830**	**129**	**0**	**2,959**
180	Cave Valley	2	0	5,914	0	5,914	1.00	1.06	0	0	0	0
		3	814	8,763	74	9,651	1.03	1.05	0	0	0	0
		4	952	0	132	1,084	2.17	0.98	1,133	0	157	1,290
180 Total			**1,766**	**14,677**	**206**	**16,649**			**1,133**	**0**	**157**	**1,290**

Table F-2
Method 1 - Scaled ET Rates and Volumes of Groundwater ET by ET Class
(Page 4 of 4)

HA Number	HA Name	ET Class	ET Area Category 1 (acres)	ET Area Category 2 (acres)	ET Area Category 3 (acres)	ET Area Total (acres)	Scaled ET Rate (ft/yr)	Avg. Annual Precipitation PRISMV2 (ft/yr)	Groundwater ET Volume Category 1 (afy)	Groundwater ET Volume Category 2 (afy)	Groundwater ET Volume Category 3 (afy)	Groundwater ET Volume Total (afy)
207	White River Valley	1	313	1	0	314	6.63	0.80	1,825	6	0	1,831
		2	28,551	68	16	28,635	1.00	0.80	5,710	14	3	5,727
		3	86,764	637	385	87,786	1.04	0.83	18,220	134	81	18,435
		4	25,124	2,545	288	27,957	2.34	0.85	37,435	3,792	429	41,656
207 Total			**140,752**	**3,251**	**689**	**144,692**			**63,190**	**3,946**	**513**	**67,649**
209	Pahranagat Valley	1	1,296	0	0	1,296	7.68	0.58	9,202	0	0	9,202
		2	260	0	0	260	1.00	0.61	101	0	0	101
		3	816	0	0	816	3.30	0.61	2,195	0	0	2,195
		4	6,285	0	0	6,285	3.30	0.59	17,032	0	0	17,032
209 Total			**8,657**	**0**	**0**	**8,657**			**28,530**	**0**	**0**	**28,530**
215	Black Mountains Area	2	54	0	0	54	1.00	0.45	30	0	0	30
		3	244	0	0	244	3.88	0.46	834	0	0	834
		4	165	0	0	165	3.88	0.44	568	0	0	568
215 Total			**463**	**0**	**0**	**463**			**1,432**	**0**	**0**	**1,432**
218	California Wash	2	37	0	0	37	1.00	0.45	20	0	0	20
		3	149	0	0	149	3.80	0.46	498	0	0	498
		4	1,194	0	0	1,194	3.80	0.46	3,988	0	0	3,988
218 Total			**1,380**	**0**	**0**	**1,380**			**4,506**	**0**	**0**	**4,506**
219	Muddy River Springs Area	2	166	0	0	166	1.00	0.46	90	0	0	90
		3	214	0	0	214	3.77	0.46	708	0	0	708
		4	1,571	0	0	1,571	3.77	0.46	5,200	0	0	5,200
219 Total			**1,951**	**0**	**0**	**1,951**			**5,998**	**0**	**0**	**5,998**
220	Lower Moapa Valley	1	137	0	0	137	9.06	0.45	1,180	0	0	1,180
		2	496	0	0	496	1.00	0.44	278	0	0	278
		3	907	0	0	907	3.89	0.44	3,129	0	0	3,129
		4	5,993	0	0	5,993	3.89	0.44	20,676	0	0	20,676
220 Total			**7,533**	**0**	**0**	**7,533**			**25,263**	**0**	**0**	**25,263**
WRFS Total			**180,151**	**18,498**	**2,191**	**200,840**			**134,017**	**4,075**	**1,625**	**139,717**
Grand Total			**949,344**	**22,605**	**14,953**	**986,902**			**514,074**	**8,715**	**15,618**	**538,407**

F.1.1.2 Method 2 - BARCASS Estimates

The detailed estimates of groundwater ET derived for basins located in the BARCASS area are documented in four USGS reports:

- The final groundwater ET estimates are documented in the summary report titled *Water Resources of the Basin and Range Carbonate-Rock Aquifer System, White Pine County, Nevada, and Adjacent Areas in Nevada and Utah* prepared by Welch et al. (2008).

- The potential groundwater ET areas and their classification are documented in a report titled *Mapping Evapotranspiration Units in the Basin and Range Carbonate-Rock Aquifer System, White Pine County, Nevada, and Adjacent Areas in Nevada and Utah* by Smith et al. (2007).

- Field measurements of ET rates and ancillary information are documented in a report titled *Evapotranspiration Rate Measurements of Vegetation Typical of Ground-Water Discharge areas in the Basin and Range Carbonate-Rock Aquifer System, White Pine County, Nevada, and Adjacent Areas in Nevada and Utah* by Moreo et al. (2007).

- The agricultural areas are documented in a report titled *Irrigated Acreage within the Basin and Range Carbonate-Rock Aquifer System, White Pine County, Nevada, and Adjacent Areas in Nevada and Utah* by Welborn and Moreo (2007).

F.1.1.3 Combined Method 1 and Method 2 (BARCASS)

The estimates of groundwater ET are derived by Method 1 for the southern basins and Method 2 (BARCASS) for the northern basins to accomplish the following:

- Directly compare the ET rates and volumes derived using Methods 1 and 2 (BARCASS).
- Calculate and compare groundwater ET volumes for each category of ET area in each basin.
- Derive stochastic estimates of groundwater ET volumes using a single ET data set.

The resulting ET areas and annual volumes of groundwater ET for the 5 ET classes for the basins of the study area are listed in Table F-3 by category. This part of the data analysis was performed before the publication of DeMeo et al. (2008) and therefore does not include their estimates.

The combined ET data set was used, and the ET rates for equivalent classes in basins that are common to Methods 1 and 2 (BARCASS) were compared directly. As shown on Figure F-1, the rates derived using the two methods are comparable. The basin groundwater ET volumes derived by BARCASS are also comparable to those derived by Method 1. See Figure F-2 and Table F-3 for the volumes derived by the combined data set.

The consistent data set was used as the source of input parameters in the Monte Carlo analysis. The estimates of annual volumes of groundwater ET, derived from this Monte Carlo analysis, are described in the following section.

Table F-3
Groundwater ET Areas and Volumes Using Combined Method 1 and Method 2 (BARCASS) Data Set
(Page 1 of 6)

HA Number	HA Name	Sub-Area Number	ET Class Number	ET Class Name	Category 1 Groundwater ET Area (ac)	Category 1 Groundwater ET Volume (afy)	Category 2 Groundwater ET Area (ac)	Category 2 Groundwater ET Volume (afy)	Category 3 Groundwater ET Area (ac)	Category 3 Groundwater ET Volume (afy)	Total Groundwater ET Area (ac)	Total Groundwater ET Volume (afy)
178B	Butte Valley (South)	N	1	Open Water	4	16	0	0	0	0	4	16
		N	2	Bare Soil/Low Vegetation	8,265	281	0	0	0	0	8,265	281
		N	3	Phreatophyte/Medium Vegetation	60,033	9,904	0	0	241	40	60,274	9,944
		N	4	Wetland/Meadow	1,092	1,559	0	0	65	93	1,157	1,652
				178B Total	**69,393**	**11,760**	**0**	**0**	**306**	**133**	**69,700**	**11,893**
172	Garden Valley	N	2	Bare Soil/Low Vegetation	12	1	0	0	9	1	21	2
		N	3	Phreatophyte/Medium Vegetation	483	906	0	0	69	130	552	1,036
		N	4	Wetland/Meadow	129	226	0	0	247	432	376	658
				172 Total	**624**	**1,133**	**0**	**0**	**325**	**563**	**949**	**1,696**
174	Jakes Valley	N	1	Open Water	0	0	0	0	26	110	26	110
		N	2	Bare Soil/Low Vegetation	0	0	0	0	6	0	6	0
		N	3	Phreatophyte/Medium Vegetation	0	0	0	0	930	384	930	384
		N	4	Wetland/Meadow	0	0	0	0	263	370	263	370
				174 Total	**0**	**0**	**0**	**0**	**1,225**	**864**	**1,225**	**864**
175	Long Valley	N	2	Bare Soil/Low Vegetation	4,858	194	45	2	0	0	4,903	196
		N	3	Phreatophyte/Medium Vegetation	12,939	2,041	440	69	0	0	13,379	2,110
		N	4	Wetland/Meadow	7	12	2	3	0	0	9	15
				175 Total	**17,804**	**2,247**	**487**	**74**	**0**	**0**	**18,291**	**2,321**
179	Steptoe Valley	1	1	Open Water	107	462	0	0	14	62	121	524
		1	2	Bare Soil/Low Vegetation	29,605	5,344	0	0	86	16	29,691	5,360
		1	3	Phreatophyte/Medium Vegetation	112,693	52,771	0	0	3,253	1,523	115,946	54,294
		1	4	Wetland/Meadow	13,136	26,521	0	0	1,439	2,906	14,575	29,427
		1	6	Playa	2,723	692	0	0	0	0	2,723	692
				Subtotal	**158,264**	**85,790**	**0**	**0**	**4,792**	**4,507**	**163,056**	**90,297**
		2	1	Open Water	296	1,238	0	0	22	94	318	1,332
		2	2	Bare Soil/Low Vegetation	398	32	14	1	4	0	416	33
		2	3	Phreatophyte/Medium Vegetation	6,417	2,783	293	127	316	137	7,026	3,047
		2	4	Wetland/Meadow	3,654	6,743	43	80	99	183	3,796	7,006
				Subtotal	**10,765**	**10,796**	**350**	**208**	**441**	**414**	**11,556**	**11,418**
				179 Total	**169,029**	**96,586**	**350**	**208**	**5,233**	**4,921**	**174,612**	**101,715**
180	Cave Valley	N	2	Bare Soil/Low Vegetation	5	0	3,548	0	2	0	3,555	0
		N	3	Phreatophyte/Medium Vegetation	1,061	56	7,542	395	136	7	8,739	458
		N	4	Wetland/Meadow	786	1,135	2	3	79	114	867	1,252
		N	6	Playa	0	0	194	0	0	0	194	0
				180 Total	**1,852**	**1,191**	**11,286**	**398**	**217**	**121**	**13,355**	**1,710**

Table F-3
Groundwater ET Areas and Volumes Using Combined Method 1 and Method 2 (BARCASS) Data Set
(Page 2 of 6)

HA Number	HA Name	Sub-Area Number	ET Class Number	ET Class Name	Category 1 Groundwater ET Area (ac)	Category 1 Groundwater ET Volume (afy)	Category 2 Groundwater ET Area (ac)	Category 2 Groundwater ET Volume (afy)	Category 3 Groundwater ET Area (ac)	Category 3 Groundwater ET Volume (afy)	Total Groundwater ET Area (ac)	Total Groundwater ET Volume (afy)
183	Lake Valley	N	1	Open Water	26	106	0	0	0	0	26	106
		N	2	Bare Soil/Low Vegetation	16,303	0	0	0	0	0	16,303	0
		N	3	Phreatophyte/Medium Vegetation	36,478	1,094	0	0	0	0	36,478	1,094
		N	4	Wetland/Meadow	2,596	4,743	0	0	0	0	2,596	4,743
		N	6	Playa	94	1	0	0	0	0	94	1
				183 Total	**55,497**	**5,944**	**0**	**0**	**0**	**0**	**55,497**	**5,944**
184	Spring Valley	1	2	Bare Soil/Low Vegetation	235	40	94	16	36	6	365	62
		1	3	Phreatophyte/Medium Vegetation	2,213	954	186	80	147	63	2,546	1,097
		1	4	Wetland/Meadow	767	1,608	0	0	49	103	816	1,711
				Subtotal	**3,215**	**2,602**	**280**	**96**	**232**	**172**	**3,727**	**2,870**
184	Spring Valley	2	1	Open Water	6	27	0	0	0	0	6	27
		2	2	Bare Soil/Low Vegetation	20,208	3,435	0	0	10	2	20,218	3,437
		2	3	Phreatophyte/Medium Vegetation	40,930	16,176	0	0	398	157	41,328	16,333
		2	4	Wetland/Meadow	6,360	13,056	0	0	10	21	6,370	13,077
		2	6	Playa	17,651	5,500	0	0	0	0	17,651	5,500
				Subtotal	**85,155**	**38,195**	**0**	**0**	**418**	**180**	**85,573**	**38,374**
184	Spring Valley	3	2	Bare Soil/Low Vegetation	3,268	560	0	0	0	0	3,268	560
		3	3	Phreatophyte/Medium Vegetation	19,194	6,967	0	0	0	0	19,194	6,967
		3	4	Wetland/Meadow	319	501	0	0	0	0	319	501
		3	6	Playa	676	83	0	0	0	0	676	83
				Subtotal	**23,457**	**8,111**	**0**	**0**	**0**	**0**	**23,457**	**8,111**
184	Spring Valley	4	2	Bare Soil/Low Vegetation	11,870	2,255	0	0	2	0	11,872	2,255
		4	3	Phreatophyte/Medium Vegetation	49,270	17,042	0	0	58	20	49,328	17,062
		4	4	Wetland/Meadow	3,266	6,695	0	0	22	45	3,288	6,740
		4	6	Playa	529	23	0	0	0	0	529	23
				Subtotal	**64,935**	**26,015**	**0**	**0**	**82**	**65**	**65,017**	**26,080**
				184 Total	**176,762**	**74,923**	**280**	**96**	**732**	**417**	**177,774**	**75,435**
185	Tippett Valley	N	2	Bare Soil/Low Vegetation	1,624	292	0	0	0	0	1,624	292
		N	3	Phreatophyte/Medium Vegetation	5,551	1,325	0	0	35	8	5,586	1,333
		N	4	Wetland/Meadow	59	79	0	0	13	17	72	96
		N	6	Playa	497	6	0	0	0	0	497	6
				185 Total	**7,731**	**1,702**	**0**	**0**	**48**	**25**	**7,779**	**1,727**
194	Pleasant Valley	2	2	Bare Soil/Low Vegetation	0	0	0	0	118	37	118	37
		2	3	Phreatophyte/Medium Vegetation	0	0	0	0	759	512	759	512
		2	4	Wetland/Meadow	0	0	0	0	226	474	226	474
				194 Total	**0**	**0**	**0**	**0**	**1,103**	**1,023**	**1,103**	**1,023**

Table F-3
Groundwater ET Areas and Volumes Using Combined Method 1 and Method 2 (BARCASS) Data Set
(Page 3 of 6)

HA Number	HA Name	Sub-Area Number	ET Class Number	ET Class Name	Category 1 Groundwater ET Area (ac)	Category 1 Groundwater ET Volume (afy)	Category 2 Groundwater ET Area (ac)	Category 2 Groundwater ET Volume (afy)	Category 3 Groundwater ET Area (ac)	Category 3 Groundwater ET Volume (afy)	Total Groundwater ET Area (ac)	Total Groundwater ET Volume (afy)
195	Snake Valley	1	2	Bare Soil/Low Vegetation	13,604	2,585	300	57	0	0	13,904	2,642
		1	3	Phreatophyte/Medium Vegetation	4,006	2,383	266	158	0	0	4,272	2,541
		1	4	Wetland/Meadow	1,239	2,852	27	63	0	0	1,266	2,915
		1	6	Playa	56,065	4,205	7	1	0	0	56,072	4,206
				Subtotal	**74,914**	**12,025**	**600**	**279**	**0**	**0**	**75,514**	**12,304**
195	Snake Valley	2	1	Open Water	54	247	0	0	0	0	54	247
		2	2	Bare Soil/Low Vegetation	11,380	3,063	0	0	3	1	11,383	3,064
		2	3	Phreatophyte/Medium Vegetation	14,951	8,503	0	0	132	75	15,083	8,578
		2	4	Wetland/Meadow	1,439	3,188	0	0	1	3	1,440	3,191
		2	6	Playa	574	44	0	0	0	0	574	44
				Subtotal	**28,398**	**15,045**	**0**	**0**	**136**	**79**	**28,534**	**15,124**
195	Snake Valley	3	1	Open Water	65	297	0	0	6	27	71	324
		3	2	Bare Soil/Low Vegetation	104,340	31,885	38	12	140	43	104,518	31,940
		3	3	Phreatophyte/Medium Vegetation	68,151	37,546	429	236	1,679	925	70,259	38,707
		3	4	Wetland/Meadow	4,482	8,787	284	558	354	694	5,120	10,039
		3	6	Playa	7,092	1,314	0	0	0	0	7,092	1,314
				Subtotal	**184,130**	**79,829**	**751**	**806**	**2,179**	**1,689**	**187,060**	**82,324**
195	Snake Valley	4	1	Open Water	302	1,344	0	0	0	0	302	1,344
		4	2	Bare Soil/Low Vegetation	3,170	951	0	0	0	0	3,170	951
		4	3	Phreatophyte/Medium Vegetation	22,563	10,662	0	0	0	0	22,563	10,662
		4	4	Wetland/Meadow	3,126	6,643	0	0	0	0	3,126	6,643
				Subtotal	**29,161**	**19,600**	**0**	**0**	**0**	**0**	**29,161**	**19,600**
				195 Total	**316,603**	**126,499**	**1,351**	**1,085**	**2,315**	**1,768**	**320,269**	**129,352**
196	Hamlin Valley	N	2	Bare Soil/Low Vegetation	98	29	4	1	0	0	102	30
		N	3	Phreatophyte/Medium Vegetation	3,612	1,714	431	205	0	0	4,043	1,919
		N	4	Wetland/Meadow	60	102	2	3	0	0	62	105
				196 Total	**3,770**	**1,845**	**437**	**209**	**0**	**0**	**4,207**	**2,054**
198	Dry Valley	N	1	Open Water	33	183	0	0	0	0	33	183
		N	2	Bare Soil/Low Vegetation	82	0	0	0	0	0	82	0
		N	3	Phreatophyte/Medium Vegetation	1,182	2,133	0	0	0	0	1,182	2,133
		N	4	Wetland/Meadow	771	1,394	0	0	0	0	771	1,394
				198 Total	**2,068**	**3,710**	**0**	**0**	**0**	**0**	**2,068**	**3,710**
199	Rose Valley	N	2	Bare Soil/Low Vegetation	0	0	0	0	0	0	0	0
		N	3	Phreatophyte/Medium Vegetation	89	153	0	0	0	0	89	153
		N	4	Wetland/Meadow	255	441	0	0	0	0	255	441
				199 Total	**344**	**594**	**0**	**0**	**0**	**0**	**344**	**594**

Table F-3
Groundwater ET Areas and Volumes Using Combined Method 1 and Method 2 (BARCASS) Data Set
(Page 4 of 6)

HA Number	HA Name	Sub-Area Number	ET Class Number	ET Class Name	Category 1 Groundwater ET Area (ac)	Category 1 Groundwater ET Volume (afy)	Category 2 Groundwater ET Area (ac)	Category 2 Groundwater ET Volume (afy)	Category 3 Groundwater ET Area (ac)	Category 3 Groundwater ET Volume (afy)	Total Groundwater ET Area (ac)	Total Groundwater ET Volume (afy)
200	Eagle Valley	N	2	Bare Soil/Low Vegetation	3	0	0	0	0	0	3	0
		N	3	Phreatophyte/Medium Vegetation	154	253	0	0	0	0	154	253
		N	4	Wetland/Meadow	477	780	0	0	0	0	477	780
				200 Total	**634**	**1,033**	**0**	**0**	**0**	**0**	**634**	**1,033**
201	Spring Valley	N	1	Open Water	52	266	0	0	0	0	52	266
		N	2	Bare Soil/Low Vegetation	7	0	3	0	0	0	10	0
		N	3	Phreatophyte/Medium Vegetation	603	955	25	40	2	4	630	999
		N	4	Wetland/Meadow	1,528	2,441	52	82	77	124	1,657	2,647
				201 Total	**2,190**	**3,662**	**80**	**122**	**79**	**128**	**2,349**	**3,912**
202	Patterson Valley	N	3	Phreatophyte/Medium Vegetation	771	1,346	0	0	0	0	771	1,346
				202 Total	**771**	**1,346**	**0**	**0**	**0**	**0**	**771**	**1,346**
203	Panaca Valley	N	2	Bare Soil/Low Vegetation	343	49	0	0	0	0	343	49
		N	3	Phreatophyte/Medium Vegetation	3,537	7,620	0	0	0	0	3,537	7,620
		N	4	Wetland/Meadow	5,224	11,226	0	0	0	0	5,224	11,226
				203 Total	**9,104**	**18,895**	**0**	**0**	**0**	**0**	**9,104**	**18,895**
204	Clover Valley	N	2	Bare Soil/Low Vegetation	36	0	0	0	150	0	186	0
		N	3	Phreatophyte/Medium Vegetation	136	225	0	0	1,641	2,710	1,777	2,935
		N	4	Wetland/Meadow	359	674	0	0	1,188	2,231	1,547	2,905
				204 Total	**531**	**899**	**0**	**0**	**2,979**	**4,941**	**3,510**	**5,840**
205	Lower Meadow Valley Wash	1	2	Bare Soil/Low Vegetation	21	1	0	0	0	0	21	1
		1	3	Phreatophyte/Medium Vegetation	257	316	0	0	0	0	257	316
		1	4	Wetland/Meadow	797	975	0	0	0	0	797	975
				Subtotal	**1,075**	**1,293**	**0**	**0**	**0**	**0**	**1,075**	**1,293**
205	Lower Meadow Valley Wash	2	2	Bare Soil/Low Vegetation	2	0	0	0	0	0	2	0
		2	3	Phreatophyte/Medium Vegetation	131	151	0	0	0	0	131	151
		2	4	Wetland/Meadow	710	808	0	0	0	0	710	808
				Subtotal	**843**	**959**	**0**	**0**	**0**	**0**	**843**	**959**
205	Lower Meadow Valley Wash	3	2	Bare Soil/Low Vegetation	30	6	0	0	0	0	30	6
		3	3	Phreatophyte/Medium Vegetation	124	169	0	0	0	0	124	169
		3	4	Wetland/Meadow	2,322	3,020	0	0	0	0	2,322	3,020
				Subtotal	**2,476**	**3,194**	**0**	**0**	**0**	**0**	**2,476**	**3,194**
205	Lower Meadow Valley Wash	4	1	Open Water	0	1	0	0	0	0	0	1
		4	2	Bare Soil/Low Vegetation	6	1	0	0	0	0	6	1
		4	3	Phreatophyte/Medium Vegetation	38	53	0	0	0	0	38	53
		4	4	Wetland/Meadow	834	1,161	0	0	0	0	834	1,161
				Subtotal	**878**	**1,216**	**0**	**0**	**0**	**0**	**878**	**1,216**

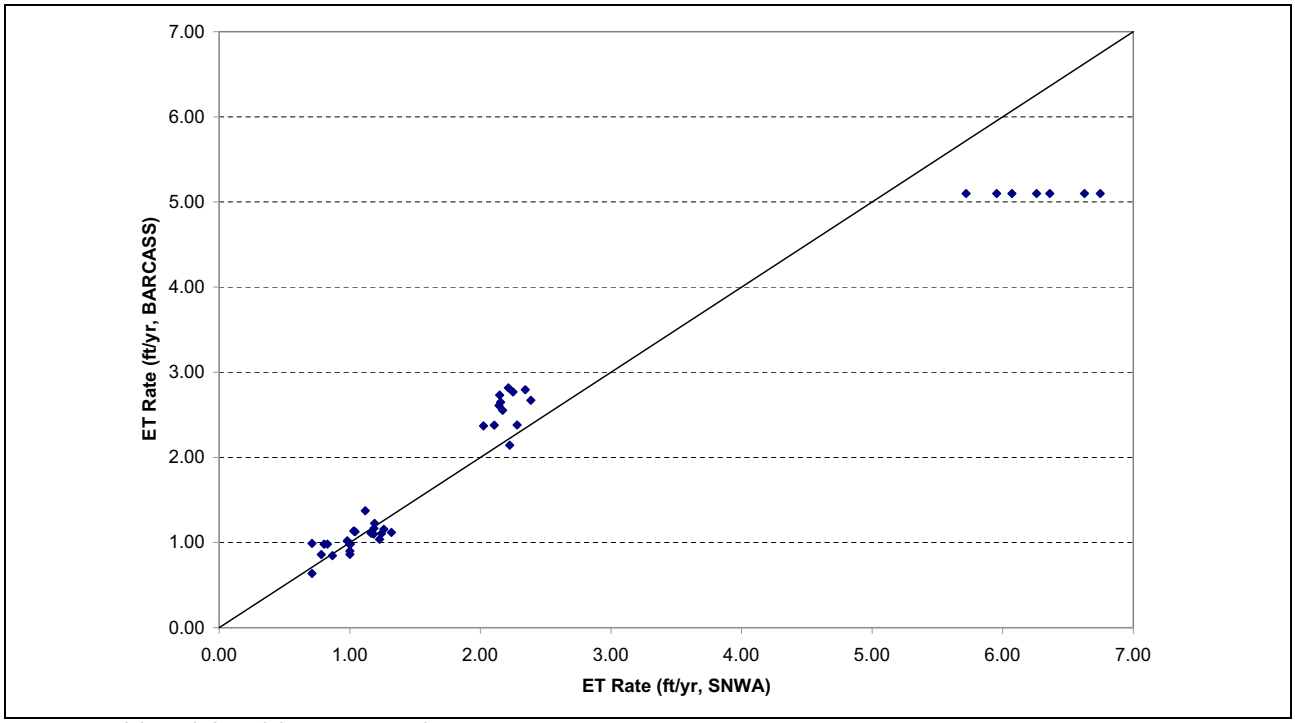
Table F-3
Groundwater ET Areas and Volumes Using Combined Method 1 and Method 2 (BARCASS) Data Set
(Page 5 of 6)

HA Number	HA Name	Sub-Area Number	ET Class Number	ET Class Name	Category 1 Groundwater ET Area (ac)	Category 1 Groundwater ET Volume (afy)	Category 2 Groundwater ET Area (ac)	Category 2 Groundwater ET Volume (afy)	Category 3 Groundwater ET Area (ac)	Category 3 Groundwater ET Volume (afy)	Total Groundwater ET Area (ac)	Total Groundwater ET Volume (afy)
205	Lower Meadow Valley Wash	5	1	Open Water	0	1	0	0	0	0	0	1
		5	2	Bare Soil/Low Vegetation	469	111	0	0	0	0	469	111
		5	3	Phreatophyte/Medium Vegetation	714	995	0	0	0	0	714	995
		5	4	Wetland/Meadow	1,360	1,899	0	0	0	0	1,360	1,899
				Subtotal	**2,543**	**3,006**	**0**	**0**	**0**	**0**	**2,543**	**3,006**
				205 Total	**7,815**	**9,668**	**0**	**0**	**0**	**0**	**7,815**	**9,668**
207	White River Valley	1	2	Bare Soil/Low Vegetation	14,564	3,043	134	28	0	0	14,698	3,071
		1	3	Phreatophyte/Medium Vegetation	79,383	27,705	2,228	778	99	35	81,710	28,518
		1	4	Wetland/Meadow	5,700	8,914	516	807	154	241	6,370	9,962
		1	6	Playa	77	7	0	0	0	0	77	7
				Subtotal	**99,724**	**39,669**	**2,878**	**1,613**	**253**	**276**	**102,855**	**41,558**
207	White River Valley	2	1	Open Water	685	2,967	0	0	0	0	685	2,967
		2	2	Bare Soil/Low Vegetation	30,226	6,488	0	0	4	1	30,230	6,489
		2	3	Phreatophyte/Medium Vegetation	37,999	12,967	0	0	822	280	38,821	13,247
		2	4	Wetland/Meadow	4,461	11,528	0	0	211	545	4,672	12,073
		2	6	Playa	907	112	0	0	0	0	907	112
				Subtotal	**74,279**	**34,062**	**0**	**0**	**1,037**	**826**	**75,315**	**34,888**
				207 Total	**174,003**	**73,731**	**2,878**	**1,613**	**1,290**	**1,102**	**178,170**	**76,446**
209	Pahranagat Valley	1	1	Open Water	384	2,693	0	0	0	0	384	2,693
		1	2	Bare Soil/Low Vegetation	97	33	0	0	0	0	97	33
		1	3	Phreatophyte/Medium Vegetation	262	689	0	0	0	0	262	689
		1	4	Wetland/Meadow	863	2,268	0	0	0	0	863	2,268
				Subtotal	**1,606**	**5,683**	**0**	**0**	**0**	**0**	**1,606**	**5,683**
209	Pahranagat Valley	2	2	Bare Soil/Low Vegetation	73	27	0	0	0	0	73	27
		2	3	Phreatophyte/Medium Vegetation	294	789	0	0	0	0	294	789
		2	4	Wetland/Meadow	2,934	7,885	0	0	0	0	2,934	7,885
				Subtotal	**3,301**	**8,701**	**0**	**0**	**0**	**0**	**3,301**	**8,701**
209	Pahranagat Valley	3	1	Open Water	464	3,302	0	0	0	0	464	3,302
		3	2	Bare Soil/Low Vegetation	37	16	0	0	0	0	37	16
		3	3	Phreatophyte/Medium Vegetation	87	239	0	0	0	0	87	239
		3	4	Wetland/Meadow	847	2,308	0	0	0	0	847	2,308
				Subtotal	**1,435**	**5,865**	**0**	**0**	**0**	**0**	**1,435**	**5,865**

Table F-3
Groundwater ET Areas and Volumes Using Combined Method 1 and Method 2 (BARCASS) Data Set
(Page 6 of 6)

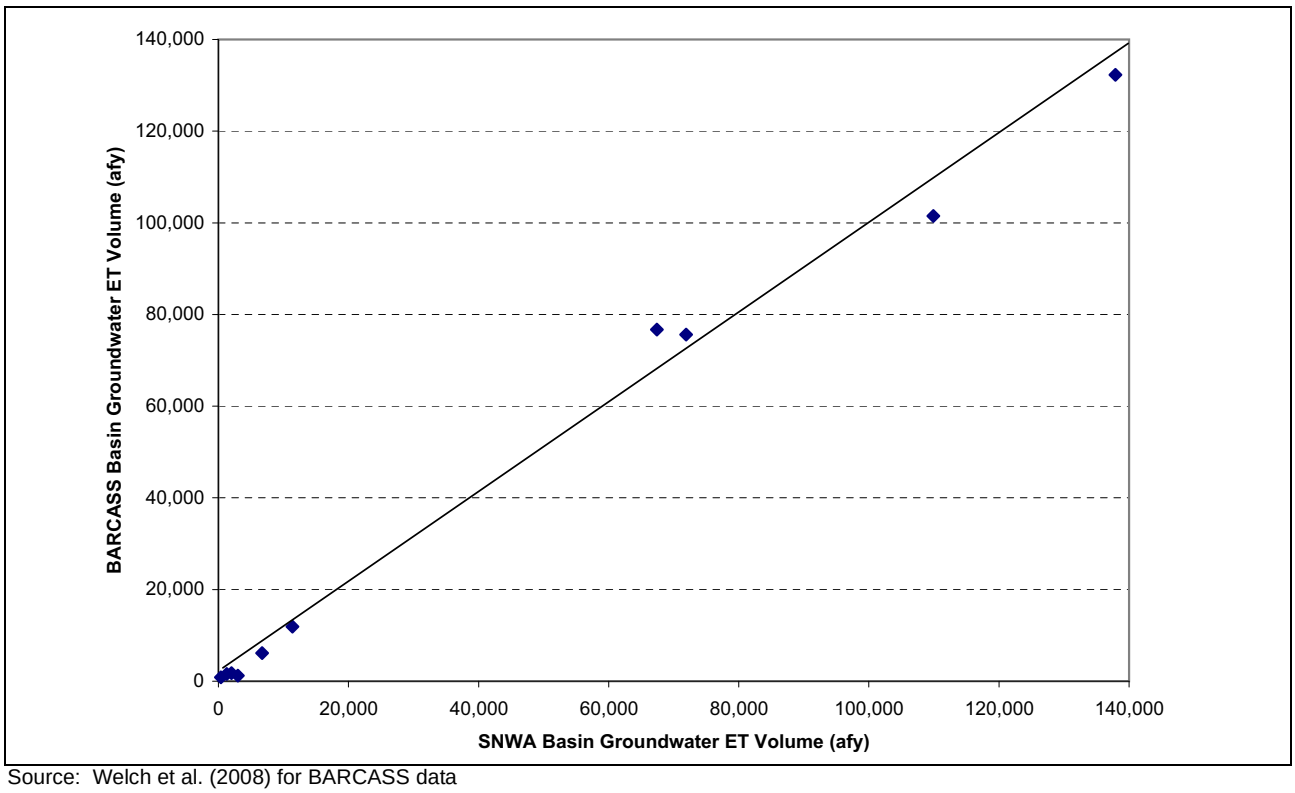
HA Number	HA Name	Sub-Area Number	ET Class Number	ET Class Name	Category 1 Groundwater ET Area (ac)	Category 1 Groundwater ET Volume (afy)	Category 2 Groundwater ET Area (ac)	Category 2 Groundwater ET Volume (afy)	Category 3 Groundwater ET Area (ac)	Category 3 Groundwater ET Volume (afy)	Total Groundwater ET Area (ac)	Total Groundwater ET Volume (afy)
209	Pahranagat Valley	4	1	Open Water	74	527	0	0	0	0	74	527
		4	2	Bare Soil/Low Vegetation	12	6	0	0	0	0	12	6
		4	3	Phreatophyte/Medium Vegetation	64	178	0	0	0	0	64	178
		4	4	Wetland/Meadow	900	2,492	0	0	0	0	900	2,492
				Subtotal	**1,050**	**3,203**	**0**	**0**	**0**	**0**	**1,050**	**3,203**
209	Pahranagat Valley	5	1	Open Water	375	2,686	0	0	0	0	375	2,686
		5	2	Bare Soil/Low Vegetation	41	20	0	0	0	0	41	20
		5	3	Phreatophyte/Medium Vegetation	108	301	0	0	0	0	108	301
		5	4	Wetland/Meadow	741	2,063	0	0	0	0	741	2,063
				Subtotal	**1,265**	**5,070**	**0**	**0**	**0**	**0**	**1,265**	**5,070**
				209 Total	**8,657**	**28,522**	**0**	**0**	**0**	**0**	**8,657**	**28,522**
215	Black Mountain Area	N	2	Bare Soil/Low Vegetation	54	30	0	0	0	0	54	30
		N	3	Phreatophyte/Medium Vegetation	244	835	0	0	0	0	244	835
		N	4	Wetland/Meadow	165	567	0	0	0	0	165	567
				215 Total	**463**	**1,432**	**0**	**0**	**0**	**0**	**463**	**1,432**
218	California Wash	N	2	Bare Soil/Low Vegetation	37	20	0	0	0	0	37	20
		N	3	Phreatophyte/Medium Vegetation	149	497	0	0	0	0	149	497
		N	4	Wetland/Meadow	1,194	3,988	0	0	0	0	1,194	3,988
				218 Total	**1,380**	**4,505**	**0**	**0**	**0**	**0**	**1,380**	**4,505**
219	Muddy River Springs Area	N	2	Bare Soil/Low Vegetation	166	89	0	0	0	0	166	89
		N	3	Phreatophyte/Medium Vegetation	214	706	0	0	0	0	214	706
		N	4	Wetland/Meadow	1,571	5,193	0	0	0	0	1,571	5,193
				219 Total	**1,951**	**5,988**	**0**	**0**	**0**	**0**	**1,951**	**5,988**
220	Lower Moapa Valley	N	1	Open Water	137	1,182	0	0	0	0	137	1,182
		N	2	Bare Soil/Low Vegetation	496	278	0	0	0	0	496	278
		N	3	Phreatophyte/Medium Vegetation	907	3,132	0	0	0	0	907	3,132
		N	4	Wetland/Meadow	5,993	20,719	0	0	0	0	5,993	20,719
				220 Total	**7,533**	**25,311**	**0**	**0**	**0**	**0**	**7,533**	**25,311**

N = Not defined



Source: Welch et al. (2008) for BARCASS data

Figure F-1
Comparison between ET Rates Derived by Methods 1 and 2 (BARCASS)



Source: Welch et al. (2008) for BARCASS data

Figure F-2
Comparison between SNWA and BARCASS ET Volumes

F.1.2 Stochastic Estimates of Groundwater ET

Stochastic estimates of groundwater ET were derived for the study area using the consistent groundwater ET data set described in the previous section. The magnitude of the uncertainty in the calculated annual volumes of groundwater ET was estimated using Monte Carlo simulations implemented in the Crystal Ball software. Considering that the groundwater ET volume of each ET class was calculated as its area times the appropriate ET rate less the precipitation volume on the area, the uncertainty on the volumes of groundwater ET is due to the uncertainty in these three input parameters. The uncertainty in the input parameters used in the analysis and the detailed results are described here.

F.1.2.1 Uncertainty of Input Parameters

The Monte Carlo analysis requires estimates of the uncertainty on each of the three variables: potential ET area, ET rate, and precipitation rate. All three variables are assumed to be normally distributed. The ET rate is, however, dependent on the precipitation rate, as total ET is the sum of groundwater ET and precipitation. Therefore, these two variables are correlated. The information supporting the uncertainty estimated for each input variable (ET class area, precipitation rate, and ET rate) is described in the following text.

F.1.2.1.1 ET Class Areas

The potential groundwater ET areas needed are those reflecting predevelopment conditions. However, no records of these areas exist prior to the Reconnaissance Series. Thus, it was assumed that mean groundwater areas derived from previous studies and satellite imagery and modified to remove the agricultural areas would provide an approximate ET map representative of predevelopment conditions. Although this was determined to be the best approach, it has many limitations. Limitations relating to the creation of the current-condition and predevelopment groundwater ET maps are as follows:

- Ground truthing of areas of ET within the study area was conducted during the summer of 2004; however, the classification of the ET areas was determined from 2002 Landsat imagery. It is possible that vegetation communities and boundaries could change, especially because of drought, in a 2-year span; however, such changes are assumed to be minimal.

- Landsat scenes, with minimal cloud cover, within the months of June and July were chosen in order to represent maximum plant growth during the height of the growing season. Therefore, only one day in the life of the plants was used to support the development of the current-condition map. Thus, the NDVI analysis used in determining the land-classification scheme also represents a single day.

- A major limitation in creating the predevelopment map is the lack of historical imagery. Because historical imagery is nonexistent, creation of a predevelopment groundwater ET map representing steady-state conditions includes some subjective interpretations.

The uncertainty on the ET class areas was estimated using previous estimates of the coefficient of variability (COV) by others (Zhu et al., 2007), differences in the estimates derived by this study and by other investigators, and the classification accuracy conducted by SNWA as a guide. In the Monte Carlo analysis conducted by DRI for BARCASS (Zhu et al., 2007), a COV of 10 percent was used for all ET units identified. Comparisons of previously reported extents of groundwater ET classes show that those of Open Water, Playa, Wetland/Meadow, and Medium Vegetation areas are more comparable than those of Bare Soil/Low Vegetation. This is well illustrated by the example of White River Valley. Estimates of the groundwater ET area made by previous investigators for White River Valley (Maxey and Eakin, 1949; Welch et al., 2008, and this study) vary by more than 100 percent. The results of the classification accuracy conducted by SNWA are provided in Table F-4. The reported accuracy provides a first estimate of the relative error (1-reported accuracy). An estimate of the COV may be obtained by dividing the relative error by 2. These crude estimates of the COV serve as a guide to deriving the final estimates of the COVs using the other available information. The COVs in Table F-4 indicate that the estimated COV for Open Water (ET Class 1) should be the lowest, the COVs for ET Classes 3, 4, and 5 should be about the same and slightly larger than for ET Class 1. The COV for ET Class 2 (Bare Soil/Low Vegetation) is the largest and should be at least twice as large as for the more densely vegetated areas.

Table F-4
Reported Accuracy and Relative Errors on ET Classification

ET Class Number	ET Class	Reported Accuracy	Relative Error	Estimated COV
1	Open Water	0.92	0.08	0.04
2	Bare Soil/Low Vegetation	0.78	0.22	0.11
3	Phreatophyte/Medium Vegetation	0.89	0.11	0.06
4	Wetland/Meadow	0.90	0.10	0.05
5	Agriculture	0.88	0.12	0.06

Note: COV is coefficient of variability

Coefficients of variability used for the ET classes are as follows:

- Wetland/Meadow and Medium Vegetation ET classes: The COV is 0.1 based on averages used by previous investigators and the accuracy assessment conducted by SNWA (Table F-3 and Table F-4).

- Open Water and Playa ET classes: These two classes are the most accurate and were assigned a COV of 0.05 based on the results of the classification accuracy results (Table F-4) and the fact that these two classes are easier to delineate.

- Bare Soil/Low Vegetation: This ET class has the largest uncertainty, as indicated by the classification accuracy results (Table F-4). However, the accuracy results do not provide an estimate of the full range of uncertainty. Furthermore, for this ET class, the uncertainty of the area increases with the size of the area. A COV of 0.5 was assumed for the largest areas (White River, Snake, Steptoe, and Spring valleys). A smaller COV of 0.25 was assigned to the areas of this type located in other basins.

F.1.2.1.2 Precipitation Rates

The uncertainty on the precipitation rates used in the calculations of the groundwater ET was treated differently for the northern basins (Method 2-BARCASS) than for the southern basins (Method 1).

For the northern basins, the COVs derived for BARCASS (Welch et al., 2008) were used to represent the uncertainties associated with the mean values. This was appropriate because the mean precipitation rates used in the groundwater ET calculations are based on a different version of the PRISM grid (modified 4-km grid).

For the southern basins, the COVs were estimated using two main types of uncertainty that affect the precipitation rates: temporal and spatial. The temporal uncertainty stems from the use of 30 years of data (PRISM normal) to represent long-term mean precipitation rates. The temporal uncertainty was estimated from statistics, conducted on yearly station data over the period of record, for a station located within or near the relevant basin. If two or more stations were used for a given basin, a single COV was derived from the data by averaging the yearly data by year for all stations and then deriving the statistics. If no stations were present within the basin, the COV calculated using all the station data was assigned to the ET units within that basin. The spatial uncertainty stems from averaging the precipitation values spatially over a given ET area to obtain a mean value. The spatial uncertainty was derived from statistics conducted on the grid values falling within each ET class. The temporal and spatial uncertainties were combined to produce an estimate of the total uncertainty represented by an overall COV.

F.1.2.1.3 ET Rates

The detailed estimates of ET rates for the five combined ET classes and their correlation to precipitation are presented in this section. The observed ET rates and associated data compiled from the literature were classified by ET class and are listed in Table F-5. ET data for each ET class were then adjusted by the PET ratio to represent each of the ET classes within each sub-area of each basin.

A statistical analysis was conducted on the ET rate data to derive descriptive statistics for each ET class within each sub-area of each basin. Because of the limited number of data points in each class, the type of probability distributions cannot be clearly identified. As a simplification, the probability distributions were assumed to be normal. A COV was then derived from the mean and standard deviations of each class in each sub-area of each basin.

The correlation coefficient between the total ET and precipitation varies between 0 and 1. For areas where all ET is from the saturated zone, the correlation coefficient should be 0 (ET Class 1). Such is the case for open-water evaporation, assuming that the source of the open water is groundwater. For ET areas where all ET is from precipitation, the correlation coefficient is equal to 1. Such is the case for areas where the depth to water is greater than the maximum extinction depths of phreatophytes.

Table F-5
Reported ET Rates by ET Class
(Page 1 of 4)

ET Unit Description	UTM Northing (m)	UTM Easting (m)	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Source
Bare Soil/Low Vegetation						
Greasewood	4,381,357	338,222	25 to 30	0.59	0.49 to 0.66	Carman (1993)
Saltgrass (sparse to very sparse)	4,031,528	557,768	---	0.62	0.21 to 0.35	Laczniak et al. (1999)[a]
Sagebrush and rabbitbrush (moderate)	4,436,956	624,967	>80	0.99	0.65	Berger et al. (2001)[b]
Rabbitbrush and wolfberry (sparse)	4,101,973	527,189	5 to 20	0.62	0.50	Reiner et al. (2002)[c]
Saltgrass, pickleweed, and shrub mesquite (low density)	4,015,751	510,177	5 to 20	0.60	0.06	DeMeo et al. (2003)
Rabbitbrush scrub	4,136,441	380,459	>16	0.31	0.11	Harrington & Steinwand (2003, 2004)
Desert sink scrub	4,125,767	381,903	>13	0.49 to 0.80	0.10	
Nevada saltbush scrub	4,132,231	379,956	13 to 14	0.59	0.35	
Nevada saltbush meadow	4,131,124	379,763	6.9 to 7.9	0.71 to 1.06	0.10 to 0.30	
Barren (≤10% vegetation)	3,894,274	721,586	---	1.66	0.16[d]	BOR (1997-2007)[d]
Barren	3,853,458	723,745	---	0.96	0.03	Westenburg et al. (2006b)
Barren	3,853,458	723,745	---	0.87	0.43	
Barren	3,853,458	723,745	---	0.88	0.57	
Desert shrubland; greasewood (moderate)	4,336,424	753,927	17.16	0.836	0.52	Moreo et al. (2007)
Desert shrubland; greasewood and rabbitbrush (sparse)	4,295,186	719,949	9.78	0.835	0.72	
Desert shrubland; greasewood and rabbitbrush (moderate)	4,296,079	720,099	7.24	1.01	0.76	
Mixed shrubland (low density)	4,294,919	719,920	15.20	0.79	0.51	SNWA Project data
Mixed shrubland (low density)	4,294,919	719,920	15.32	0.62	0.42	
Greasewood, rabbitbrush, and shadscale (moderate)	4,375,912	715,857	17.38	0.80	0.27	
Monotypic stand of greasewood (moderate)	4,325,090	754,601	30.47	0.64	0.16	
Phreatophyte/Medium Vegetation						
Saltgrass and greasewood	4,107,584	388,935	8 to 9	1.26	0.52	Duell (1990)
Alkali meadow; sacaton and thistle	4,140,145	377,591	10 to 15	2.71	0.49[e]	
Saltgrass, sacaton, and rabbitbrush	4,093,688	390,978	7 to 9	2.05	0.39[e]	
Nevada saltbush, sacaton, and rabbitbrush	4,077,998	394,522	5 to 7	2.69	0.33[e]	
Rabbitbrush, sacaton, and ephedra	4,123,439	381,782	10 to 11	1.99	0.51[e]	
Saltgrass, rabbitbrush, sacaton, and greasewood	4,130,915	378,873	10 to 11	1.55	0.49	
Rabbitbrush	4,355,737	456,918	10 to 15	1.05	0.66 to 0.98	Carman (1993)
Saltgrass (sparse)	4,025,243	562,370	---	1.88	0.21 to 0.35	Laczniak et al. (1999)[a]
Saltgrass (sparse to moderate)	4,037,549	559,594	---	1.92	0.21 to 0.35	

Table F-5
Reported ET Rates by ET Class
(Page 2 of 4)

ET Unit Description	UTM Northing (m)	UTM Easting (m)	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Source
Saltgrass, rabbitbrush, wildrye, and greasewood (moderate)	4,447,894	631,577	<5	1.33	0.65	Berger et al. (2001)[b]
Saltgrass, rabbitbrush, wildrye, and greasewood (moderate)	4,447,801	631,532	<5	1.32	0.65	
Rabbitbrush, wildrye, greasewood, and sagebrush (moderate)	4,461,364	634,578	5	1.33	0.65	
Rabbitbrush, wildrye, greasewood, and sagebrush (moderate)	4,444,761	632,318	10	1.33	0.65	
Greasewood, rabbitbrush, wildrye, sagebrush (sparse to moderate)	4,447,817	632,478	17	1.33	0.65	
Primarily greasewood (moderate to dense)	4,099,904	525,961	5 to 20	1.38	0.50	Reiner et al. (2002)[c]
Saltgrass (sparse to moderate)	4,100,119	525,664	few to 10	1.63	0.50	
Wire and saltgrass (sparse to moderate)	4,096,110	524,613	few to 10	2.49	0.50	
Grasses, arrowweed, mesquite, and pickleweed (moderate)	4,005,708	511,887	2 to 20	2.0	0.23	DeMeo et al. (2003)
Rabbitbrush meadow	4,093,461	391,331	8.5 to 11	1.68	0.23	Harrington & Steinwand (2003, 2004)
Desert vegetation	3,894,274	721,586	---	1.34	0.16[d]	BOR (1997-2007)[d]
Rush and saltgrass	4,211,928	1,500,833	3.0	1.34	0.60	Cooper et al. (2006)
Greasewood and rabbitbrush	4,211,928	1,500,833	8.2	0.91	0.63	
Saltgrass, grass, yerba mansa, arrowweed, desert baccharis, and mesquite	4,096,966	465,743	0 to 15	2.28 to 2.68	0.05 to 0.49	Laczniak et al. (2006)
Rabbitbrush and greasewood	4,323,822	257,119	3 to 5	1.9	0.66[f]	Maurer et al. (2006)
Bitterbrush and sage	4,310,759	254,378	60	1.5	0.66[f]	
Arrowweed (low to medium density)	3,853,458	723,745	8	2.87	0.03	Westenburg et al. (2006b)
Arrowweed (low to medium density)	3,853,458	723,745	8	2.65	0.43	
Arrowweed (low to medium density)	3,853,458	723,745	8	2.71	0.57	
Mixed vegetation (medium density)	3,850,483	726,385	4 to 8	2.85	0.03	
Mixed vegetation (medium density)	3,850,483	726,385	4 to 8	2.61	0.43	
Mixed vegetation (medium density)	3,850,483	726,385	4 to 8	2.63	0.57	
Desert shrubland; greasewood (dense)	4,253,549	670,158	32.39	1.06	0.74	Moreo et al. (2007)
Desert shrubland; greasewood (moderate)	4,278,646	665,098	23.58	1.02	0.95	
Mixed shrubland (moderate)	4,277,445	665,017	18.95	1.38	0.87	SNWA Project data
Mixed shrubland (moderate)	4,277,445	665,017	18.85	0.68	0.45	
Monotypic stand of greasewood (high density)	4,287,266	753,182	19.31	1.65	0.37	

Table F-5
Reported ET Rates by ET Class
(Page 3 of 4)

ET Unit Description	UTM Northing (m)	UTM Easting (m)	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Source
Playa						
Playa, often salt covered	4,434,212	764,573	0 to 1	0.75	0.42	Malek et al. (1990)
Playa; sparse seepweed, greasewood, and saltgrass	---	---	<10	1.2 to 1.3	<0.16	Czarnecki (1997)
Bunch grass (very sparse)	4,029,199	559,627	---	2.58	0.21 to 0.35	Laczniak et al. (1999)[a]
Bunch grass (sparse to very sparse)	4,025,676	562,516	---	2.60	0.21 to 0.35	
Bare soil playa	4,437,735	627,276	---	0.80	0.65	Berger et al. (2001)[b]
Salt-encrusted playa	4,009,234	519,297	≤5	0.17 to 0.39	0.04 to 0.28	DeMeo et al. (2003)
Bare soil playa	4,007,757	520,249	≤10	0.21 to 0.37	0.06 to 0.35	
Wetland/Meadow						
Saltgrass, sacaton, and rush	4,071,453	394,441	≤4	3.24	0.26	Duell (1990)
Mixed grasses, clover, and scattered shrubs (dense)	4,030,891	559,192	---	3.44	0.21 to 0.35	Laczniak et al. (1999)[a]
Meadow; mixed sedges, rushes, and grasses (dense)	4,437,444	626,476	<2	3.19	0.65	Berger et al. (2001)[b]
Grasslands	4,437,444	626,476	---	2.36	0.65	
Saltgrass (dense), surface periodically floods	4,037,732	559,269	---	3.07[i]	0.21 to 0.35	Reiner et al. (2002)[c]
Meadow and marsh grass (dense)	4,097,156	523,993	0 to 20	3.14	0.50	
Sacaton, saltgrass, and wildrye	4,084,272	389,787	6.6 to 11	1.37 to 2.25	0.11 to 0.99	Harrington & Steinwand (2003, 2004)
Grasses and mesquites (high density)	4,066,686	487,824	≤20	2.9	0.16	DeMeo et al. (2003)
Mixed grasses/meadow	4,312,948	723,534	3.89	2.25	0.66	Moreo et al. (2007)
Irrigated pasture; perennial grasses (dense)	4,360,829	716,743	---	3.56	0.35	SNWA Project data
Open water						
Open water body; submerged aquatic vegetation	4,033,564	558,128	---	8.6	0.21 to 0.35	Laczniak et al. (1999)[a]
Open water body; submerged aquatic vegetation	4,437,735	627,276	---	5.31	0.65	Berger et al. (2001)[b]
Lake Mead; Water Barge Cove	4,000,515	704,576	---	7.0	0.28 to 0.34[h]	Westenburg et al. (2006a)
Lake Mead; Sentinel Island	3,992,296	702,539	---	7.5	0.28 to 0.34[h]	
Lake Mead; Virgin Basin	3,997,837	728,438	---	7.6	0.28 to 0.34[h]	
Lake Mead; Overton Arm	4,021,370	735,435	---	6.8	0.28 to 0.34[h]	
Riparian						
Riparian; mostly tamarix	4,051,962	738,583	---	2.5 to 4.8	0.35[g]	Devitt et al. (1998)
Cattails and reeds (dense)	4,037,793	559,173	---	3.91	0.21 to 0.35	Laczniak et al. (1999)[a]
Wiregrass and salt grass (sparse to moderate)	4,037,613	559,842	---	3.23	0.21 to 0.35	

Table F-5
Reported ET Rates by ET Class
(Page 4 of 4)

ET Unit Description	UTM Northing (m)	UTM Easting (m)	Depth to Water (ft bgs)	Total ET (ft/yr)	Precipitation (ft/yr)	Source
Moderate to dense bulrush and cattails	4,453,980	630,360	1 to 3	4.19	0.65	Berger et al. (2001)[b]
Grasses and mesquites (high density)	4,065,886	487,005	≤20	3.9	0.25	DeMeo et al. (2003)
Saltcedar (high density)	3,854,463	725,587	8	3.80	0.03	Westenburg et al. (2006b)
Saltcedar (high density)	3,854,463	725,587	8	3.56	0.43	
Saltcedar (high density)	3,854,463	725,587	8	3.59	0.57	
Seasonal wetland (flooded in winter and not irrigated in summer)	3,894,274	721,586	---	3.65	0.16[d]	BOR (1997-2007)[d]
Screwbean and honey mesquite (11% to 60%) and arrowweed (≤25%)	3,894,274	721,586	---	3.99	0.16[d]	
Low Vegetation - phreatophyte vegetation (>10% to ≤30%)	3,894,274	721,586	---	4.29	0.16[d]	
Saltcedar (11% to 60%) and arrowweed (≤25%)	3,894,274	721,586	---	4.36	0.16[d]	
Arrowweed (51% to 100%) and trees (≤10%)	3,894,274	721,586	---	4.69	0.16[d]	
Mesquite (21% to 60%), arrowweed (31% to 60%), and saltcedar (≤20%)	3,894,274	721,586	---	4.76	0.16[d]	
Cottonwood and willow trees (61% to 100%)	3,894,274	721,586	---	4.96	0.16[d]	
Screwbean and honey mesquite (61% to 100%), arrowweed (≤25%)	3,894,274	721,586	---	4.99	0.16[d]	
Moist soil unit (flooded in winter and irrigated in summer)	3,894,274	721,586	---	5.03	0.16[d]	
Saltcedar (61 to 100%), arrowweed (≤25%)	3,894,274	721,586	---	5.12	0.16[d]	
Saltcedar (≤75%), arrowweed (≥25%)	3,894,274	721,586	---	5.29	0.16[d]	
Saltcedar (15 to 45%), mesquite (15 to 45%), arrowweed (20 to 40%)	3,894,274	721,586	---	5.43	0.16[d]	
Saltcedar (11 to 60%), mesquite (11 to 60%), arrowweed (≤25%)	3,894,274	721,586	---	5.45	0.16[d]	
Marsh, cattail, bullrush, phragmites (bamboo)	3,894,274	721,586	---	5.93	0.16[d]	

[a]Evapotranspiration measured at an individual site (Laczniak et al., 1999).
[b]Rates for growing season only (or less).
[c]Evapotranspiration measured at an individual site (Reiner et al., 2002).
[d]Precipitation data are for the Mohave station (BOR, 2007) and ET data are averaged for 1995 to 2005 (BOR, 1997; 1998; 1999; 2000a and b; 2001; 2002; 2004a and b; 2005; and 2007).
[e]Estimated as the average of the precipitation reported for the two nearest sites (Duell, 1990).
[f]Precipitation reported for the test hole that is nearest to the evapotranspiration stations, CL-1 (Maurer, et al., 2006).
[g]Estimated as the average precipitation reported for 1994 to 1996 for the Overton, Nevada, station (WRCC, 2008).
[h]Average annual precipitation (1961 to 1990) measured at McCarran Airport, Las Vegas, Nevada (0.34 ft), and Overton, Nevada (0.28), from DRI (Westenburg et al., 2006a).
[i]Data reported from Reiner et al. (2002); data set for this site was more complete than that reported by Laczniak et al. (1999).

For the three phreatophyte ET classes, the correlation of ET rates with precipitation rates was interpreted using the ET site data collected by SNWA. Monthly ET site data, including the ET and precipitation rates, were compiled (Table F-6). The site data were then grouped by ET class, and correlation coefficients were derived for the three ET classes represented by the data, i.e., Wetland/Meadow, Phreatophyte/Medium Vegetation and Bare Soil/Low Vegetation. The correlation coefficient derived for the Wetland/Meadow ET class is 0.2. The correlation coefficients calculated for the Phreatophyte/Medium Vegetation and Bare Soil/Low Vegetation, 0.57 and 0.54 respectively, were very similar and reversed, i.e., the Phreatophyte/Medium Vegetation ET rates should have a lower correlation to precipitation than the Bare Soil/Low Vegetation ET rates. Based on this observation, the four stations used to derive the two correlations (SV3, WRV2, SNV2, SV1) were combined to derive a single correlation. The resulting correlation coefficient is about 0.6 and was assumed to represent the Bare Soil/Low Vegetation ET class. The correlation coefficient for the Phreatophyte/Medium Vegetation ET class must be greater than 0.2 and less than 0.6. The middle of this interval, 0.4, was selected.

ET from wet playas generally consists of evaporation only and, given the same climatological conditions, it is highly variable depending on the depth to water. Therefore, the correlation coefficient is also variable depending on the depth to water. An average correlation coefficient of 0.5 was selected to accommodate all wet playas in the study area. The resulting correlation coefficients are presented in Table F-7.

F.1.2.2 Detailed Input Data

The uncertainty information for each input variable was estimated and is presented in Table F-8. Ten thousand (10,000) realizations were made using the random number method (seed = 999) and the input parameters listed in Table F-8.

Table F-6
Monthly ET Site Data Used to Estimate Correlation Coefficients between ET and Precipitation Rates

		SV2B		SNV1		SV3		WRV2		SNV2		SV1	
		Wetland/Meadow				Phreatophyte/ Medium Vegetation				Bare Soil/Low Vegetation			
Year	Month	ETA	P	ETA	P	ETA	P	ETA	P	ETA	P	ETA	P
2005	January	NA	NA	NA	NA	NA	NA	0.075	0.185	NA	NA	NA	NA
2005	February	NA	NA	NA	NA	NA	NA	0.130	0.129	NA	NA	NA	NA
2005	March	NA	NA	NA	NA	NA	NA	0.178	0.130	NA	NA	NA	NA
2005	April	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2005	May	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2005	June	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2005	July	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2005	August	NA	NA	NA	NA	NA	NA	0.148	0.042	NA	NA	NA	NA
2005	September	NA	NA	NA	NA	NA	NA	0.184	0.057	NA	NA	NA	NA
2005	October	NA	NA	NA	NA	NA	NA	0.081	0.065	NA	NA	NA	NA
2005	November	NA	NA	NA	NA	NA	NA	0.042	0.025	NA	NA	NA	NA
2005	December	NA	NA	NA	NA	NA	NA	0.031	0.018	NA	NA	NA	NA
2006	January	NA	NA	NA	NA	NA	NA	0.036	0.068	NA	NA	0.031	0.034
2006	February	NA	NA	NA	NA	NA	NA	0.040	0.081	NA	NA	0.044	0.046
2006	March	NA	NA	NA	NA	NA	NA	0.195	0.145	NA	NA	0.115	0.093
2006	April	NA	NA	NA	NA	NA	NA	0.227	0.111	NA	NA	0.094	0.070
2006	May	NA	NA	NA	NA	NA	NA	0.181	0.004	NA	NA	0.070	0.005
2006	June	NA	NA	NA	NA	NA	NA	0.115	0.043	NA	NA	0.079	0.015
2006	July	NA	NA	NA	NA	NA	NA	0.250	0.190	NA	NA	0.142	0.141
2006	August	NA	NA	NA	NA	NA	NA	0.111	0.002	NA	NA	0.087	0.001
2006	September	NA	NA	NA	NA	NA	NA	0.127	0.128	NA	NA	0.055	0.024
2006	October	NA	NA	NA	NA	NA	NA	0.036	0.081	NA	NA	0.039	0.073
2006	November	NA	NA	NA	NA	NA	NA	0.034	0.003	NA	NA	0.013	0.002
2006	December	NA	NA	NA	NA	NA	NA	0.036	0.015	NA	NA	0.020	0.008
2007	January	NA	NA	NA	NA	NA	NA	0.036	0.008	NA	NA	0.036	0.000
2007	February	NA	NA	NA	NA	NA	NA	0.041	0.038	NA	NA	0.038	0.074
2007	March	NA	NA	NA	NA	NA	NA	0.042	0.035	NA	NA	0.058	0.056
2007	April	0.216	0.019	NA	NA	0.048	0.012	0.079	0.063	NA	NA	0.070	0.041
2007	May	0.524	0.021	0.229	0.008	0.086	0.021	0.064	0.001	0.081	0.009	0.068	0.002
2007	June	0.673	0.002	0.262	0.005	0.119	0.000	0.073	0.023	0.077	0.001	0.059	0.002
2007	July	0.595	0.071	0.291	0.040	0.141	0.044	0.060	0.026	0.106	0.025	0.078	0.026
2007	August	0.560	0.051	0.257	0.075	0.141	0.058	0.151	0.137	0.074	0.013	0.100	0.083
2007	September	0.456	0.053	0.136	0.076	0.078	0.033	0.083	0.096	0.068	0.043	0.065	0.090
2007	October	0.222	0.062	0.044	0.001	0.045	0.029	0.040	0.011	0.028	0.001	0.029	0.003
2007	November	0.084	0.006	0.016	0.013	0.012	0.002	0.013	0.000	0.010	0.001	0.015	0.005

NA = Not Available

Table F-7
Correlation Coefficients for ET Rate and Precipitation

ET Class	Correlation Coefficient for Precipitation and ET Rate
Open Water	0.00
Bare Soil/Low Vegetation	0.60
Phreatophyte/Medium Vegetation	0.40
Wetland/Meadow	0.20
Playa/Moisture Soil	0.50

Table F-8
Groundwater ET Uncertainty Analysis - Monte Carlo Input Parameter Data
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HA Sub-Area	HA Name	ET Class	ET Rate			Precipitation Rate				ET - P Correlation Coefficient	Groundwater ET Area		
			Mean (ft/yr) (area weighted)	COV (-)	STD (ft/yr)	(ft/yr) (area weighted)	Spatial COV	Temporal COV	STD (ft/yr)		(acre)	COV (-)	STD (acre)
172-N	Garden Valley	Bare Soil/Low Vegetation	1.00	0.41	0.41	0.92	0.04	0.34	0.31	0.60	21	0.25	5
		Phreatophyte/Medium Vegetation	2.82	0.26	0.73	0.94	0.06	0.34	0.32	0.40	552	0.10	55
		Wetland/Meadow	2.82	0.24	0.67	1.07	0.13	0.34	0.39	0.20	377	0.10	38
174-N	Jakes Valley	Open Water	5.10	0.01	0.05	0.96	0.10	0.36	0.36	0.00	26	0.05	1
		Bare Soil/Low Vegetation	0.98	0.15	0.15	0.96	0.10	0.36	0.36	0.60	6	0.25	1
		Phreatophyte/Medium Vegetation	1.37	0.14	0.19	0.96	0.10	0.36	0.36	0.40	930	0.10	93
		Wetland/Meadow	2.37	0.11	0.26	0.96	0.10	0.36	0.36	0.20	263	0.10	26
175-N	Long Valley	Bare Soil/Low Vegetation	0.98	0.15	0.15	0.94	0.02	0.36	0.34	0.60	4,903	0.25	1,226
		Phreatophyte/Medium Vegetation	1.10	0.18	0.20	0.94	0.02	0.36	0.34	0.40	13,379	0.10	1,338
		Wetland/Meadow	2.61	0.09	0.24	0.94	0.02	0.36	0.34	0.20	9	0.10	1
179-1	Steptoe Valley	Open Water	5.10	0.01	0.05	0.77	0.14	0.28	0.24	0.00	121	0.05	6
		Bare Soil/Low Vegetation	0.86	0.17	0.15	0.68	0.12	0.28	0.20	0.60	29,691	0.50	14,846
		Phreatophyte/Medium Vegetation	1.16	0.17	0.20	0.69	0.12	0.28	0.21	0.40	115,946	0.10	11,595
		Wetland/Meadow	2.75	0.09	0.24	0.73	0.13	0.28	0.23	0.20	14,576	0.10	1,458
		Playa	0.92	0.14	0.13	0.67	0.11	0.28	0.20	0.50	2,723	0.05	136
179-2	Steptoe Valley	Open Water	5.10	0.01	0.05	0.92	0.10	0.28	0.27	0.00	319	0.05	16
		Bare Soil/Low Vegetation	0.88	0.17	0.15	0.80	0.13	0.28	0.25	0.60	416	0.50	208
		Phreatophyte/Medium Vegetation	1.26	0.16	0.20	0.83	0.12	0.28	0.25	0.40	7,026	0.10	703
		Wetland/Meadow	2.66	0.10	0.26	0.81	0.13	0.28	0.25	0.20	3,797	0.10	380
180-N	Cave Valley	Bare Soil/Low Vegetation	0.98	0.15	0.15	1.08	0.09	0.36	0.41	0.60	3,554	0.25	888
		Phreatophyte/Medium Vegetation	1.14	0.18	0.20	1.08	0.09	0.36	0.41	0.40	8,739	0.10	874
		Wetland/Meadow	2.55	0.10	0.26	1.11	0.02	0.36	0.40	0.20	867	0.10	87
		Playa	0.75	0.08	0.06	1.08	0.09	0.36	0.41	0.50	194	0.05	10
183-N	Lake Valley	Open Water	5.10	0.01	0.05	0.99	0.07	0.43	0.43	0.00	26	0.05	1
		Bare Soil/Low Vegetation	0.98	0.15	0.15	0.99	0.07	0.43	0.43	0.60	16,303	0.25	4,076
		Phreatophyte/Medium Vegetation	1.02	0.17	0.17	0.99	0.07	0.43	0.43	0.40	36,478	0.10	3,648
		Wetland/Meadow	2.82	0.09	0.24	0.99	0.07	0.43	0.43	0.20	2,596	0.10	260
		Playa	1.00	0.13	0.13	0.99	0.07	0.43	0.43	0.50	94	0.05	5

Table F-8
Groundwater ET Uncertainty Analysis - Monte Carlo Input Parameter Data
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HA Sub-Area	HA Name	ET Class	ET Rate			Precipitation Rate				ET - P Correlation Coefficient	Groundwater ET Area		
			Mean (ft/yr) (area weighted)	COV (-)	STD (ft/yr)	(ft/yr) (area weighted)	Spatial COV	Temporal COV	STD (ft/yr)		(acre)	COV (-)	STD (acre)
184-1	Spring Valley	Bare Soil/Low Vegetation	0.88	0.17	0.15	0.71	0.05	0.24	0.17	0.60	364	0.50	182
		Phreatophyte/Medium Vegetation	1.17	0.17	0.20	0.74	0.04	0.24	0.18	0.40	2,546	0.10	255
		Wetland/Meadow	2.87	0.09	0.25	0.77	0.03	0.24	0.19	0.20	816	0.10	82
184-2	Spring Valley	Open Water	5.10	0.01	0.05	0.69	0.05	0.24	0.17	0.00	6	0.05	0
		Bare Soil/Low Vegetation	0.86	0.17	0.15	0.69	0.05	0.24	0.17	0.60	20,218	0.50	10,109
		Phreatophyte/Medium Vegetation	1.09	0.18	0.19	0.69	0.05	0.24	0.17	0.40	41,328	0.10	4,133
		Wetland/Meadow	2.74	0.09	0.25	0.69	0.05	0.24	0.17	0.20	6,370	0.10	637
		Playa	1.00	0.13	0.13	0.69	0.05	0.24	0.17	0.50	17,651	0.05	883
184-3	Spring Valley	Bare Soil/Low Vegetation	0.87	0.17	0.15	0.70	0.05	0.24	0.17	0.60	3,268	0.50	1,634
		Phreatophyte/Medium Vegetation	1.06	0.19	0.20	0.70	0.05	0.24	0.17	0.40	19,194	0.10	1,919
		Wetland/Meadow	2.28	0.12	0.27	0.71	0.05	0.24	0.17	0.20	319	0.10	32
		Playa	0.81	0.15	0.13	0.69	0.05	0.24	0.17	0.50	676	0.05	34
184-4	Spring Valley	Bare Soil/Low Vegetation	0.98	0.15	0.15	0.79	0.03	0.24	0.19	0.60	11,873	0.50	5,936
		Phreatophyte/Medium Vegetation	1.14	0.17	0.20	0.79	0.03	0.24	0.19	0.40	49,327	0.10	4,933
		Wetland/Meadow	2.84	0.09	0.24	0.79	0.03	0.24	0.19	0.20	3,288	0.10	329
		Playa	0.83	0.15	0.13	0.79	0.03	0.24	0.19	0.50	529	0.05	26
185-N	Tippett Valley	Bare Soil/Low Vegetation	0.98	0.15	0.15	0.80	0.02	0.36	0.29	0.60	1,624	0.25	406
		Phreatophyte/Medium Vegetation	1.04	0.19	0.20	0.80	0.02	0.36	0.29	0.40	5,585	0.10	559
		Wetland/Meadow	2.14	0.13	0.27	0.80	0.02	0.36	0.29	0.20	72	0.10	7
		Playa	0.81	0.15	0.13	0.80	0.02	0.36	0.29	0.50	497	0.05	25
194-2	Pleasant Valley	Bare Soil/Low Vegetation	0.86	0.17	0.15	0.55	0.06	0.00	0.03	0.60	118	0.25	30
		Phreatophyte/Medium Vegetation	1.22	0.14	0.18	0.55	0.06	0.00	0.03	0.40	759	0.10	76
		Wetland/Meadow	2.65	0.09	0.24	0.55	0.06	0.00	0.03	0.20	226	0.10	23
195-1	Snake Valley	Bare Soil/Low Vegetation	0.74	0.20	0.15	0.55	0.05	0.27	0.15	0.60	13,904	0.50	6,952
		Phreatophyte/Medium Vegetation	1.14	0.16	0.18	0.55	0.05	0.27	0.15	0.40	4,272	0.10	427
		Wetland/Meadow	2.85	0.08	0.24	0.55	0.05	0.27	0.15	0.20	1,266	0.10	127
		Playa	0.63	0.20	0.12	0.55	0.05	0.27	0.15	0.50	56,072	0.05	2,804

Table F-8
Groundwater ET Uncertainty Analysis - Monte Carlo Input Parameter Data
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HA Sub-Area	HA Name	ET Class	ET Rate			Precipitation Rate				ET - P Correlation Coefficient	Groundwater ET Area		
			Mean (ft/yr) (area weighted)	COV (-)	STD (ft/yr)	(ft/yr) (area weighted)	Spatial COV	Temporal COV	STD (ft/yr)		(acre)	COV (-)	STD (acre)
195-2	Snake Valley	Open Water	5.10	0.01	0.05	0.55	0.06	0.27	0.15	0.00	54	0.05	3
		Bare Soil/Low Vegetation	0.82	0.18	0.15	0.55	0.06	0.27	0.15	0.60	11,384	0.50	5,692
		Phreatophyte/Medium Vegetation	1.12	0.18	0.20	0.55	0.05	0.27	0.15	0.40	15,082	0.10	1,508
		Wetland/Meadow	2.77	0.08	0.23	0.55	0.06	0.27	0.15	0.20	1,440	0.10	144
		Playa	0.63	0.20	0.12	0.55	0.05	0.27	0.15	0.50	574	0.05	29
195-3	Snake Valley	Open Water	5.10	0.01	0.05	0.55	0.07	0.27	0.16	0.00	71	0.05	4
		Bare Soil/Low Vegetation	0.86	0.17	0.15	0.55	0.07	0.27	0.16	0.60	104,518	0.50	52,259
		Phreatophyte/Medium Vegetation	1.11	0.18	0.19	0.56	0.08	0.27	0.16	0.40	70,259	0.10	7,026
		Wetland/Meadow	2.52	0.10	0.26	0.56	0.08	0.27	0.16	0.20	5,120	0.10	512
		Playa	0.74	0.17	0.13	0.55	0.07	0.27	0.16	0.50	7,092	0.05	355
195-4	Snake Valley	Open Water	5.10	0.01	0.05	0.64	0.06	0.27	0.18	0.00	302	0.05	15
		Bare Soil/Low Vegetation	0.98	0.15	0.15	0.68	0.05	0.27	0.19	0.60	3,170	0.50	1,585
		Phreatophyte/Medium Vegetation	1.15	0.17	0.19	0.68	0.05	0.27	0.19	0.40	22,563	0.10	2,256
		Wetland/Meadow	2.80	0.09	0.25	0.68	0.05	0.27	0.19	0.20	3,126	0.10	313
196-4	Hamlin Valley	Bare Soil/Low Vegetation	0.98	0.15	0.15	0.68	0.05	0.00	0.03	0.60	102	0.25	25
		Phreatophyte/Medium Vegetation	1.15	0.17	0.20	0.68	0.05	0.00	0.03	0.40	4,043	0.10	404
		Wetland/Meadow	2.38	0.11	0.27	0.68	0.05	0.00	0.03	0.20	62	0.10	6
198-N	Dry Valley	Open Water	6.68	0.11	0.74	1.08	0.00	0.36	0.39	0.00	33	0.05	2
		Bare Soil/Low Vegetation	1.00	0.41	0.41	1.08	0.02	0.36	0.39	0.60	82	0.25	21
		Phreatophyte/Medium Vegetation	2.87	0.26	0.74	1.07	0.01	0.36	0.39	0.40	1,182	0.10	118
		Wetland/Meadow	2.87	0.24	0.68	1.07	0.01	0.36	0.39	0.20	771	0.10	77
199-N	Rose Valley	Bare Soil/Low Vegetation	1.00	0.41	0.41	1.12	0.00	0.36	0.41	0.60	0	0.25	0
		Phreatophyte/Medium Vegetation	2.83	0.26	0.73	1.10	0.01	0.36	0.40	0.40	89	0.10	9
		Wetland/Meadow	2.83	0.24	0.67	1.10	0.01	0.36	0.40	0.20	255	0.10	26
200-N	Eagle Valley	Bare Soil/Low Vegetation	1.00	0.41	0.41	1.14	0.02	0.36	0.41	0.60	3	0.25	1
		Phreatophyte/Medium Vegetation	2.79	0.26	0.72	1.14	0.02	0.36	0.42	0.40	154	0.10	15
		Wetland/Meadow	2.79	0.24	0.66	1.15	0.02	0.36	0.42	0.20	477	0.10	48

Table F-8
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HA Sub-Area	HA Name	ET Class	ET Rate			Precipitation Rate				ET - P Correlation Coefficient	Groundwater ET Area		
			Mean (ft/yr) (area weighted)	COV (-)	STD (ft/yr)	(ft/yr) (area weighted)	Spatial COV	Temporal COV	STD (ft/yr)		(acre)	COV (-)	STD (acre)
201-N	Spring Valley	Open Water	6.28	0.11	0.70	1.15	0.01	0.38	0.44	0.00	52	0.05	3
		Bare Soil/Low Vegetation	1.00	0.41	0.41	1.14	0.06	0.38	0.44	0.60	10	0.25	2
		Phreatophyte/Medium Vegetation	2.70	0.26	0.70	1.12	0.03	0.38	0.43	0.40	630	0.10	63
		Wetland/Meadow	2.70	0.24	0.64	1.10	0.05	0.38	0.42	0.20	1,657	0.10	166
202-N	Patterson Valley	Phreatophyte/Medium Vegetation	2.81	0.26	0.72	1.06	0.00	0.36	0.39	0.40	771	0.10	77
203-N	Panaca Valley	Bare Soil/Low Vegetation	1.00	0.41	0.41	0.86	0.05	0.36	0.32	0.60	343	0.25	86
		Phreatophyte/Medium Vegetation	3.03	0.26	0.78	0.88	0.05	0.36	0.32	0.40	3,537	0.10	354
		Wetland/Meadow	3.03	0.24	0.72	0.88	0.05	0.36	0.32	0.20	5,224	0.10	522
204-N	Clover Valley	Bare Soil/Low Vegetation	1.00	0.41	0.41	1.36	0.19	0.36	0.56	0.60	186	0.25	47
		Phreatophyte/Medium Vegetation	2.90	0.26	0.75	1.42	0.14	0.36	0.55	0.40	1,777	0.10	178
		Wetland/Meadow	2.90	0.24	0.69	1.21	0.19	0.36	0.50	0.20	1,547	0.10	155
205-1	Lower Meadow Valley Wash	Bare Soil/Low Vegetation	1.00	0.41	0.41	0.84	0.01	0.67	0.57	0.60	21	0.25	5
		Phreatophyte/Medium Vegetation	3.62	0.26	0.93	0.84	0.01	0.67	0.56	0.40	257	0.10	26
		Wetland/Meadow	3.62	0.24	0.86	0.85	0.03	0.67	0.57	0.20	797	0.10	80
205-2	Lower Meadow Valley Wash	Bare Soil/Low Vegetation	1.00	0.41	0.41	0.97	0.03	0.67	0.65	0.60	2	0.25	1
		Phreatophyte/Medium Vegetation	3.62	0.26	0.93	1.01	0.03	0.67	0.68	0.40	131	0.10	13
		Wetland/Meadow	3.62	0.24	0.86	1.05	0.07	0.67	0.71	0.20	710	0.10	71
205-3	Lower Meadow Valley Wash	Bare Soil/Low Vegetation	1.00	0.41	0.41	0.55	0.02	0.67	0.37	0.60	30	0.25	7
		Phreatophyte/Medium Vegetation	3.62	0.26	0.93	0.54	0.02	0.67	0.36	0.40	124	0.10	12
		Wetland/Meadow	3.62	0.24	0.86	0.68	0.28	0.67	0.50	0.20	2,322	0.10	232
205-4	Lower Meadow Valley Wash	Open Water	8.43	0.11	0.94	0.45	0.07	0.67	0.30	0.00	0	0.05	0
		Bare Soil/Low Vegetation	1.00	0.41	0.41	0.49	0.08	0.67	0.33	0.60	6	0.25	1
		Phreatophyte/Medium Vegetation	3.62	0.26	0.93	0.47	0.07	0.67	0.32	0.40	38	0.10	4
		Wetland/Meadow	3.62	0.24	0.86	0.47	0.07	0.67	0.32	0.20	834	0.10	83

Table F-8
Groundwater ET Uncertainty Analysis - Monte Carlo Input Parameter Data
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HA Sub-Area	HA Name	ET Class	ET Rate			Precipitation Rate				ET - P Correlation Coefficient	Groundwater ET Area		
			Mean (ft/yr) (area weighted)	COV (-)	STD (ft/yr)	(ft/yr) (area weighted)	Spatial COV	Temporal COV	STD (ft/yr)		(acre)	COV (-)	STD (acre)
205-5	Lower Meadow Valley Wash	Open Water	8.43	0.11	0.94	0.46	0.01	0.67	0.31	0.00	0	0.05	0
		Bare Soil/Low Vegetation	1.00	0.41	0.41	0.46	0.01	0.67	0.31	0.60	469	0.25	117
		Phreatophyte/Medium Vegetation	3.62	0.26	0.93	0.47	0.01	0.67	0.31	0.40	714	0.10	71
		Wetland/Meadow	3.62	0.24	0.86	0.46	0.01	0.67	0.31	0.20	1,360	0.10	136
207-1	White River Valley	Bare Soil/Low Vegetation	0.98	0.15	0.15	0.77	0.06	0.43	0.34	0.60	14,699	1.00	14,699
		Phreatophyte/Medium Vegetation	1.14	0.17	0.19	0.79	0.05	0.43	0.34	0.40	81,711	0.10	8,171
		Wetland/Meadow	2.38	0.11	0.27	0.82	0.05	0.43	0.36	0.20	6,370	0.10	637
		Playa	0.88	0.14	0.12	0.78	0.06	0.43	0.34	0.50	77	0.05	4
207-2	White River Valley	Open Water	5.10	0.01	0.05	0.77	0.06	0.43	0.34	0.00	685	0.05	34
		Bare Soil/Low Vegetation	0.98	0.15	0.15	0.77	0.06	0.43	0.33	0.60	30,230	1.00	30,230
		Phreatophyte/Medium Vegetation	1.11	0.18	0.20	0.77	0.06	0.43	0.33	0.40	38,821	0.10	3,882
		Wetland/Meadow	3.35	0.05	0.18	0.77	0.06	0.43	0.33	0.20	4,672	0.10	467
		Playa	0.89	0.14	0.12	0.77	0.06	0.43	0.34	0.50	907	0.05	45
209-1	Pahranagat Valley	Open Water	7.68	0.11	0.86	0.67	0.02	0.44	0.29	0.00	384	0.05	19
		Bare Soil/Low Vegetation	1.00	0.41	0.41	0.67	0.03	0.44	0.29	0.60	97	0.25	24
		Phreatophyte/Medium Vegetation	3.30	0.26	0.85	0.67	0.03	0.44	0.29	0.40	262	0.10	26
		Wetland/Meadow	3.30	0.24	0.78	0.67	0.02	0.44	0.29	0.20	863	0.10	86
209-2	Pahranagat Valley	Bare Soil/Low Vegetation	1.00	0.41	0.41	0.63	0.03	0.44	0.27	0.60	73	0.25	18
		Phreatophyte/Medium Vegetation	3.30	0.26	0.85	0.62	0.04	0.44	0.27	0.40	294	0.10	29
		Wetland/Meadow	3.30	0.24	0.78	0.61	0.04	0.44	0.27	0.20	2,934	0.10	293
209-3	Pahranagat Valley	Open Water	7.68	0.11	0.86	0.56	0.01	0.44	0.24	0.00	464	0.05	23
		Bare Soil/Low Vegetation	1.00	0.41	0.41	0.57	0.01	0.44	0.25	0.60	37	0.25	9
		Phreatophyte/Medium Vegetation	3.30	0.26	0.85	0.57	0.02	0.44	0.25	0.40	87	0.10	9
		Wetland/Meadow	3.30	0.24	0.78	0.58	0.01	0.44	0.25	0.20	847	0.10	85
209-4	Pahranagat Valley	Open Water	7.68	0.11	0.86	0.52	0.01	0.44	0.23	0.00	74	0.05	4
		Bare Soil/Low Vegetation	1.00	0.41	0.41	0.54	0.02	0.44	0.23	0.60	12	0.25	3
		Phreatophyte/Medium Vegetation	3.30	0.26	0.85	0.54	0.02	0.44	0.23	0.40	64	0.10	6
		Wetland/Meadow	3.30	0.24	0.78	0.53	0.02	0.44	0.23	0.20	900	0.10	90

Table F-8
Groundwater ET Uncertainty Analysis - Monte Carlo Input Parameter Data
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HA Sub-Area	HA Name	ET Class	ET Rate			Precipitation Rate				ET - P Correlation Coefficient	Groundwater ET Area		
			Mean (ft/yr) (area weighted)	COV (-)	STD (ft/yr)	(ft/yr) (area weighted)	Spatial COV	Temporal COV	STD (ft/yr)		(acre)	COV (-)	STD (acre)
209-5	Pahranagat Valley	Open Water	7.68	0.11	0.86	0.53	0.01	0.44	0.23	0.00	375	0.05	19
		Bare Soil/Low Vegetation	1.00	0.41	0.41	0.52	0.01	0.44	0.23	0.60	41	0.25	10
		Phreatophyte/Medium Vegetation	3.30	0.26	0.85	0.52	0.01	0.44	0.23	0.40	108	0.10	11
		Wetland/Meadow	3.30	0.24	0.78	0.52	0.01	0.44	0.23	0.20	741	0.10	74
215-N	Black Mountains Area	Bare Soil/Low Vegetation	1.00	0.41	0.41	0.45	0.08	0.57	0.26	0.60	54	0.25	14
		Phreatophyte/Medium Vegetation	3.88	0.26	1.00	0.46	0.08	0.57	0.26	0.40	244	0.10	24
		Wetland/Meadow	3.88	0.24	0.92	0.44	0.08	0.57	0.25	0.20	165	0.10	16
218-N	California Wash	Bare Soil/Low Vegetation	1.00	0.41	0.41	0.45	0.01	0.36	0.17	0.60	37	0.25	9
		Phreatophyte/Medium Vegetation	3.80	0.26	0.98	0.46	0.01	0.36	0.17	0.40	149	0.10	15
		Wetland/Meadow	3.80	0.24	0.90	0.46	0.01	0.36	0.17	0.20	1,194	0.10	119
219-N	Muddy River Springs Area	Bare Soil/Low Vegetation	1.00	0.41	0.41	0.46	0.02	0.36	0.17	0.60	166	0.25	42
		Phreatophyte/Medium Vegetation	3.77	0.26	0.97	0.46	0.02	0.36	0.17	0.40	214	0.10	21
		Wetland/Meadow	3.77	0.24	0.89	0.46	0.01	0.36	0.17	0.20	1,571	0.10	157
220-N	Lower Moapa Valley	Open Water	9.06	0.11	1.01	0.45	0.05	0.64	0.29	0.00	137	0.05	7
		Bare Soil/Low Vegetation	1.00	0.41	0.41	0.44	0.06	0.64	0.28	0.60	496	0.25	124
		Phreatophyte/Medium Vegetation	3.89	0.26	1.00	0.44	0.06	0.64	0.28	0.40	907	0.10	91
		Wetland/Meadow	3.89	0.24	0.92	0.44	0.05	0.64	0.28	0.20	5,993	0.10	599
178B-N	Butte Valley South	Open Water	5.10	0.01	0.05	0.95	0.05	0.36	0.35	0.00	4	0.05	0
		Bare Soil/Low Vegetation	0.98	0.15	0.15	0.95	0.05	0.36	0.35	0.60	8,265	0.25	2,066
		Phreatophyte/Medium Vegetation	1.11	0.18	0.20	0.95	0.05	0.36	0.35	0.40	60,274	0.10	6,027
		Wetland/Meadow	2.38	0.05	0.12	0.95	0.05	0.36	0.35	0.20	1,157	0.10	116

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Appendix G

Major Spring Discharge and Muddy River Stream Flow Gage Data

G.1.0 MAJOR SPRING DISCHARGE AND MUDDY RIVER STREAM FLOW GAGE DATA

This appendix contains detailed data and information for the major springs of the study area and historical stream flow measurements for two gaging stations located on the Muddy River. It is very important to note the relationship between all springs and seeps in the Muddy River Springs Area and stream flow in the Muddy River. In fact, under predevelopment conditions, the stream flow gage located on the Muddy River near Moapa measures total discharge from the springs and seeps located upstream and surface water runoff. The information presented here was used to derive mean predevelopment spring and stream flow rates.

G.1.1 Major Springs

The long-term mean discharge rates of major springs located in the study area are provided in this section, followed by descriptions of the methods used to derive temperature-depth relationships (geothermal gradients). These relationships were derived to support the depth estimates of the aquifers feeding the regional springs.

G.1.1.1 Long-Term Mean Discharge

Spring information, including mean spring flow rates and standard deviations derived from individual measurements, is listed in Table G-1. The individual, historical spring discharge measurements for gaged springs in the study area have been reported in SNWA (2008). Most of these springs are located in White River Valley, Pahranagat Valley, and the Muddy River Springs Area. Spring discharge measurements for the Muddy River Springs Area are reported as stream flow measurements on the Muddy River. Mean spring discharge estimates were also derived, using USGS data (USGS, 2008), for some of the springs listed in Table G-1. These estimates are provided in Table G-2.

G.1.1.2 Temperature-Depth Relationships

Temperature-depth relationships are used to estimate geothermal gradients. These relationships can be used to estimate the average flow depth of water discharging from the regional springs. For this method of depth estimation, groundwater temperatures measured at the surface are assumed to represent subsurface temperatures at the source of the water. This section describes the estimates of the geothermal gradients considered in this study. Estimates of the geothermal gradients for the study area are available from several sources, including Mifflin (1968), the Great Basin Center for Geothermal Energy (UNR, 2008a and b), and thermal logs obtained from monitor wells drilled by

Table G-1
Regional Springs and Selected Intermediate Springs Information
(Page 1 of 3)

HA Number	Spring ID	Local Number	Site Name	UTM Northing[a] (m)	UTM Easting[a] (m)	Elevation (ft amsl)	Number of Discharge Measurements	Average Discharge (gpm)	Discharge STD (gpm)
Regional Springs									
195	1953101	195 (C-10-14) 33C	Wilson Hot Spring 1	4,423,960	805,047	4,293	0	---	---
195	1953102	195 (C-10-14) 33CDC	Wilson Hot Spring 2	4,423,459	805,030	4,293	1	1	---
195	1953103	195 (C-10-14) 33CDD	Wilson Hot Spring 3	4,423,580	805,163	4,293	1	10	---
195	1953104	195 (C-10-14) 33DBA	Wilson Hot Spring 4	4,423,985	805,447	4,298	1	60	---
195	1953105	195 (C-10-14) 33DCB	Wilson Hot Spring 5	4,423,694	805,343	4,298	1	30	---
203	2030101	203 S02 E68 04BADD	Panaca Spring	4,187,657	730,624	4,799	15	1,455	1,677
207	2070501	207 N06 E61 18AADA	Hot Creek Spring	4,249,926	661,290	5,225	23	5,038	1,263
207	2071901	207 N06 E60 25BDAD	Moon River Spring	4,246,394	658,908	5,223	8	1,676	574
207	2071101	207 N09 E61 32DABC	Moorman Spring	4,273,440	662,053	5,299	26	522	944
207	2070901	207 N12 E61 02ACAB	Preston Big Spring	4,311,153	666,296	5,732	9	3,519	278
209	2090501	209 S06 E61 06BBBB	Ash Springs	4,147,834	659,848	3,622	3	7,831	800
209	2090401	209 S05 E60 10ADBB	Crystal Springs	4,155,349	656,168	3,803	3	5,724	73
209	2090101	209 S04 E60 14	Hiko Spring	4,162,744	657,549	3,875	17	2,583	399
219	2190401	219 S14 E65 16DB	Baldwin Spring	4,066,270	703,257	1,798	1	1,066	---
219	2190301	219 S14 E65 16DD	Jones Spring	4,065,661	703,714	1,784	12	517	227
219	2191701	219 S14 E65 16ABB 1	M-10	4,066,695	703,637	1,722	2	278	17
219	2190701	219 S14 E65 21AABB1	M-11	4,065,194	704,070	1,800	17	547	311
219	2190801	219 S14 E65 21AABB4	M-12	4,065,162	704,021	1,800	16	119	98
219	2190901	219 S14 E65 21AABB3	M-13	4,065,131	704,022	1,800	18	288	94
219	2191001	219 S14 E65 21AAAA1	M-15	4,065,200	704,318	1,780	14	714	257
219	2191101	219 S14 E65 21AAAB2	M-16	4,065,198	704,268	1,780	13	135	92
219	2191201	219 S14 E65 21AABB5	M-19	4,065,101	704,047	1,800	8	414	24
219	2191301	219 S14 E65 21 1	M-20	4,065,170	704,368	1,778	7	357	136
219	2190501	219 S14 E65 16DA	Muddy Spring	4,066,348	704,018	1,747	20	3,450	227
219	2190101	219 S14 E65 21BA	Pederson East Spring	4,065,062	703,965	1,800	4	94	6
219	2190201	219 S14 E65 21BA	Pederson Spring	4,065,088	704,008	1,811	17	101	11
219	2191401	219 S14 E65 21AAAA2	Warm Springs East	4,065,137	704,294	1,790	18	996	357
258	2580407	258 (C-11-14) 26AD	Crater Spring	4,415,708	808,950	4,305	0	---	---

Table G-1
Regional Springs and Selected Intermediate Springs Information
(Page 2 of 3)

HA Number	Spring ID	Local Number	Site Name	UTM Northing[a] (m)	UTM Easting[a] (m)	Elevation (ft amsl)	Number of Discharge Measurements	Average Discharge (gpm)	Discharge STD (gpm)
258	2580201	258 (C-11-14) 03DBD	Deadman Spring	4,420,367	807,286	4,310	2	53	67
258	2580401	258 (C-11-14) 23ACA	House Spring	4,417,323	808,385	4,315	1	850	---
258	2580404	258 (C-11-14) 26AAA	Lost Spring	4,415,980	808,796	4,310	1	1,100	---
258	2580403	258 (C-11-14) 23DDC	Middle Spring	4,416,434	808,564	4,315	1	5,400	---
258	2580408	258 (C-11-14) 23AD	Mirror Spring	4,417,204	808,509	4,315	0	---	---
258	2580101	258 (C-11-14) 03DBD	North Springs	4,421,366	806,770	4,303	1	3,140	---
258	2580406	258 (C-11-14) 26DAA	Percy Spring	4,415,332	808,823	4,315	1	1,700	---
258	2580405	258 (C-11-14) 26ADD	South Spring	4,415,581	808,860	4,310	1	3,600	---
258	2580402	258 (C-11-14) 23DBD	Thomas Spring	4,416,770	808,479	4,315	1	2,400	---
258	2580301	258 (C-11-14) 11CDB	Walter Spring	4,419,580	807,675	4,308	1	150	---
Intermediate Springs									
179	1792301	179 N23 E63 6C	Cherry Creek Hot Springs	4,417,460	679,565	6,250	3	37	7
179	1792601	179 N21 E63 12DC	Cold Spring	4,396,434	688,748	5,958	1	Dry	---
179	1792001	179 N16 E64 21	McGill Spring	4,364,930	691,168	6,104	14	4,734	734
179	1792501	179 N21 E63 25BA	Monte Neva Hot Springs	4,393,119	688,116	6,011	2	649	35
184	1846401	184 N11 E67 23DA	Blind Spring	4,297,977	724,792	5,773	2	Dry	---
184	1847001	184 N15 E67 30BD	Four Wheel Drive Spring	4,335,256	716,255	5,754	1	16	---
184	1847101	184 N18 E66 01DC	Keegan Spring	4,369,756	714,906	5,617	1	233	---
184	1845901	184 N14 E67 04DB	Layton Spring	4,331,794	720,204	5,698	4	<1	<1
184	1847201	184 N11 E67 12DB	Minerva Spring	4,301,025	726,101	5,825	2	272	40
184	1845701	184 N17 E67 25DB	North Millick Spring	4,353,981	725,760	5,590	4	283	61
184	1846001	184 N12 E67 18AD	North Spring	4,309,388	717,768	5,763	1	10	---
184	1846601	184 N21 E66 09BB	Osborne Springs	4,398,798	711,959	6,127	1	3	---
184	1845801	184 N15 E67 29	South Bastian Spring	4,334,865	718,388	5,660	3	3	2
184	1845802	184 N15 E67 29DC	South Bastian Spring 2	4,334,397	718,361	5,669	1	1	---
184	1845702	184 N17 E67 25CD	South Millick Spring	4,353,599	725,201	5,592	5	473	164
184	1847401	184 N22 E66 17CA	Stonehouse Spring	4,406,507	710,511	6,256	1	Dry	---
184	1847501	184 N12 E67 26AC	The Seep	4,306,263	724,060	5,764	1	5	---
184	1847701	184 N15 E67 09BBB	Unnamed 5 Spring	4,340,641	718,911	5,645	0	---	---

Table G-1
Regional Springs and Selected Intermediate Springs Information
(Page 3 of 3)

HA Number	Spring ID	Local Number	Site Name	UTM Northing[a] (m)	UTM Easting[a] (m)	Elevation (ft amsl)	Number of Discharge Measurements	Average Discharge (gpm)	Discharge STD (gpm)
184	1845601	184 N14 E67 32AC	Willard Springs	4,323,976	718,691	5,755	2	2	2
184	1845501	184 N21 E66 15BC	Willow Spring	4,397,068	713,830	5,982	3	14	19
195	1953202	195 (C-11-14) 04BBB	(C-11-14)4bbb-S1	4,422,636	803,797	4,298	1	20	---
195	1951901	195 N10 E70 33B	Big Springs	4,287,141	749,475	5,568	2	4,547	89
195	1952401	195 (C-19-20) 24 CB	Caine Spring	4,336,186	755,138	5,028	1	5	---
195	1953201	195 (C-11-14) 4AB	Cold Spring	4,422,428	804,999	4,310	0	---	---
195	1953401	195 (C-16-18) 16DAD	Foote Res. Spring	4,367,388	769,356	4,825	1	1,300	---
195	1953701	195 (C-17-19) 21	Kell Spring	4,356,001	759,929	4,910	1	120	---
195	1952701	195 (C-18-18) 16AB	Knoll Spring	4,348,105	769,378	4,869	2	3	<1
195	1954001	195 (C-16-18)22cab-S1	Twin Spring	4,366,197	770,137	4,826	1	1,795	---
195	1953901	195 (C-18-18) 08A	Unnamed Spring	4,350,397	768,130	4,853	1	2	---
195	1952001	195 (C-15-19) 31CB	Warm Creek near Gandy, UT	4,371,945	754,812	5,156	2	7,451	127
207	2070601	207 N12 E61 2DCCD	Arnoldson Spring	4,308,473	667,919	5,625	27	1,544	232
207	2071401	207 N07 E62 28ABDC	Butterfield Spring	4,256,472	673,530	5,320	23	1,222	193
207	2070701	207 N12 E61 12BDAD	Cold Spring	4,309,454	667,609	5,653	20	589	315
207	2072001	207 N09 E62 19DB	Emigrant Springs	4,276,841	669,895	5,480	12	852	281
207	2071303	207 N07 E62 33BCAB	Flag Springs 1	4,254,696	672,719	5,290	21	1,022	137
207	2071302	207 N07 E62 33BCCB	Flag Springs 2	4,254,570	672,576	5,280	21	1,294	200
207	2071301	207 N07 E62 33BCCC	Flag Springs 3	4,254,416	672,579	5,290	22	963	181
207	2071502	207 N09 E61 13CB	Hardy Spring NW	4,278,196	667,352	5,345	1	5	---
207	2071501	207 N09 E61 13CB	Hardy Springs	4,278,196	667,553	5,354	2	200	<1
207	2071001	207 N11 E62 04AABA	Lund Spring	4,302,019	673,266	5,608	29	3,516	871
207	2071601	207 N12 E61 12DBDD	Nicolas Spring	4,308,847	668,104	5,635	26	1,149	233
209	2090701	209 S05 E60 26DAD 1	Brownie Spring	4,149,897	658,088	3,695	1	224	---
215	2150301	215 S19 68E 07AB	Blue Point Spring	4,030,173	730,235	1,550	8	247	10
215	2150201	215 S18 E67 12DD	Rogers Spring	4,028,821	729,274	1,594	22	746	43
258	2580601	258 (C-12-14) 23DCC	Cane Spring	4,406,988	809,493	4,333	0	---	---

[a]North American Datum of 1983, Zone 11

Table G-2
Statistics for USGS Discharge Measurements of Selected Springs

HA Number	Spring ID	Local Number	Site Name	Number of Discharge Measurements	Average Annual Discharge (gpm)	Discharge STD (gpm)
195	1951901	195 N10 E70 33B	Big Springs	2	4,547	89
195	1952001	195 (C-15-19) 31CB	Warm Creek near Gandy, UT	2	7,451	127
207	2070901	207 N12 E61 02ACAB	Preston Big Spring	9	3,519	278
209	2090501	209 S06 E61 06BBBB	Ash Springs	3	7,831	800
209	2090401	209 S05 E60 10ADBB	Crystal Springs	3	5,724	73
215	2150301	215 S19 68E 07AB	Blue Point Spring	8	247	10
215	2150201	215 S18 E67 12DD	Rogers Spring	22	746	43
219	2190101	219 S14 E65 21BA	Pederson East Spring	4	94	6
219	2190201	219 S14 E65 21BA	Pederson Spring	17	101	11
219	2190501	219 S14 E65 16DA	Muddy Spring	20	3,450	227

Source: USGS (2008)

SNWA. These methods are described, followed by the application of the selected method to the springs listed in Table G-1.

G.1.1.2.1 Interpretation by Mifflin (1968)

Mifflin (1968, p. 26) states that:

> Ground-water temperatures in Nevada are generally higher, by at least 5 to 10°F, than the mean annual air temperature at the point of sample. [and that] …within Nevada, ground-water temperatures observed in the 40's or 50's °F (temperatures which closely approximate mean annual air temperature) are most frequently found in the areas where saturation is relatively shallow, and active recharge to the system is often nearby or in the immediate vicinity of observation points.

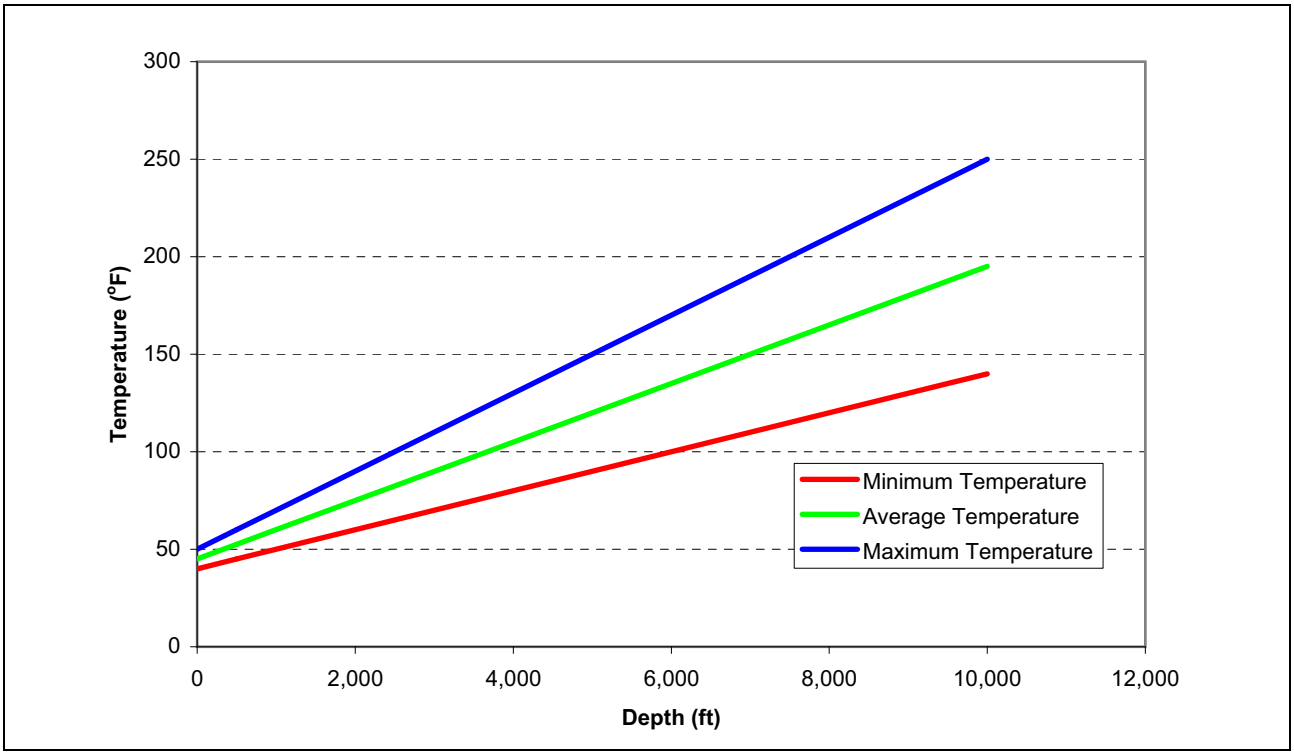
These statements imply that the temperature of groundwater at the sampling point must be larger than about 45°F (mean air temperature in Nevada) to be affected by the geothermal gradient.

Mifflin (1968, p. 27) also states that:

> Many geothermal gradients could be illustrated in Nevada by picking the area. However, it seems likely that the gradients of 1°F to 2°F per 100 ft of depth are more common than 3°F per 100 feet or more.

Mifflin's interpretations of the mean geothermal gradient in Nevada may be depicted by three linear relationships of temperature versus depth that represent the mean trend and minimum and maximum trends. For the line representing the mean trend, the slope of the line is the average of the prevailing gradients in Nevada (i.e., 1.5°F per 100 ft or the middle of the range cited by Mifflin [1968]: 1°F to 2°F per 100 ft of depth). The intercept is the average air temperature in Nevada (i.e., 45°F or the

middle of the range cited by Mifflin [1968]: 40°F to 50°F). The lower and upper ends of the ranges of thermal gradients and the mean air temperature provided by Mifflin (1968) form the basis of the minimum and maximum trends (Figure G-1).



Source: Interpreted from Mifflin (1968)

Figure G-1
Mifflin Geothermal Gradient Trends in Nevada

G.1.1.2.2 Great Basin Center Data

The Great Basin Center for Geothermal Energy is part of UNR. In support of research in the field of geothermal energy, the center conducts data compilation and analysis activities. Data types of interest include geologic, geochemical, geodetic, geophysical, and tectonic data. Data analysis products include maps and databases. Of particular interest to this study is the geochemistry database (UNR, 2008a) and the Temperature Gradient Map of the Great Basin (UNR, 2008b).

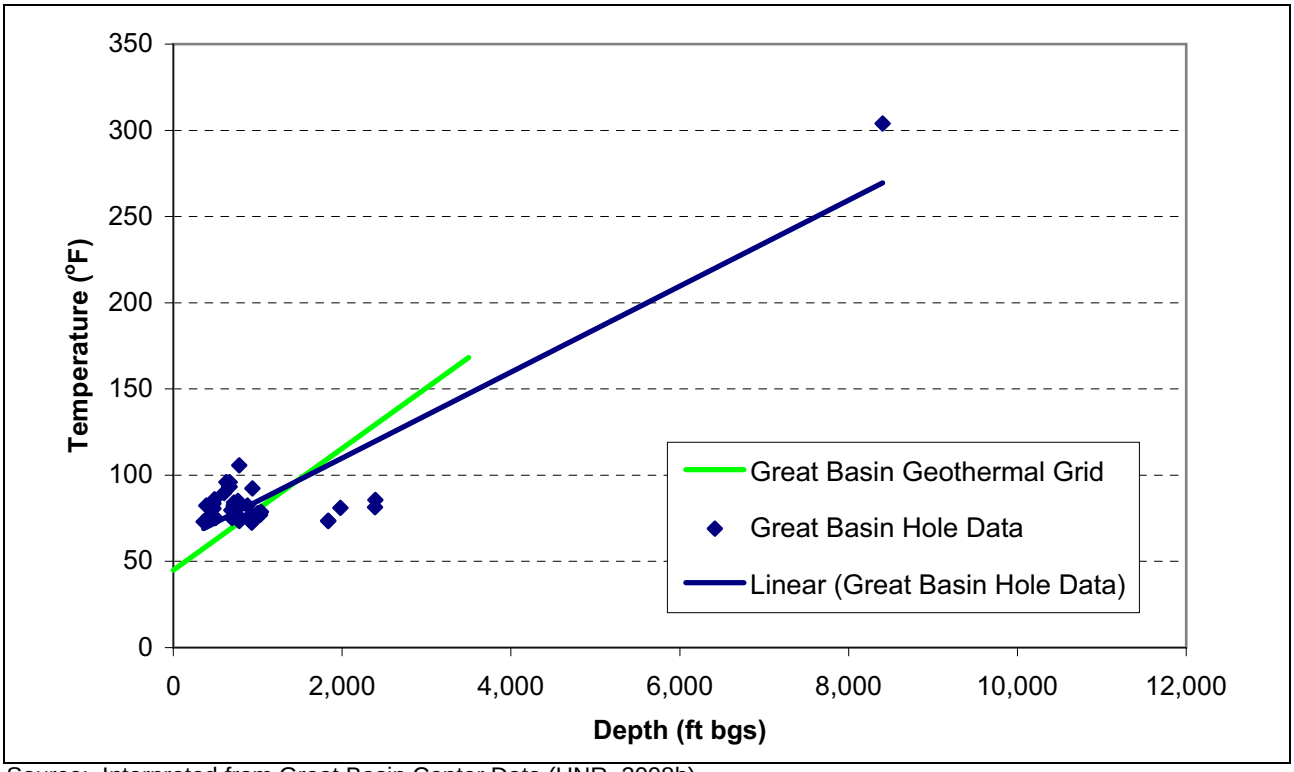
The geochemical database contains various types of information for fluids from wells and springs in the Great Basin. Hole depths and their respective water temperatures for boreholes located in Nevada were used to estimate a geothermal gradient for this study. Data points with temperatures less than 70°F and depths less than 100 m (328 ft) were first removed from the data set. The selected data are listed in Table G-3 and shown in blue on Figure G-2. A linear regression line through the data is also shown in blue on Figure G-2.

Average values of the geothermal gradient were derived from the Temperature Gradient Map of the Great Basin for each of the basins of the study area. The derived values are listed in Table G-4. The basin geothermal gradient values were averaged to obtain a mean value for the study area. The mean

Table G-3
Well Temperatures and Depths from UNR Great Basin Center for Geothermal Energy

Well Name	County	Hole Depth (m bgs)	Hole Depth (ft bgs)	Temperature (°C)	Temperature (°F)
Nellis 1 USAF	Clark	244	801	24	75
Nellis 12 (C) USAF	Clark	305	1,001	25	77
Nellis 12 (C) USAF	Clark	305	1,001	26	79
Nellis 13 (B) USAF	Clark	212	696	24	75
NWIS Well 209 S13 E63 23DD 1	Clark	204	669	34	93
NWIS Well 209 S13 E63 23DD 1	Clark	204	669	36	97
NWIS Well 212 N19 E60 04DAB 2 NV Division of Forestry	Clark	238	781	23	73
NWIS Well 215 S18 E63 14CBAC1	Clark	210	689	26	79
NWIS Well 215 S20 E64 29DADB1	Clark	149	489	30	86
NWIS Well 216 S18 E63 05AADB1	Clark	603	1,978	27	81
NWIS Well 216 S18 E63 11AAA 1	Clark	152	499	24	75
Railroad Well - Farrier, NV	Clark	110	361	23	73
USAF Lake Mead 3	Clark	313	1,027	25	77
USAF Lake Mead 3	Clark	313	1,027	25	77
USAF Lake Mead 4	Clark	268	879	28	82
USBLM SHV-1	Clark	280	919	25	77
USFWS DR-1	Clark	283	932	22	72
USFWS DR-1	Clark	284	932	25	77
USFWS SBH-1	Clark	220	722	29	84
USGS CSV-1	Clark	233	764	30	86
USGS CSV-2	Clark	146	479	27	81
USGS CSV-2	Clark	146	479	29	84
USGS CSV-3	Clark	238	781	41	106
USGS-MX CE-DT-5	Clark	192	630	36	97
USGS-MX CE-DT-6	Clark	286	938	34	93
North Dry Lake USGS-MX	Lincoln	730	2,395	30	86
NWIS Well 181 N03 E63 03DCC 1	Lincoln	729	2,392	28	82
NWIS Well 205 S04 E66 12AADC1	Lincoln	119	390	28	82
USGS Well VF-1, Desert NWR	Lincoln	218	715	28	82
Coal Valley Well USGS MX	Nye	560	1,837	23	73
Coal Valley Well USGS MX	Nye	560	1,837	23	73
Hans L. Anderson Water Well	White Pine	317	1,040	26	79
Henroid Well, D Henroid Ranch	White Pine	183	600	32	90
Shell Oil Co. NE Cherry Creek Unit No.1 Well	White Pine	2,562	8,406	151	304
USBLM Well, Shoshone Ponds	White Pine	124	407	24	75
USBLM Well, Shoshone Ponds	White Pine	134	440	24	75
Well at Alligator Ridge	White Pine	201	659	34	93

Source: UNR (2008a)
NWIS = National Water Information System



Source: Interpreted from Great Basin Center Data (UNR, 2008b)

Figure G-2
Great Basin Center Geothermal Gradient Trends

geothermal gradient calculated by this method is about 0.035° F/ft. This value was used to generate the corresponding temperature-depth relationship shown in green on Figure G-2.

G.1.1.2.3 SNWA Monitor Well Thermal Logs

SNWA conducted thermal logging in the monitor wells drilled as part of the Project. Their locations are provided on Figure A-1 (Appendix A). The thermal logs are shown on Figure G-3. These thermal logs were conducted before the wells were developed and conditions in the wells stabilized. Thus, groundwater was still mixed with drilling fluids, which may have resulted in cooler temperatures during the measurement period (Eastman, 2007a through g). A mean temperature-depth relationship was derived from these thermal logs by averaging the temperatures at each depth. The resulting relationship is shown on Figure G-4.

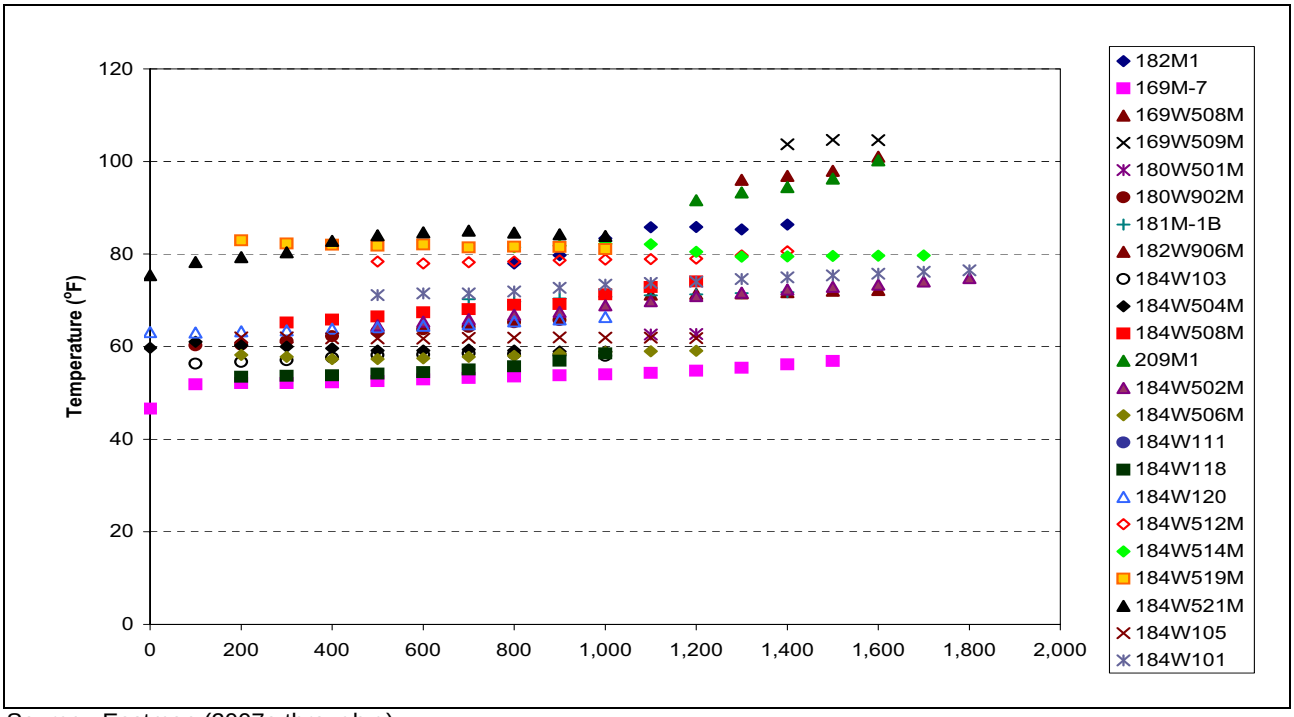
G.1.1.3 Spring Source Depth Estimates

Source aquifer depths were estimated for the selected regional and intermediate springs using the mean geothermal gradient interpreted by Mifflin (1968). Ranges of source depths were estimated when ranges of spring flow temperatures were available. The results are provided in Table G-5. These estimates constitute initial estimates only.

Table G-4
Average Basin Geothermal Gradients from the Temperature Gradient Map

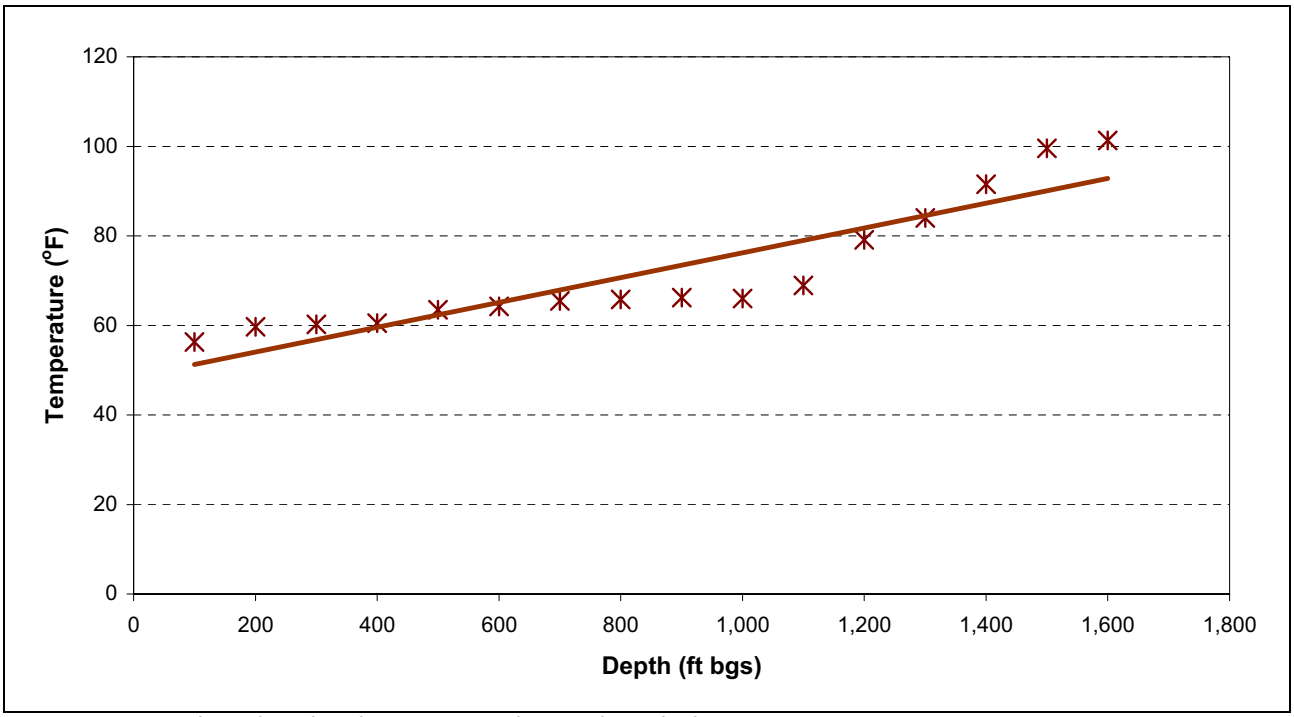
HA Number	Mean Gradient (°C/km)	Mean Gradient (°F/km)	Mean Gradient (°F/ft)
171	36.0	96.8	0.0295
172	41.3	106.3	0.0324
174	44.1	111.4	0.0339
175	43.1	109.7	0.0334
178B	49.2	120.6	0.0368
179	52.3	126.1	0.0384
180	37.8	100.1	0.0305
181	44.0	111.2	0.0339
182	48.1	118.6	0.0362
183	48.6	119.5	0.0364
184	50.0	121.9	0.0372
185	46.6	116.0	0.0353
194	38.0	100.4	0.0306
195	42.5	108.4	0.0330
196	43.5	110.3	0.0336
198	51.7	125.1	0.0381
199	50.3	122.5	0.0373
200	51.1	123.9	0.0378
201	48.3	118.9	0.0362
202	48.6	119.6	0.0364
203	46.9	116.4	0.0355
204	52.8	127.1	0.0387
205	49.8	121.7	0.0371
206	49.7	121.4	0.0370
207	46.3	115.4	0.0352
208	38.5	101.2	0.0308
209	42.3	108.2	0.0330
210	46.9	116.4	0.0355
212	44.6	112.3	0.0342
215	44.9	112.9	0.0344
216	49.0	120.2	0.0366
217	43.5	110.4	0.0336
218	49.3	120.8	0.0368
219	43.9	111.0	0.0338
220	46.0	114.8	0.0350
258	61.0	141.8	0.0432

Source: UNR (2008b)



Source: Eastman (2007a through g)

Figure G-3
Thermal Logs from SNWA Monitor Wells



Source: Average based on data from Eastman (2007a through g)

Figure G-4
Mean Temperature-Depth Relationship Based on Thermal Logs from SNWA Monitor Wells

Table G-5
Spring Source Depths Estimated Using Mifflin's Mean Geothermal Gradient
(Page 1 of 2)

HA Number	Spring ID	Site Name	Temperature	Temperature Range (°C)	Temperature Range (°F)	Source Depth Range (ft bgs)
Regional Springs						
195	1953101	Wilson Hot Spring 1	Hot	60	141	6,394
195	1953102	Wilson Hot Spring 2	Hot	56	132	5,806
195	1953103	Wilson Hot Spring 3	Hot	59	138	6,202
195	1953104	Wilson Hot Spring 4	Hot	61	141	6,406
195	1953105	Wilson Hot Spring 5	Hot	60	140	6,334
203	2030101	Panaca Spring	Warm	NA	NA	NA
207	2070501	Hot Creek Spring	Warm	32	90	2,974
207	2071901	Moon River Spring	NA	33	91	3,094
207	2071101	Moorman Spring	Hot	37	99	3,622
207	2070901	Preston Big Spring	Warm	21	70	1,660
209	2090501	Ash Springs	Hot	32	90	2,974
209	2090401	Crystal Springs	Warm	28	82	2,434
209	2090101	Hiko Spring	Warm	27	80	2,356
219	2190401	Baldwin Spring	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2190301	Jones Spring	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2191701	M-10	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2190701	M-11	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2190801	M-12	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2190901	M-13	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2191001	M-15	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2191101	M-16	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2191201	M-19	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2191301	M-20	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2190501	Muddy Spring	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2190101	Pederson East Spring	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2190201	Pederson Spring	Warm	29 to 33	84 to 91	2,614 to 3,094
219	2191401	Warm Springs East	Warm	29 to 33	84 to 91	2,614 to 3,094
258	2580407	Crater Spring	NA	NA	NA	NA
258	2580201	Deadman Spring	Warm	23	73	1,894
258	2580401	House Spring	Warm	22	72	1,774
258	2580404	Lost Spring	Warm	26	78	2,224
258	2580403	Middle Spring	Warm	24	76	2,074
258	2580408	Mirror Spring	NA	NA	NA	NA
258	2580101	North Springs	Warm	24	74	1,954
258	2580406	Percy Spring	Warm	26	79	2,254
258	2580405	South Spring	Warm	24	76	2,044
258	2580402	Thomas Spring	Warm	26	79	2,254
258	2580301	Walter Spring	Cold	20	69	1,594

Table G-5
Spring Source Depths Estimated Using Mifflin's Mean Geothermal Gradient
(Page 2 of 2)

HA Number	Spring ID	Site Name	Temperature	Temperature Range (°C)	Temperature Range (°F)	Source Depth Range (ft bgs)
Intermediate Springs						
179	1792301	Cherry Creek Hot Springs	Hot	47 to 57	117 to 135	4,774 to 5,974
179	1792601	Cold Spring	Cold	NA	NA	NA
179	1792001	McGill Spring	Warm	17	63	1,174
179	1792501	Monte Neva Hot Springs	Hot	77	171	8,422
184	1846401	Blind Spring	Cold	14	56	754
184	1847001	Four Wheel Drive Spring	Cold	15	58	898
184	1847101	Keegan Spring	Cold	13	56	706
184	1845901	Layton Spring	Cold	15	60	977
184	1847201	Minerva Spring	Cold	NA	NA	NA
184	1845701	North Millick Spring	Cold	15	59	949
184	1846001	North Spring	Warm	23	73	1,858
184	1846601	Osborne Springs	Cold	13	56	718
184	1845801	South Bastian Spring	Cold	12	54	628
184	1845802	South Bastian Spring 2	Cold	14	58	874
184	1845702	South Millick Spring	Cold	13	56	733
184	1847401	Stonehouse Spring	Cold	4	38	Negative
184	1847501	The Seep	Warm	24	74	1,966
184	1847701	Unnamed 5 Spring	Cold	14	58	841
184	1845601	Willard Springs	Cold	8	46	81
184	1845501	Willow Spring	Warm	13	56	709
195	1953202	(C-11-14)4bbb-S1	Cold	18	64	1,294
195	1951901	Big Springs	Cold	17	62	1,156
195	1952401	Caine Spring	Cold	14	58	862
195	1953201	Cold Spring	Cold	NA	NA	NA
195	1953401	Foote Res. Spring	NA	NA	NA	NA
195	1953701	Kell Spring	NA	NA	NA	NA
195	1952701	Knoll Spring	Cold	20	68	1,498
195	1954001	Twin Spring	Cold	20	68	1,534
195	1953901	Unnamed Spring	NA	NA	NA	NA
195	1952001	Warm Creek near Gandy, UT	Warm	26	80	2,305
207	2070601	Arnoldson Spring	Warm	22	72	1,786
207	2071401	Butterfield Spring	NA	NA	NA	NA
207	2070701	Cold Spring	Warm	22	71	1,738
207	2072001	Emigrant Springs	NA	20	68	1,534
207	2071303	Flag Springs 1	Warm	NA	NA	NA
207	2071302	Flag Springs 2	Warm	NA	NA	NA
207	2071301	Flag Springs 3	Warm	NA	NA	NA
207	2071502	Hardy Spring NW	Cold	17	63	1,174
207	2071501	Hardy Springs	Cold	17	63	1,174
207	2071001	Lund Spring	Cold	19	66	1,414
207	2071601	Nicolas Spring	Warm	70	159	7,594
209	2090701	Brownie Spring	NA	NA	NA	NA
215	2150301	Blue Point Spring	Warm	27	80	2,338
215	2150201	Rogers Spring	Warm	27	80	2,338
258	2580601	Cane Spring	Cold	20	68	1,534

NA = Not available

G.1.2 Selected Muddy River Stream Gages

Mean annual stream flow measurements for the Muddy River near Moapa gage and the Muddy River near Glendale gage are provided in Table G-6. The mean annual stream flow values adjusted to remove water from flooding events are also provided in this table.

A graph of the adjusted stream flow rates at the Glendale gage and the Moapa gage for the periods of record shows a great correlation between the two gaging stations (Figure G-5). The data for the common period of record 1951 to 2004 (Table G-6), not including 1984, were used to derive a correlation coefficient between the two stations. A correlation coefficient of 0.92 was derived indicating a high degree of correlation between adjusted stream flow at the two gages.

Table G-6
Stream Flow Measurements (afy)
on the Muddy River near Moapa and Glendale
(Page 1 of 3)

Year	Mean Actual Value		Mean Adjusted Value[a]	
	Moapa Gage	Glendale Gage	Moapa Gage	Glendale Gage
1913	13,343[b]	---	---	---
1914	34,438	---	34,380	---
1915	13,625[b]	---	---	---
1916	33,819	---	33,819	---
1917	34,057	---	34,057	---
1918	---	---	---	---
1944	33,109	---	32,938	---
1945	33,938	---	33,761	---
1946	34,568	---	34,568	---
1947	33,583	---	33,583	---
1948	34,057	---	34,057	---
1949	33,454	---	33,454	---
1950	33,585	---	33,585	---
1951	33,920	31,908	33,920	31,542
1952	33,840	38,922	33,793	33,431
1953	33,325	33,305	33,251	33,253
1954	33,317	31,720	33,317	31,433
1955	34,184	39,708	33,899	34,215
1956	33,216	31,628	33,216	31,296
1957	34,507	34,935	33,928	33,841
1958	35,929	34,969	35,645	32,550
1959	35,384	32,598	35,100	32,208
1960	34,666	32,077	34,578	31,932
1961	33,493	43,967	32,646	33,505

Table G-6
Stream Flow Measurements (afy)
on the Muddy River near Moapa and Glendale
(Page 2 of 3)

Year	Mean Actual Value		Mean Adjusted Value[a]	
	Moapa Gage	Glendale Gage	Moapa Gage	Glendale Gage
1962	32,212	32,401	32,158	31,585
1963	32,335	29,056	32,335	28,810
1964	32,613	29,026	32,613	28,815
1965	31,419	31,999	31,327	31,258
1966	30,296	30,347	29,836	28,044
1967	33,333	32,749	30,416	29,127
1968	29,477	31,860	29,393	30,826
1969	30,907	39,462	30,507	30,543
1970	29,604	32,633	29,604	30,566
1971	27,602	30,784	27,412	29,846
1972	31,552	30,446	30,161	28,197
1973	32,928	32,039	31,643	29,582
1974	29,352	27,902	29,352	27,856
1975	28,874	29,422	28,834	28,519
1976	29,883	30,177	28,622	28,783
1977	27,130	27,645	26,170	25,601
1978	26,200	40,108	25,703	27,143
1979	28,370	30,641	26,926	26,184
1980	28,927	33,796	28,550	28,107
1981	27,452	32,463	27,176	24,677
1982	27,331	26,838	27,047	26,432
1983	28,493	39,796	28,104	27,704
1984	30,786	---	26,371	---
1985	27,662	26,568	27,579	26,220
1986	26,507	27,141	26,438	26,631
1987	27,247	27,026	27,247	27,027
1988	28,792	27,871	28,268	26,650
1989	24,397	22,270	24,397	22,269
1990	26,490	29,909	24,710	23,393
1991	26,111	25,968	25,801	24,371
1992	26,418	26,595	26,335	25,504
1993	28,668	39,265	27,563	26,992
1994	28,521	25,144	28,431	25,145
1995	25,770	23,760	25,770	23,760

Table G-6
Stream Flow Measurements (afy)
on the Muddy River near Moapa and Glendale
(Page 3 of 3)

Year	Mean Actual Value		Mean Adjusted Value[a]	
	Moapa Gage	Glendale Gage	Moapa Gage	Glendale Gage
1996	24,332	22,663	24,332	22,663
1997	23,560	22,015	23,560	21,731
1998	25,210	39,777	24,782	25,652
1999	25,230	27,019	24,994	26,930
2000	25,073	28,862	24,727	25,125
2001	23,276	22,848	23,276	22,802
2002	22,665	22,919	22,665	22,919
2003	22,961	22,931	22,961	22,931
2004	22,059	23,266	22,059	23,266

[a]Removed water from flooding events.
[b]Reported values were identified as outliers.

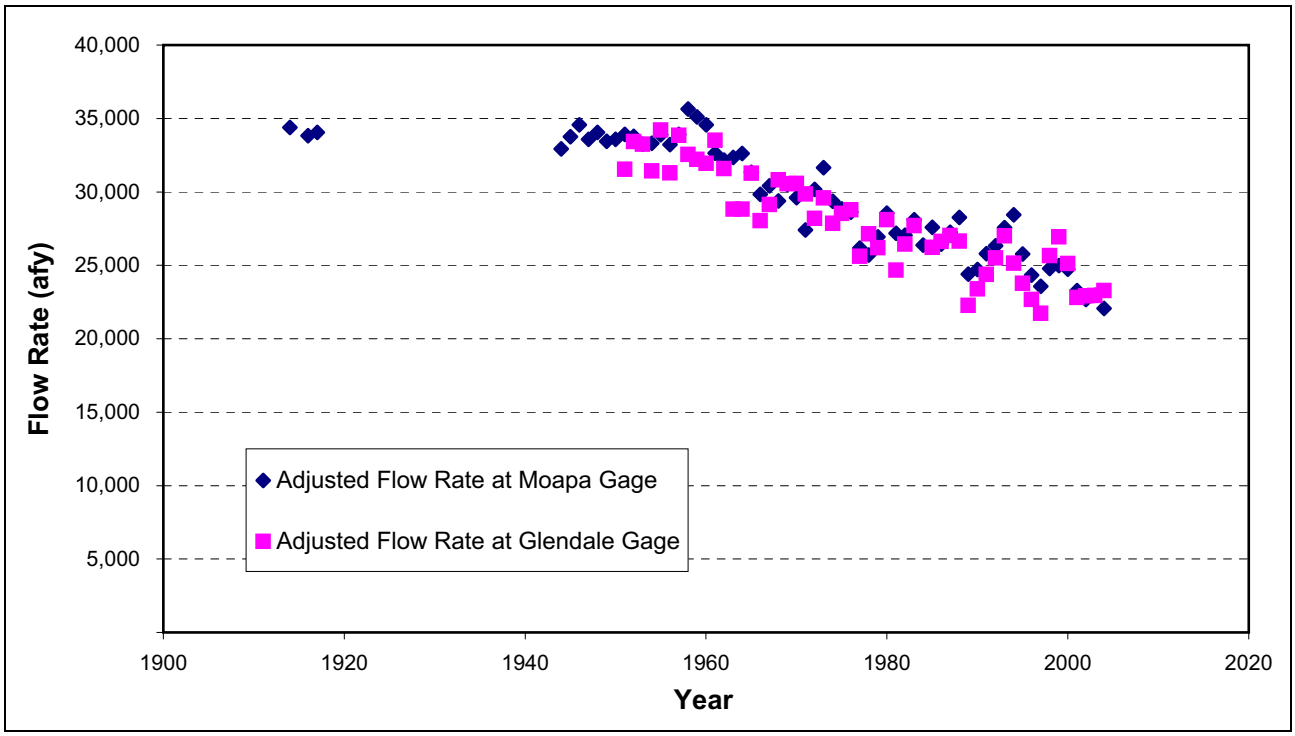


Figure G-5
Adjusted Stream Flow Rates at the Glendale and Moapa Gages on the Muddy River

G.2.0 REFERENCES

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Appendix H

Interbasin Flow

H.1.0 INTERBASIN FLOW

This appendix contains reported estimates of interbasin flow for the basins in the study area and estimates of subsurface flow through the external boundary of the model area using the Monte Carlo method.

H.1.1 Reported Estimates of Interbasin Flow

A literature review was conducted to compile estimates of interbasin flow for all basins in the study area to support the discussion presented in the main text. The locations of interbasin flow are shown in Figure H-1. The reported values and overall ranges of flow across each segment boundary are presented in Table H-1.

H.1.2 External Boundary Flow–Monte Carlo Method

Interbasin flow volumes across most external boundaries of the model area were estimated using Darcy's equation and the Monte Carlo method. The method consisted of conducting Monte Carlo simulations using Crystal Ball software to generate stochastic estimates of total flux across each flow-boundary segment.

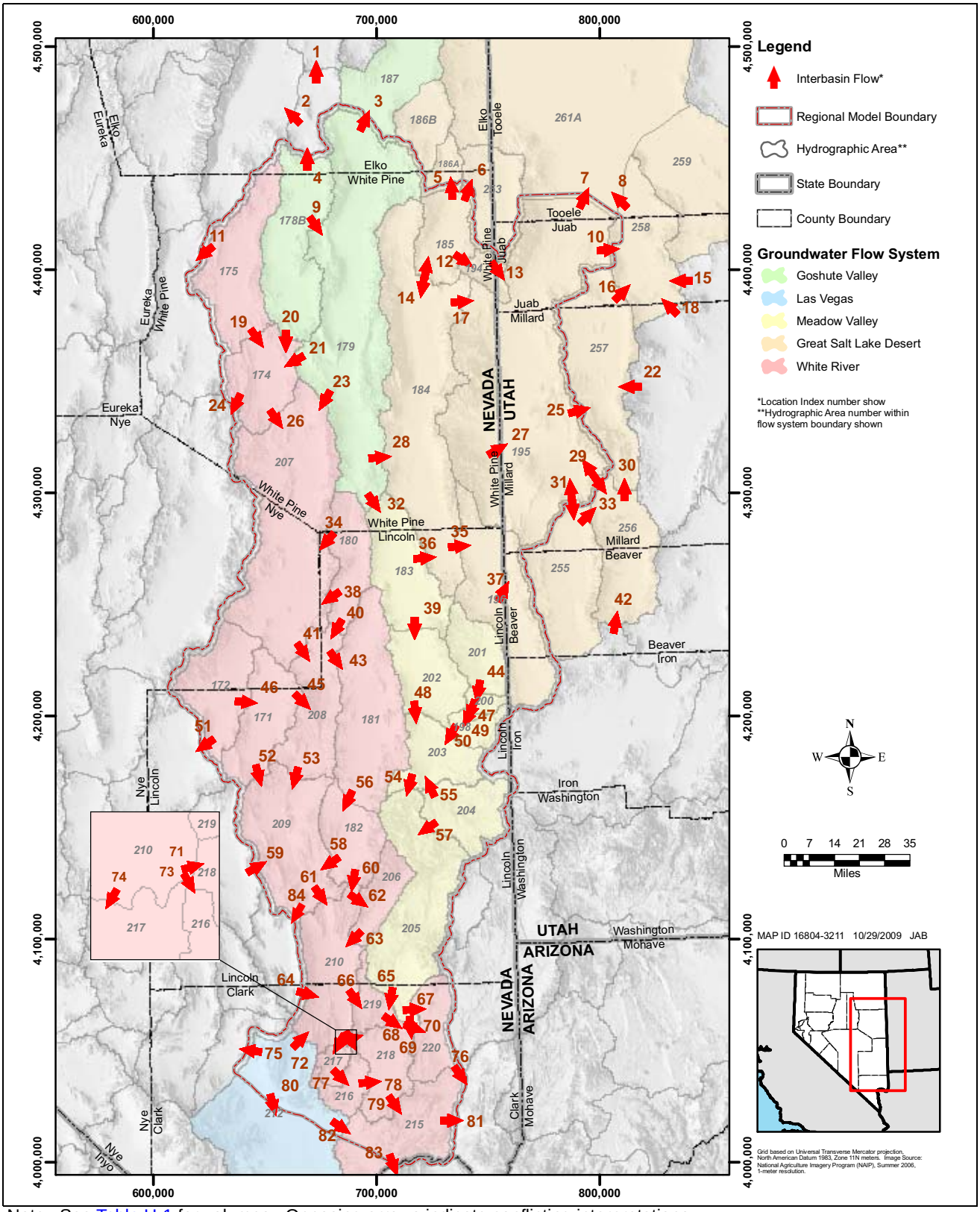
The analysis process included the following steps:

1. Began with the approximate locations of flow-boundary segments where groundwater flow is permissible (SNWA, 2008). Permissible means only that the flow-boundary segment is permeable, not that flow actually occurs through it under predevelopment conditions.

2. Extracted the RMU column from the simplified hydrogeologic framework model for each permeable flow-boundary segment.

3. Prepared input data (see Section H.1.3):

   - Estimated mean transmissivities and standard deviations using the available hydraulic head data.
   - Using the surficial RMU map and the available potentiometric maps, estimated the flow width of each permeable boundary segment.
   - Using the same maps as above and measured water levels, estimated the hydraulic gradient across each permeable flow-boundary segment.



Note: See Table H-1 for volumes. Opposing arrows indicate conflicting interpretations.

Figure H-1
Locations of Interbasin Flow within Study Area

Table H-1
Reported Volumes of Interbasin Flow in Study Area
(Page 1 of 7)

Location Index[a]	Interbasin Flow Range (afy)	Interbasin Flow (afy)	Sources
1	22,500	22,500	Nichols (2000)
2	800 to 2,000	800	Scott et al. (1971)
		1,000	Harrill et al. (1988)
		2,000	Nichols (2000)
3	M to 7,000	M	Harrill et al. (1988)
		S	Scott et al. (1971)
		2,130 to 5,330	Frick (1985)
		4,000	Nichols (2000)
		7,000	Welch et al. (2008)
4	3,000 to 8,000	3,000	Glancy (1968)
		8,000	Welch et al. (2008)
5	3,000	3,000	Harrill et al. (1988)
6	2,000 to 12,000	2,000	Harrill et al. (1988)
		6,000	Nichols (2000)
		12,000	Welch et al. (2008)
7	3,500 to 29,000	3,500	Carlton (1985)
		10,000	Hood and Rush (1965)
		10,000	Gates and Kruer (1981)
		10,000	Harrill et al. (1988)
		29,000	Welch et al. (2008)
8	1,000 to 8,500	1,000	Harrill et al. (1988)
		8,500	Carlton (1985)
9	?	?	Harrill et al. (1988)
10	? to 18,500	?	Harrill et al. (1988)
		15,000?	Gates and Kruer (1981)
		18,500	Carlton (1985)
11	? to 12,700	?	Harrill et al. (1988)
		5,000	Welch et al. (2008)
		8,000	Thomas et al. (2001)
		10,000	Nichols (2000)
		12,700	Prudic et al. (1995)
12	3,600	3,600	Nichols (2000)
13	3,000	3,000	Scott et al. (1971)
14	-2,000 to 2,000	-2,000	Welch et al. (2008)
		2,000	Harrill (1971)
		2,000	Harrill et al. (1988)
15	6,000	6,000	Carlton (1985)
16	25,500 to 27,000	25,500	Carlton (1985)
		27,000	Harrill et al. (1988)
17	4,000 to 16,000	4,000	Nichols (2000)
		16,000	Welch et al. (2008)
18	?	?	Harrill et al. (1988)

Table H-1
Reported Volumes of Interbasin Flow in Study Area
(Page 2 of 7)

Location Index[a]	Interbasin Flow Range (afy)	Interbasin Flow (afy)	Sources
19	8,000 to 19,000	8,000	Eakin (1961)
		8,000	Eakin (1966)
		8,000	Harrill et al. (1988)
		8,000	Scott et al. (1971)
		12,000	LVVWD (2001)
		12,000	Thomas et al. (2001)
		14,000	Nichols (2000)
		16,900	Thomas and Mihevc (2007)
		19,000	Welch et al. (2008)
20	16,000	16,000	Welch et al. (2008)
21	14,000	14,000	Welch et al. (2008)
22	5,500 to 9,000	5,500	Carlton (1985)
		9,000	Harrill et al. (1988)
23	8,000	8,000	Welch et al. (2008)
24	? to 700	?	Harrill et al. (1988)
		700	Nichols (2000)
25	15,000 to 42,000	15,000	Hood and Rush (1965)
		22,000 to 42,000	Harrill et al. (1988)
26	16,527 to 63,000	16,527 to 27,145	Kirk and Campana (1990)
		25,000	Eakin (1966)
		25,000	Scott et al. (1971)
		28,800	Thomas and Mihevc (2007)
		35,000	LVVWD (2001)
		35,000	Thomas et al. (2001)
		51,200	Nichols (2000)
		63,000	Welch et al. (2008)
27	30,000	30,000	Scott et al. (1971)
28	4,000	4,000	Welch et al. (2008)
29	-4,250 to 4,000	-4,250	Harrill et al. (1988)[b]
		4,000	Carlton (1985)
30	4,250 to 26,500	4,250	Harrill et al. (1988)[b]
		26,500	Carlton (1985)
31	-5,500 to 16,500	-5,500	Harrill et al. (1988)[b]
		16,500	Carlton (1985)
32	20,000	20,000	Welch et al. (2008)
33	5,500 to 30,000	5,500	Harrill et al. (1988)[b]
		30,000	Carlton (1985)
34	4,000 to 11,180	4,000	Thomas and Mihevc (2007)
		9,000	Welch et al. (2008)
		8,571 to 11,180	Kirk and Campana (1990)

Table H-1
Reported Volumes of Interbasin Flow in Study Area
(Page 3 of 7)

Location Index[a]	Interbasin Flow Range (afy)	Interbasin Flow (afy)	Sources
35	4,000 to 33,000	4,000	Rush and Kazmi (1965)
		4,000	Gates and Kruer (1981)
		4,000	Harrill et al. (1988)
		4,000	Scott et al. (1971)
		10,000	Nichols (2000)
		33,000	Welch et al. (2008)
36	29,000	29,000	Welch et al. (2008)
37	10,000	10,000	Scott et al. (1971)
38	14,000 to 15,000	14,000	Eakin (1962)
		14,000	Eakin (1966)
		14,000	Harrill et al. (1988)
		14,000	Scott et al. (1971)
		15,000	LVVWD (2001)
39	3,000 to 17,000	3,000	Rush and Eakin (1963)
		3,000	Harrill et al. (1988)
		3,000	Scott et al. (1971)
		5,600	Thomas and Mihevc (2007)
		17,000	LVVWD (2001)
		17,000	Thomas et al. (2001)
40	9,400 to 15,000	9,400	Thomas and Mihevc (2007)
		15,000	Thomas et al. (2001)
41	6,400 to 40,000	6,400	Thomas and Mihevc (2007)
		17,000	Thomas et al. (2001)
		32,000	LVVWD (2001)
		39,000	Welch et al. (2008)
		40,000	Eakin (1966)
		40,000	Harrill et al. (1988)
		40,000	Scott et al. (1971)
42	1,500	1,500	Carlton (1985)
43	2,000	2,000	Thomas and Mihevc (2007)
44	M to 15,000	M	Scott et al. (1971)
		M	Harrill et al. (1988)
		7,200	Thomas and Mihevc (2007)
		15,000	LVVWD (2001)
		15,000	Thomas et al. (2001)
45	20,000 to 27,000	20,000	LVVWD (2001)
		27,000	Thomas and Mihevc (2007)
46	8,000 to 23,100	8,000	Eakin (1966)
		8,000	Harrill et al. (1988)
		8,000	Scott et al. (1971)
		14,000	LVVWD (2001)
		14,000	Thomas et al. (2001)
		23,100	Thomas and Mihevc (2007)

Table H-1
Reported Volumes of Interbasin Flow in Study Area
(Page 4 of 7)

Location Index[a]	Interbasin Flow Range (afy)	Interbasin Flow (afy)	Sources
47	0 to 16,000	0	Scott et al. (1971)
		1,000	Harrill et al. (1988)
		8,300	Thomas and Mihevc (2007)
		16,000	LVVWD (2001)
		16,000	Thomas et al. (2001)
48	9,000 to 28,000	9,000	Harrill et al. (1988)
		9,000	Scott et al. (1971)
		14,900	Thomas and Mihevc (2007)
		28,000	LVVWD (2001)
		28,000	Thomas et al. (2001)
49	0 to 16,000	0	Scott et al. (1971)
		7,900	Thomas and Mihevc (2007)
		16,000	LVVWD (2001)
		16,000	Thomas et al. (2001)
50	7,400 to 16,000	7,400	Thomas and Mihevc (2007)
		16,000	LVVWD (2001)
		16,000	Thomas et al. (2001)
51	1,216 to 3,758	1,216	San Juan et al. (2004
		3,758	Faunt et al. (2004)
52	10,000 to 20,000	10,000	Eakin (1963)
		10,000	Eakin (1966)
		10,000	Harrill et al. (1988)
		10,000	Scott et al. (1971)
		20,000	Thomas et al. (2001)
53	1,330 to 59,000	1,330 to 1,970	Kirk and Campana (1990)
		39,000	Thomas et al. (2001)
		42,000	Eakin (1966)
		42,000	Harrill et al. (1988)
		42,000	Scott et al. (1971)
		45,300	Thomas and Mihevc (2007)
		59,000	LVVWD (2001)
54	M to 36,000	M	Harrill et al. (1988)
		8,900	Thomas and Mihevc (2007)
		27,000	LVVWD (2001)
		36,000	Thomas et al. (2001)
55	M to 9,000	M	Scott et al. (1971)
		9,000	Thomas et al. (2001)
56	5,000 to 17,700	5,000	Eakin (1966)
		5,000	Harrill et al. (1988)
		5,000	Scott et al. (1971)
		12,000	LVVWD (2001)
		12,000	Thomas et al. (2001)
		17,700	Thomas and Mihevc (2007)

Table H-1
Reported Volumes of Interbasin Flow in Study Area
(Page 5 of 7)

Location Index[a]	Interbasin Flow Range (afy)	Interbasin Flow (afy)	Sources
57	9,000 to 9,700	9,000	LVVWD (2001)
		9,700	Thomas and Mihevc (2007)
58	6,000	6,000	Eakin (1966)
		6,000	Harrill et al. (1988)
		6,000	Scott et al. (1971)
59	811 to 11,307	811	San Juan et al. (2004)
		11,307	Faunt et al. (2004)
60	16,000 to 24,100	16,000	Thomas et al. (2001)
		16,000	LVVVWD (2001)
		24,100	Thomas and Mihevc (2007)
61	22,300 to 35,000	22,300	Thomas and Mihevc (2007)
		27,247 to 29,370	Kirk and Campana (1990)
		28,000	LVVWD (2001)
		28,000	Thomas et al. (2001)
		35,000	Eakin (1966)
		35,000	Scott et al. (1971)
		35,000	Harrill et al. (1988)
62	S	S	Scott et al. (1971)
63	M to 6,000	M	Scott et al. (1971)
		M	Harrill et al. (1988)
		4,200	Thomas and Mihevc (2007)
		6,000	LVVWD (2001)
		6,000	Thomas et al. (2001)
64	? to 14,023	5,513	San Juan et al. (2004)
		14,023	Faunt et al. (2004)
		?	Harrill et al. (1988)
65	2,400 to 13,000	2,400 to 7,200	Buqo (2002)
		4,000	Thomas and Mihevc (2007)
		8,000	Thomas et al. (1996)
		5,500 to 9,000	Kirk and Campana (1990) as reported by Thomas et al. (1996)
		13,000	Prudic et al. (1995)
66	28,000 to 37,700	28,000	Thomas et al. (1996)
		37,000	Eakin (1966)
		37,000	Harrill et al. (1988)
		37,000	LVVWD (2001)
		37,000	Scott et al. (1971)
		37,000	Thomas et al. (2001)
		37,700	Thomas and Mihevc (2007)
67	32,000	32,000	LVVWD (2001)
		32,000	Thomas et al. (2001)

Table H-1
Reported Volumes of Interbasin Flow in Study Area
(Page 6 of 7)

Location Index[a]	Interbasin Flow Range (afy)	Interbasin Flow (afy)	Sources
68	M to 41,804	M	Rush (1968)
		M	Scott et al. (1971)
		1,700	Thomas and Mihevc (2007)
		32,000	LVVWD (2001)
		32,000	Thomas et al. (2001)
		34,700	Eakin (1966)
		35,843 to 41,804	Kirk and Campana (1990)
69	5,300 to 7,000	5,300	Thomas and Mihevc (2007)
		7,000	Rush (1968)
		7,000	Harrill et al. (1988)
		7,000	Scott et al. (1971)
70	M to 41,000	M[c]	Rush (1968)
		M[c]	Harrill et al. (1988)
		6,000	Thomas et al. (2001)
		18,900	Thomas and Mihevc (2007)
		41,000	LVVWD (2001)
71, 73, 74	15,000 to 16,000	15,000	Thomas and Mihevc (2007)
		16,000	Thomas et al. (2001)
		16,000	LVVWD (2001)
72	?	?	Harrill et al. (1988)
75	5,000	5,000	Harrill et al. (1988)
76	1,100 to 49,000	1,100	Scott et al. (1971)
		11,100[d]	Rush (1968)
		15,300	Thomas and Mihevc (2007)
		26,000	Thomas et al. (2001)
		49,000[e]	LVVWD (2001)
77	?,M to 15,000	?	LVVWD (2001)
		M	Harrill et al. (1988)
		300	Thomas et al. (2001)
		400	Rush (1968)
		400	Scott et al. (1971)
		15,000	Thomas and Mihevc (2007)
78	? to 17,000	?	LVVWD (2001)
		800	Rush (1968)
		800	Scott et al. (1971)
		1,000	Harrill et al. (1988)
		15,100	Thomas and Mihevc (2007)
		17,000	Thomas et al. (2001)
79	M to 4,000	M	Scott et al. (1971)
		2,000	Thomas and Mihevc (2007)
		2,300	LVVWD (2001)
		4,000	Thomas et al. (2001)
80	1,378	1,378	San Juan et al. (2004)

Table H-1
Reported Volumes of Interbasin Flow in Study Area
(Page 7 of 7)

Location Index[a]	Interbasin Flow Range (afy)	Interbasin Flow (afy)	Sources
81	600 to 1,000	600	Thomas and Mihevc (2007)
		1,000	LVVWD (2001)
82	400 to 1,200	400	Rush (1968)
		1,200	Harrill et al. (1988)
83	M to 2,000	M	Scott et al. (1971)
		2,000	Thomas et al. (2001)
84	4,000	4,000	Kirk and Campana (1990)

[a]Location of interbasin flow is shown on Figure H-1 with arrows.
[b]The reported interbasin flow was evenly distributed among multiple flowpaths.
[c]This value doesn't include stream flow.
[d]This value includes 10,000 afy of stream flow that is considered as groundwater here (Rush, 1968).
[e]This value includes 1,000 afy outflow from Black Mountains Area to Lake Mead.
? = Flow volume not specified.
M = Minor quantity. An amount which is either less than 500 afy, or small in comparison to other quantities in the particular hydrologic area (Scott et al., 1971).
S = Some quantity. Sufficient information is not currently available to make an estimate (Scott et al., 1971).

4. Set up an Excel® file containing all data necessary to calculate fluxes in the Crystal Ball software.

5. Ran 10,000 Monte Carlo simulations using the Crystal Ball software.

H.1.3 Description of Input Data Preparation

Estimates of lateral interbasin flow were derived for all external boundaries, except Las Vegas Valley, using the available information. The required data consist of estimates of the probability distributions of the transmissivity, flow widths, and hydraulic gradients across the flow-boundary segment.

Probability distributions of transmissivities were derived from the hydraulic-property database described in Appendix C. Records in the database containing transmissivity values were extracted to form a data subset. If several records were available for a single location, they were reduced to one value by averaging. The reduced data set was then sorted by RMU, and the derived data were analyzed by RMU.

For RMUs with sufficient constant-rate pumping tests, records of other types of tests were removed from the data set. All records were kept for all other RMUs. Except for the carbonate aquifer, the remaining data sets were used for the statistical analyses. For the carbonate aquifers, low and high values were eliminated from the reduced data set prior to the analysis. Low transmissivity values represent matrix-only carbonate rocks, and high transmissivity values represent faults or highly fractured carbonate rocks. For RMUs with sufficient data records, the probability distributions were confirmed to be log-normal. The statistics, means, and standard deviations were as calculated. For other RMUs, the probability distributions were assumed to also be log-normal.

The flow widths across permeable segments of the model boundary were identified from a combination of information: (1) the map of permissible flow segments, (2) the regional

potentiometric map (Prudic et al., 1995), and (3) the hydrogeology map including the locations of major structural features. The three maps were superposed, and the most probable flow width was identified and measured. The probability distribution was assumed to be normal with COV values ranging from 0.5 to 1.

Hydraulic gradients across permeable-segment boundaries were derived from a combination of water-level data and previous interpretations of the potentiometric surface. Potentiometric contours for the entire region (Prudic et al., 1995) were used to identify the approximate directions of groundwater flow. Water-level data were used to actually calculate the hydraulic gradients. To approximate the regional hydraulic gradient between basins, water levels from the central parts of the basins were used rather than water levels on the mountain blocks. Because of the scarcity of carbonate wells, water levels in the central parts of the basins were assumed to represent regional potentiometric levels, i.e., carbonate aquifer is connected to alluvial aquifers. Also, water levels from groups of wells rather than single-well measurements were preferred to capture the magnitude of the mean gradient. The probability distribution was assumed to be normal with COV values ranging between 0.5 and 1.

The input data are presented in Table H-2. The last column is not part of the input but provides a deterministic Darcy flux value of the flow rate across each boundary segment and each RMU, using the listed input data.

Table H-2
Input Data for Monte Carlo Simulations of Boundary Fluxes

Boundary Segment	HGU	Transmissivity (ft^2/day)		Hydraulic Gradient (ft/ft)		Flow Width (ft)		Flux (ft^3/day)
		Geometric Mean	STD	Mean	STD	Mean	STD	
Snake Valley to Tule Valley	LC3	6,000	10	0.0045	0.0034	65,617	49,213	1,772,029
Butte Valley South to Butte Valley North	UVF	3,500	10	0.0014	0.0010	19,685	14,764	93,763
	LVF	1,500	10	0.0014	0.0010	19,685	14,764	40,184
	UC	6,000	10	0.0014	0.0010	19,685	14,764	160,737
	UA	50	30	0.0014	0.0010	19,685	14,764	1,339
	LC3	6,000	10	0.0014	0.0010	19,685	14,764	160,737
Steptoe Valley to Goshute Valley	UVF	3,500	10	0.0025	0.0013	16,404	8,202	143,789
	LVF	1,500	10	0.0025	0.0013	16,404	8,202	61,624
	UC	6,000	10	0.0025	0.0013	16,404	8,202	246,495
	UA	50	30	0.0025	0.0013	16,404	8,202	2,054
	LC3	6,000	10	0.0025	0.0013	16,404	8,202	246,495
Tippett Valley to Antelope Valley	UVF	3,500	10	0.0028	0.0021	32,808	24,606	319,695
	LVF	1,500	10	0.0028	0.0021	32,808	24,606	137,012
	UC	6,000	10	0.0028	0.0021	32,808	24,606	548,049
	UA	50	30	0.0028	0.0021	32,808	24,606	4,567
	LC3	6,000	10	0.0028	0.0021	32,808	24,606	548,049
Snake Valley to Great Salt Lake Desert	UVF	3,500	10	0.0004	0.0004	262,467	262,467	346,228
	LVF	1,500	10	0.0004	0.0004	262,467	262,467	148,383
	LC3	6,000	10	0.0004	0.0004	262,467	262,467	593,534
Tikaboo Valley South to Coyote Springs Valley	LC2	6,000	10	0.0076	0.0038	12,467	6,234	570,147
Lower Moapa Valley to Lake Mead	UVF	3,500	10	0.0030	0.0015	39,370	19,685	413,386
	LVF	1,500	10	0.0030	0.0015	39,370	19,685	177,165
	Kps2	1	10	0.0030	0.0015	39,370	19,685	118
	LC3	6,000	10	0.0030	0.0015	39,370	19,685	708,661
Lower Moapa Valley to Colorado River (pre-Lake Mead)	UVF	3,500	10	0.0040	0.0020	39,370	19,685	551,181
	LVF	1,500	10	0.0040	0.0020	39,370	19,685	236,220
	Kps2	1	10	0.0040	0.0020	39,370	19,685	157
	LC3	6,000	10	0.0040	0.0020	39,370	19,685	944,882

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Appendix I

Flow System Budget Solutions

I.1.0 FLOW SYSTEM BUDGET SOLUTIONS

The groundwater-balance method was used to derive recharge efficiencies and was implemented using the Excel® Solver. The solver is designed to find optimal solutions to numerical problems such as the one at hand, in which the main variables requiring a solution are the recharge efficiencies for the flow systems in the study area. 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® 2003 version help menu and/or the "Microsoft Excel® 2003 Bible" (Walkenbach, 2003).

To initialize and run the solver, the target cell, parameters, constraints, and initial conditions must first be defined. To do so, the necessary data were compiled and analyzed to estimate values for these inputs. This included compiling the following information and data:

- Precipitation station data and a spatial distribution for the area encompassing the study area
- Hydrologic data for the flow system to assist in defining constraints
- Geologic information and data to assist in identifying likely areas of interbasin flow
- Maps delineating groundwater discharge areas and ET classes
- ET rate data, PET data, and a PET distribution encompassing the groundwater discharge areas
- Estimates of boundary inflow and outflow
- Digital elevation model

This section presents details on the application of the Excel® Solver and solution process used to derive the groundwater budgets for each flow system in the study area. Also presented are the estimated recharge volumes and comparisons to those reported in the literature and the resulting detailed groundwater budgets.

I.1.1 Solver Application Process

The solver was used in conjunction with the PRISM precipitation grid (Section 6.0) and boundary flow estimates (Section 8.0) to calculate recharge efficiencies for 1-in. precipitation intervals (Section 9.0) and boundary fluxes from the flow systems. The derived recharge distribution, along with estimates of interbasin flow at selected locations, were used to construct groundwater budgets for individual basins within the flow systems. The data processing and analyses performed to estimate these efficiencies, including the solver setup, targets, parameters, and constraints, are described in the following sections.

I.1.1.1 Delineation of Areas of Potential Recharge

For the purpose of this study, areas of potential recharge are defined as areas where most of the in-place recharge occurs and mountain-front runoff is generated. This area of potential recharge is used to estimate the recharge distribution at the basin scale, not at the local scale. For example, the recharge that may result from infiltration of mountain-front runoff is not distributed to the actual areas where it may occur. For a given basin, potential recharge is assumed to occur in all areas of a given basin except (1) the valley floor, (2) groundwater discharge areas, and (3) areas where the precipitation is less than 8 in.

The valley floor was delineated for each basin of the study area using the USGS DEM (USGS, 2006) and was subsequently excluded as an area of potential recharge. Land-surface slopes were calculated using the DEM grid, and the relatively flat areas of each basin 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 composed of coarse-grained material that can accommodate recharge if the precipitation is significant (i.e., greater than 8 in.).

It was assumed that groundwater ET areas are not 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.

It was also assumed that a minimum of 8 in. of precipitation is necessary before groundwater recharge may occur. The first 8 in. of precipitation are assumed to satisfy the soil-moisture deficit and losses to the atmosphere (ET) (Anderson et al., 1992). This assumption is consistent with the Maxey-Eakin (1949) method, which assumes that recharge is zero below 8 in. of precipitation. Thus, areas receiving less than 8 in. of precipitation are not considered to be areas of potential recharge.

The resulting potential recharge areas are depicted in Plate 1. The union of the valley floors, groundwater discharge areas, and areas receiving less than 8 in. of precipitation are considered "areas of no recharge" only for the purpose of this report. As stated before, direct recharge from precipitation may actually occur in these areas, depending on local conditions.

I.1.1.2 Preparation of Precipitation Data

The PRISM precipitation distribution serves as the basis for the solver calculations and the derivation of the spatial distribution of recharge. The PRISM grid for the study area was contoured to generate 1-in. precipitation intervals starting from a minimum depth of 3 in. to the maximum depth occurring within the flow system. Next, the area corresponding to each interval was calculated, and then adjusted as necessary to exclude the areas of no recharge, as defined in the previous section. For each basin, the adjusted areas were then exported to Excel® to create a table containing the precipitation rate and corresponding area for each 1-in. interval within the basin. This table forms the basis of the calculations performed by the solver.

I.1.1.3 Solver Target

In the solver, the target is represented by the estimated value of total groundwater ET for a flow system. The target cell contains a formula relating groundwater ET to the other components of the budget as follows:

$$ET_{gw} = R_T + Inflow - Outflow \qquad \text{(Eq. I-1)}$$

where,

ET_{gw} = Total groundwater ET for the flow system (afy)
R_T = Total recharge for the flow system (afy)
Inflow = Total groundwater inflow to the flow system (afy)
Outflow = Total groundwater outflow from the flow system (afy)

I.1.1.4 Solver Parameters

Parameters represent the flow system variables that require a solution. For this analysis, the primary parameters are the recharge efficiencies and interbasin flow rates for selected basin boundaries of the flow system. The parameter solutions are determined through an optimization process in which the recharge efficiencies and boundary flows are adjusted within the predefined constraints, described in Section I.1.1.5, to ensure that the total recharge is equal to the sum of the total groundwater discharge and outflow, less the groundwater inflow as shown in Equation I-1 above.

Considering that the solution to the problem depends on many variables, but only a few of them are known within reasonable bounds of uncertainty, 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 flow system. It is, therefore, important to provide reasonable initial estimates for all parameters.

I.1.1.4.1 Recharge Efficiencies

Recharge efficiency, by definition, is the ratio of recharge to precipitation. For this analysis, recharge is expressed as a function of effective precipitation (Kumar and Seethapathi, 2002) as follows:

$$R = a(P - 8)^b \qquad \text{(Eq. I-2)}$$

where,

R = Recharge (in./yr)
a = Power function constant
b = Power function exponent
P = Precipitation (in./yr)
$P - 8$ = Effective precipitation (in./yr)

For this analysis, it was assumed that precipitation contributes to recharge (effective precipitation), starting at 8 in./yr where the effective precipitation and recharge are assumed to be zero. The effective precipitation and recharge increases with increasing precipitation. This equation is also similar to that of Contor (2004) and Anderson et al. (1992), except these authors express recharge as a function of total precipitation rather than effective precipitation.

To calculate the recharge efficiencies for use in the solver, each side of Equation I-2 is divided by precipitation, *P*, to yield the following equation expressing recharge efficiency:

$$Eff = \frac{[a \times (P - 8)^b]}{P} \qquad \text{(Eq. I-3)}$$

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)

Equation I-3 was used in the solver for direct calculation of the recharge efficiencies. The primary parameters are the coefficients of the power function (i.e., the constant *a* and the exponent *b*). Initial estimates for these two primary parameters were derived from a power function derived from the step-function defined by the standard Maxey-Eakin efficiencies. They are as follows:

- Power function constant: $a = 8.0 \times 10^{-5}$
- Power function exponent: $b = 3.62$

Details on how these initial estimates were derived using the Maxey-Eakin recharge efficiencies are provided in Appendix E of SNWA (2007).

I.1.1.4.2 Interbasin Flow Volumes

The interbasin flow volumes for each flow system are the secondary solver parameters. Initial estimates of the interbasin flow volumes for each flow system are presented in Section 8.0.

I.1.1.5 Solver Constraints

Constraints were placed on the coefficients of the power function, the maximum recharge efficiency, and the volumes of subsurface flow at the selected interbasin flow locations used as secondary parameters in the solver. The common constraints are as follows:

- Power function constant, *a* is positive.
- Power function exponent, *b* is positive.
- Maximum recharge efficiency is less than or equal to 0.63.

The constraint imposed on the recharge efficiency was derived from a literature review of maximum recharge efficiencies estimated for the region of the study area (Watson et al., 1976). The maximum reported value of 63 percent or 0.63 was selected as the constraint value.

I.1.2 Solution Process

The solution process includes two major steps: (1) the Excel® Solver was used to derive a recharge distribution, and (2) the resulting recharge distribution was used to derive basin budgets.

I.1.2.1 Derivation of Recharge Distribution

The solver was used to inversely solve for the recharge efficiencies and the selected underflow volumes using the target ET estimates, the parameters, and the constraints. Because there is more than one unknown parameter, the derived solution is not unique. To converge to a solution, the solver uses an iterative process and 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 band. This recharge value is then divided by precipitation to obtain a recharge efficiency, which in turn, is used to calculate recharge volumes. The calculated recharge volumes and values of the secondary parameters are tested in the budget. Once the calculated recharge volumes yield a total groundwater ET value that matches the target value, a solution is reached. The final values of all parameters are part of the solution and are used to estimate the final recharge distribution.

I.1.2.2 Derivation of Basin Groundwater Budgets

The process of deriving a groundwater budget for each basin in a flow system is conducted in Excel®, but outside of the solver. The solver provides a recharge distribution for each basin. Assuming that each basin is under predevelopment conditions, a groundwater budget may be derived for each basin. The process starts from the most up-gradient basin of the flow system and ends at the most down-gradient basins. For each basin, any inflow to the basin is added to the estimate of basin recharge, and the basin's groundwater ET value is then subtracted. The remainder is the outflow to the next contiguous basin(s) located down-gradient. For basins having more than one outflow boundary, independent estimates of selected outflow boundaries were made.

I.1.3 Solver Input Information and Solutions

Summary tables of the information used for the four flow systems and the solver solution are provided in Tables I-1 through I-4. No separate solution was sought for the small portion of Las Vegas Valley located within the model area. Recharge for this area was calculated using the solution derived for the nearest flow system, namely the WRFS.

I.1.3.1 Recharge Solutions and Detailed Comparisons to Reported Values

The estimated recharge volumes and previously reported estimates are provided in Tables I-5 and I-6. Table I-5 contains estimates reported prior to 2004, and Table I-6 contains values reported starting in 2004. The annual recharge volume for the portion of Las Vegas Valley contained within the model area was calculated using the recharge efficiencies derived for the WRFS and is included in the groundwater budgets presented in the next section.

I.1.3.2 Groundwater Budgets

The detailed groundwater budgets derived using the Excel® Solver are presented in Table I-7. The portion of Las Vegas Valley contained within the model area was added to the budget. In this budget, the recharge was assumed to flow out to Three Lakes Valley. The groundwater budgets for the flow systems with solutions are shown on four separate maps depicting the regional flow patterns within each of the flow systems in the following order: GVFS, GSLDFS, MVFS, and WRFS (Figures I-1 through I-4). The regional direction of groundwater flow is represented by arrows on basin boundaries where interbasin flow was interpreted to occur.

Table I-1
GVFS: Solver Information

Target: Groundwater ET	113,373 afy
Parameters	*a*
	b
	Outflow through northern HA boundary of Steptoe Valley
	Outflow from Butte Valley South to Butte Valley North
Constraints	Total outflow: 3,000 to 18,000 afy
	Inflow from Butte Valley South to Steptoe Valley: ≥ 0 afy
	Outflow from northern Butte Valley South: 1,000 to 8,000 afy
	Outflow from northern Steptoe Valley: 2,000 to 10,000 afy
	$a \geq 0$
	$b \geq 0$
	a initial: 0.00008
	b initial: 3.62
	Maximum efficiency: ≤ 0.63
Solution: *a*	0.01670
Solution: *b*	2.2232
Solution: Outflow through northern HA boundary of Steptoe Valley	2,000 afy
Solution: Outflow from Butte Valley South to Butte Valley North	1,000 afy

Table I-2
GSLDFS: Solver Information

Target: Groundwater ET	209,642 afy
Parameters	*a*
	b
	Outflow through Confusion Range
	Outflow through northern Snake Valley
	Inflow to Spring Valley from Tippett Valley
Constraints	Outflow from Snake Valley to Tule Valley: 1,000 to 52,000 afy (this range was adjusted to 15,000 to 52,000 afy following preliminary testing)
	Outflow from northern Snake Valley: 1,000 to 30,000 afy
	Outflow to Tule Valley is 1.6 times that to the north as determined using the outflow means from the Monte Carlo analysis
	Outflow from Tippett Valley to north: 3,000 to 29,000 afy
	Inflow to Spring Valley from Tippett Valley: ≥ 0 afy
	Recharge of volcanic area in southern Hamlin: 23,921 afy
	$a \geq 0$
	$b \geq 0$
	a initial: 0.00008
	b initial: 3.62
	Maximum efficiency: ≤ 0.63
Solution: *a*	0.0151
Solution: *b*	2.2364
Solution: Outflow through Confusion Range	15,000 afy
Solution: Outflow through northern Snake Valley	9,375 afy
Solution: Inflow to Spring Valley from Tippett Valley	0 afy

Table I-3
MVFS: Solver Information

Target: Groundwater ET	54,228 afy
Parameters:	*a*
	b
Constraints	Total outflow: 2,400 to 13,000 afy
	$a \geq 0$
	$b \geq 0$
	a initial: 0.00008
	b initial: 3.62
	Maximum efficiency: ≤ 0.63
Solution: *a*	0.00008
Solution: *b*	4.1811

Table I-4
WRFS: Solver Information

Target: Groundwater ET	147,791 afy
Parameters	*a*
	b
	Total outflow
	Inflow from Tikaboo Valley to Coyote Spring Valley
	Outflow from Coyote Spring Valley to Hidden Valley, Garnet Valley, and California Wash
	Outflow from Coyote Spring Valley to Muddy River Springs Area
Constraints	Total outflow: 13,000 to 37,000 afy
	Outflow from Coyote Spring Valley to Hidden Valley, Garnet Valley, and California Wash: ≥ 2,000 afy
	Inflow to White River Valley from Cave Valley: 4,000 afy
	Outflow from White River Valley to Pahroc Valley: 0 to 40,000 afy
	Outflow from Pahroc Valley to Dry Lake Valley: 2,000 afy
	Inflow to Muddy River Springs Area from Coyote Spring Valley and Lower Meadow Valley Wash: ≥ 28,000 afy and ≤40,000 afy
	Inflow from Tikaboo Valley: 1,000 to 12,000 afy
	Inflow from Lower Meadow Valley Wash to Muddy River Springs Area: 1,346 afy
	Inflow from Lower Meadow Valley Wash to California Wash: 1,749 afy
	$a \geq 0$
	$b \geq 0$
	a initial: 0.00008
	b initial: 3.62
	Maximum efficiency: ≤ 0.63
Solution: *a*	0.00285
Solution: *b*	3.0173
Solution: Total Outflow	22,082 afy
Solution: Inflow from Tikaboo Valley	7,200 afy
Solution: Outflow from Coyote Spring Valley to Muddy River Springs Area	40,000 afy
Solution: Coyote Spring Valley to Hidden Valley, Garnet Valley and California Wash Inflow	16,002 afy

Table I-5
Comparison of Estimated Recharge Volumes to Reported Values Prior to 2004 in afy
(Page 1 of 2)

HA Number	HA Name	This Study	Reconnaissance Series and Scott et al. (1971)	Gates and Kruer (1981)	Frick (1985)	Carlton (1985)	Dettinger (1989)	Kirk and Campana (1990)	Brothers et al. (1993a and b; 1994; 1996)	Nichols (2000)	LVVWD (2001) and Thomas et al. (2001)
Goshute Valley Flow System											
178B	Butte Valley South	24,688	15,000	---	---	---	12,165	---	---	---	---
179	Steptoe Valley	91,685	85,000	---	98,900	---	---	---	---	131,469	---
	Total	**116,373**	**100,000**								
Great Salt Lake Desert Flow System											
184	Spring Valley	81,339	75,000	---	---	---	61,636	---	72,000	103,569	---
185	Tippett Valley	5,616	6,900	---	---	---	---	---	---	12,389	---
194	Pleasant Valley	5,388	---	---	---	---	---	---	---	---	---
195	Snake Valley	104,210	---	---	---	---	---	---	---	---	---
196	Hamlin Valley	41,358	---	---	---	---	---	---	---	---	---
254	Big Snake	150,956	100,000	100,000	---	104,000	---	---	110,000	---	---
	Total	**237,911**	**181,900**								
Meadow Valley Flow System											
183	Lake Valley	9,861	13,000	---	---	---	---	---	---	---	41,320
198	Dry Valley	1,953	1,300	---	---	---	---	---	---	---	4,237
199	Rose Valley	79	<100	---	---	---	---	---	---	---	352
200	Eagle Valley	1,465	1,100	---	---	---	---	---	---	---	2,349
201	Spring Valley	9,644	10,000	---	---	---	---	---	---	---	16,151
202	Patterson Valley	5,656	6,000	---	---	---	---	---	---	---	15,761
203	Panaca Valley	2,381	1,500	---	---	---	---	---	---	---	9,041
204	Clover Valley	15,110	1,700	---	---	---	---	---	---	---	10,557
205	Lower Meadow Valley Wash	8,078	1,300	---	---	---	---	---	---	---	22,823
	Total	**54,227**	**35,900**								**122,591**
White River Flow System											
171	Coal Valley	4,020	2,000	---	---	---	---	---	---	---	7,002

Table I-5
Comparison of Estimated Recharge Volumes to Reported Values Prior to 2004 in afy
(Page 2 of 2)

HA Number	HA Name	This Study	Reconnaissance Series and Scott et al. (1971)	Gates and Kruer (1981)	Frick (1985)	Carlton (1985)	Dettinger (1989)	Kirk and Campana (1990)	Brothers et al. (1993a and b; 1994; 1996)	Nichols (2000)	LVVWD (2001) and Thomas et al. (2001)
White River Flow System (Continued)											
172	Garden Valley	25,292	10,000	---	---	---	---	10,994	---	---	19,153
174	Jakes Valley	12,658	17,000	---	---	---	---	17,999	---	38,203	24,194
175	Long Valley	20,496	10,300	---	---	---	---	5,011	---	47,740	31,112
180	Cave Valley	15,044	14,000	---	---	---	---	10,994	13,000	---	19,595
181	Dry Lake Valley	16,208	5,000	---	---	---	---	7,491	5,000	---	13,254
182	Delamar Valley	6,627	1,000	---	---	---	---	1,994	1,000	---	4,597
206	Kane Springs Valley	4,329	500	---	---	---	---	997	---	---	6,757
207	White River Valley	42,037	38,000	---	---	---	---	35,000	---	---	62,133
208	Pahroc Valley	4,705	2,200	---	---	---	---	1,994	---	---	7,545
209	Pahranagat Valley	5,726	1,800	---	---	---	---	1,508	---	---	7,407
210	Coyote Spring Valley	2,215	1,900	---	---	---	---	5,011	---	---	4,000
215	Black Mountains Area	0	<100	---	---	---	---	---	---	---	438
216	Garnet Valley	101	400	---	---	---	---	---	---	---	393
217	Hidden Valley	45	400	---	---	---	---	---	---	---	339
218	California Wash	0	<100	---	---	---	---	---	---	---	311
219	Muddy River Springs Area	41	<100	---	---	---	---	---	---	---	237
220	Lower Moapa Valley	35	<50	---	---	---	---	---	---	---	1,354
	Total	**159,579**	**104,500**								**197,227**
Las Vegas Flow System											
212	Las Vegas Valley (Partial)	2,843	---	---	---	---	---	---	---	---	---
	Total (Project Study Area)	**570,933**	---	---	---	---	---	---	---	---	---

Table I-6
Comparison of Estimated Recharge Volumes to Reported Values Starting in 2004 in afy
(Page 1 of 2)

HA Number	HA Name	This Study	Flint et al. (2004) BCM-Mean Year	Flint et al. (2004) BCM-Time Series	Epstein (2004) Maxey-Eakin Method Evaluation	Epstein (2004) Nichols Method Evaluation	Epstein (2004) Bootstrap Brute-Force Model	Epstein (2004) Numeric Maxey-Eakin Method	Epstein (2004) Numeric Nichols Method	SNWA (2006, 2007)	Welch et al. (2008)	Mizell et al. (2007)	Halford (2008)
Goshute Valley Flow System													
178B	Butte Valley South	24,688	22,240	18,284	30,360	34,310	28,535	20,758	55,029	---	35,345	33,000	22,369
179	Steptoe Valley	91,685	111,419	94,391	115,106	117,586	101,338	84,885	171,952	---	154,068	121,000	129,126
	Total	**116,373**	**133,659**	**112,675**	**145,466**	**151,896**	**129,873**	**105,643**	**226,981**	**---**	**189,413**	**154,000**	**151,495**
Great Salt Lake Desert Flow System													
184	Spring Valley	81,339	66,987	56,179	66,402	93,840	92,965	53,335	139,194	87,000	93,128	62,000	98,764
185	Tippett Valley	5,616	9,717	7,659	7,569	10,502	9,269	5,752	18,418	---	12,357	---	4,282
194	Pleasant Valley	5,388	---	---	5,833	7,721	2,931	4,267	10,756	---	---	---	5,016
195	Snake Valley	104,210	---	---	40,500	63,767	66,265	34,697	88,194	---	---	---	106,556
196	Hamlin Valley	41,358	---	---	8,773	28,294	18,547	6,451	39,322	---	---	---	50,269
254	Big Snake	150,956	92,728	81,955	55,106	99,782	87,743	45,415	138,272	---	111,337	37,000	161,841
	Total	**237,911**	**169,432**	**145,793**	**129,077**	**204,124**	**189,977**	**104,502**	**295,884**	**---**	**216,822**	**---**	**264,887**
Meadow Valley Flow System													
183	Lake Valley	9,861	14,718	12,353	16,831	44,694	23,740	10,875	62,123	---	13,092	34,000	20,686
198	Dry Valley	1,953	2,192	1,815	4,444	9,712	4,263	2,644	14,055	---	---	---	1,791
199	Rose Valley	79	48	43	69	1,006	380	98	1,541	---	---	---	85
200	Eagle Valley	1,465	890	999	1,822	5,327	1,960	1,144	7,509	---	---	---	1,300
201	Spring Valley	9,644	10,874	8,930	15,783	35,206	14,716	8,892	43,969	---	---	---	15,942
202	Patterson Valley	5,656	6,643	6,759	9,347	35,885	15,579	6,608	51,852	---	---	---	14,453
203	Panaca Valley	2,381	4,741	4,984	2,127	17,344	10,354	2,945	28,408	---	---	---	4,939
204	Clover Valley	15,110	16,274	14,389	3,750	35,336	14,071	3,528	46,946	---	---	---	5,714
205	Lower Meadow Valley Wash	8,078	11,683	20,092	5,047	26,854	17,864	6,779	44,841	---	---	---	4,120
	Total	**54,227**	**68,063**	**70,364**	**59,220**	**211,364**	**102,927**	**43,513**	**301,244**	**---**	**---**	**---**	**69,030**

Table I-6
Comparison of Estimated Recharge Volumes to Reported Values Starting in 2004 in afy
(Page 2 of 2)

HA Number	HA Name	This Study	Flint et al. (2004) BCM-Mean Year	Flint et al. (2004) BCM-Time Series	Epstein (2004) Maxey-Eakin Method Evaluation	Epstein (2004) Nichols Method Evaluation	Epstein (2004) Bootstrap Brute-Force Model	Epstein (2004) Numeric Maxey-Eakin Method	Epstein (2004) Numeric Nichols Method	SNWA (2006, 2007)	Welch et al. (2008)	Mizell et al. (2007)	Halford (2008)
White River Flow System													
171	Coal Valley	4,020	3,839	3,110	5,104	4,446	7,789	4,683	12,107	3,857	---	---	2,095
172	Garden Valley	25,292	17,974	15,559	6,098	20,900	17,342	5,331	32,223	24,818	---	---	21,770
174	Jakes Valley	12,658	10,974	8,310	20,266	18,989	13,653	11,834	30,405	12,288	15,680	39,000	7,242
175	Long Valley	20,496	16,289	13,536	30,664	33,249	22,398	20,851	52,736	19,928	24,665	---	15,451
180	Cave Valley	15,044	10,264	9,380	21,838	32,507	15,166	13,592	45,913	14,659	10,859	33,000	8,964
181	Dry Lake Valley	16,208	10,627	11,298	9,159	28,559	20,187	8,947	50,389	15,667	---	---	12,470
182	Delamar Valley	6,627	7,764	6,404	3,119	12,930	10,248	3,567	21,442	6,401	---	---	4,186
206	Kane Springs Valley	4,329	5,421	6,328	460	9,680	6,184	1,429	13,864	4,189	---	---	2,305
207	White River Valley	42,037	34,925	30,759	46,671	53,286	42,392	35,507	89,570	41,065	35,243	59,000	35,436
208	Pahroc Valley	4,705	4,432	4,832	4,561	9,044	10,251	4,934	19,362	4,507	---	---	3,791
209	Pahranagat Valley	5,726	7,043	7,186	2,968	6,271	10,209	5,996	15,979	5,507	---	---	2,253
210	Coyote Spring Valley	2,215	5,184	5,951	535	3,892	5,815	3,077	8,331	2,128	---	---	1,369
215	Black Mountains Area	0	54	1,470	94	0	3,178	3,644	1,338	0	---	---	34
216	Garnet Valley	101	294	1,000	0	164	976	591	679	96	---	---	49
217	Hidden Valley	45	188	571	0	35	521	288	327	42	---	---	52
218	California Wash	0	23	652	0	0	1,738	1,467	732	0	---	---	8
219	Muddy River Springs Area	41	12	207	0	0	509	360	214	38	---	---	1
220	Lower Moapa Valley	35	0	147	0	49	1,454	1,027	778	33	---	---	24
	Total	**159,579**	**135,307**	**126,700**	**151,537**	**234,001**	**190,010**	**127,125**	**396,389**	**155,223**	**---**	**---**	**117,500**
Las Vegas Flow System													
212	Las Vegas Valley (Partial)	2,843	---	---	11,923	28,130	24,004	15,246	43,865	---	---	---	---
	Total (Project Study Area)	**570,933**	**506,461**	**455,532**	**497,223**	**829,515**	**636,791**	**396,029**	**1,264,363**	**---**	**---**	**---**	**602,912**

Table I-7
Detailed Groundwater Budgets Derived Using Excel® Solvers
(Page 1 of 2)

HA Number	HA Name	Recharge (afy)	Groundwater ET (afy)	Inflow (afy)	Inflow From	Outflow (afy)	Outflow To
178B	Butte Valley South	24,688	11,876	0	---	11,812	Steptoe Valley (HA 179)
						1,000	Butte Valley North (HA 178A)
179	Steptoe Valley	91,685	101,497	11,812	Butte Valley South (HA 178B)	2,000	Out of model boundary
---	Goshute Valley Flow System (partial)	116,373	113,373	0	---	3,000	Out of model boundary
184	Spring Valley	81,339	75,615	0	---	5,724	Hamlin Valley (HA 196)
185	Tippett Valley	5,616	1,742	0	---	3,874	Out of model boundary
194	Pleasant Valley	5,388	912	0	---	4,476	Snake (HA 195)
195	Snake Valley	104,210	129,041	49,226	Hamlin and Pleasant valleys (HAs 196 and 194)	24,395	Out of model boundary
196	Hamlin Valley	41,358	2,333	5,724	Spring Valley (HA 184)	44,749	Snake (HA 195)
254	Big Snake	150,956	132,285	5,724	Spring Valley (HA 184)	24,395	Out of model boundary
---	Great Salt Lake Desert Flow System (partial)	237,911	209,642	0	---	28,270	Out of model boundary
183	Lake Valley	9,861	6,134	0	---	3,727	Patterson Valley (HA 202)
198	Dry Valley	1,953	3,709	5,647	Rose Valley (HA 199)	3,891	Panaca Valley (HA 203)
199	Rose Valley	79	594	6,163	Eagle Valley (HA 200)	5,647	Dry Valley (HA 198)
200	Eagle Valley	1,465	1,034	5,731	Spring Valley (HA 201)	6,163	Rose Valley (HA 199)
201	Spring Valley	9,644	3,913	0	---	5,731	Eagle Valley (HA 200)
202	Patterson Valley	5,656	1,346	3,727	Lake Valley (HA 183)	8,037	Panaca Valley (HA 203)
203	Panaca Valley	2,381	18,895	21,198	Dry, Patterson, and Clover valleys (HAs 198, 202, and 204)	4,684	Lower Meadow Valley Wash (HA 205)
204	Clover Valley	15,110	5,840	0	---	9,270	Panaca Valley (HA 203)
205	Lower Meadow Valley Wash	8,078	9,668	4,684	Panaca Valley (HA 203)	3,095	Muddy River Springs Area and California Wash (HAs 219 and 218)
---	Meadow Valley Flow System	54,227	51,133	0	---	3,095	Out of MVFS
171	Coal Valley	4,020	0	23,596	Garden Valley (HA 172)	27,615	Pahroc Valley (HA 208)
172	Garden Valley	25,292	1,696	0	---	23,596	Coal Valley (HA 171)
174	Jakes Valley	12,658	858	19,263	Long Valley (HA 175)	31,063	White River Valley (HA 207)
175	Long Valley	20,496	1,233	0	---	19,263	Jakes Valley (HA 174)

Table I-7
Detailed Groundwater Budgets Derived Using Excel® Solvers
(Page 2 of 2)

HA Number	HA Name	Recharge (afy)	Groundwater ET (afy)	Inflow (afy)	Inflow From	Outflow (afy)	Outflow To
180	Cave Valley	15,044	1,550	0	---	13,494	White River and Pahroc valleys (HAs 207 and 208)
181	Dry Lake Valley	16,208	0	2,000	Pahroc (HA 208)	18,208	Delamar Valley (HA 182)
182	Delamar Valley	6,627	0	18,208	Dry Lake Valley (HA 181)	24,835	Coyote Spring Valley (HA 210)
206	Kane Springs Valley	4,329	0	0	---	4,329	Coyote Spring Valley (HA 210)
207	White River Valley	42,037	76,701	35,063	Jakes and Cave valleys (HAs 174 and 180)	398	Pahroc Valley (HA 208)
208	Pahroc Valley	4,705	0	37,507	Coal, Cave and White River valleys (HAs 171, 180, and 207)	42,212	Dry Lake and Pahranagat valleys (HAs 181 and 209)
209	Pahranagat Valley	5,726	28,516	40,212	Pahroc (HA 208)	17,423	Coyote Spring Valley (HA 210)
210	Coyote Spring Valley	2,215	0	53,787	Delamar, Kane Springs, Pahranagat valleys (HAs 182, 206, and 209), and Tikaboo Valley South (HA 169B)	56,002	Muddy River Springs Area, Hidden and Garnet valleys and California Wash (HAs 219, 216, 217, and 218)
215	Black Mountains Area	0	1,432	2,000	California Wash (HA 218)	568	Out of model boundary
216	Garnet Valley	101	0	10,713	Hidden and Coyote Spring valleys (HAs 217 and 210)	10,814	California Wash (HA 218)
217	Hidden Valley (North)	45	0	5,334	Coyote Spring Valley (HA 210)	5,379	Garnet Valley (HA 216)
218	California Wash	0	4,505	53,295	Lower Meadow Valley Wash, Garnet Valley, and Muddy River Springs Area (HAs 205, 216, and 219)	48,790	Black Mountains Area (HA 215) and Lower Moapa Valley (HA 220)
219	Muddy River Springs Area	41	5,989	41,346	Lower Meadow Valley Wash and Coyote Spring Valley (HAs 205 and 210)	35,398	California Wash (HA 218)
220	Lower Moapa Valley	35	25,311	46,790	California Wash (HA 218)	21,515	Out of model boundary
---	White River Flow System	159,579	147,791	10,295	Lower Meadow Valley Wash (HA 205) and Tikaboo Valley South (HA 169B)	22,083	Out of model boundary
---	**Total Four Flow Systems**	**568,090**	**521,940**	**7,200**	**Tikaboo Valley South (HA 169B)**	**53,352**	**Out of model boundary**
---	**Las Vegas (Partial)**	**2,843**	**0**	**0**	**---**	**2,843**	**Three Lakes Valley**
---	**Project Model**	**570,933**	**521,940**	**7,200**	**Tikaboo Valley South (HA 169B)**	**56,196**	**Out of model boundary**

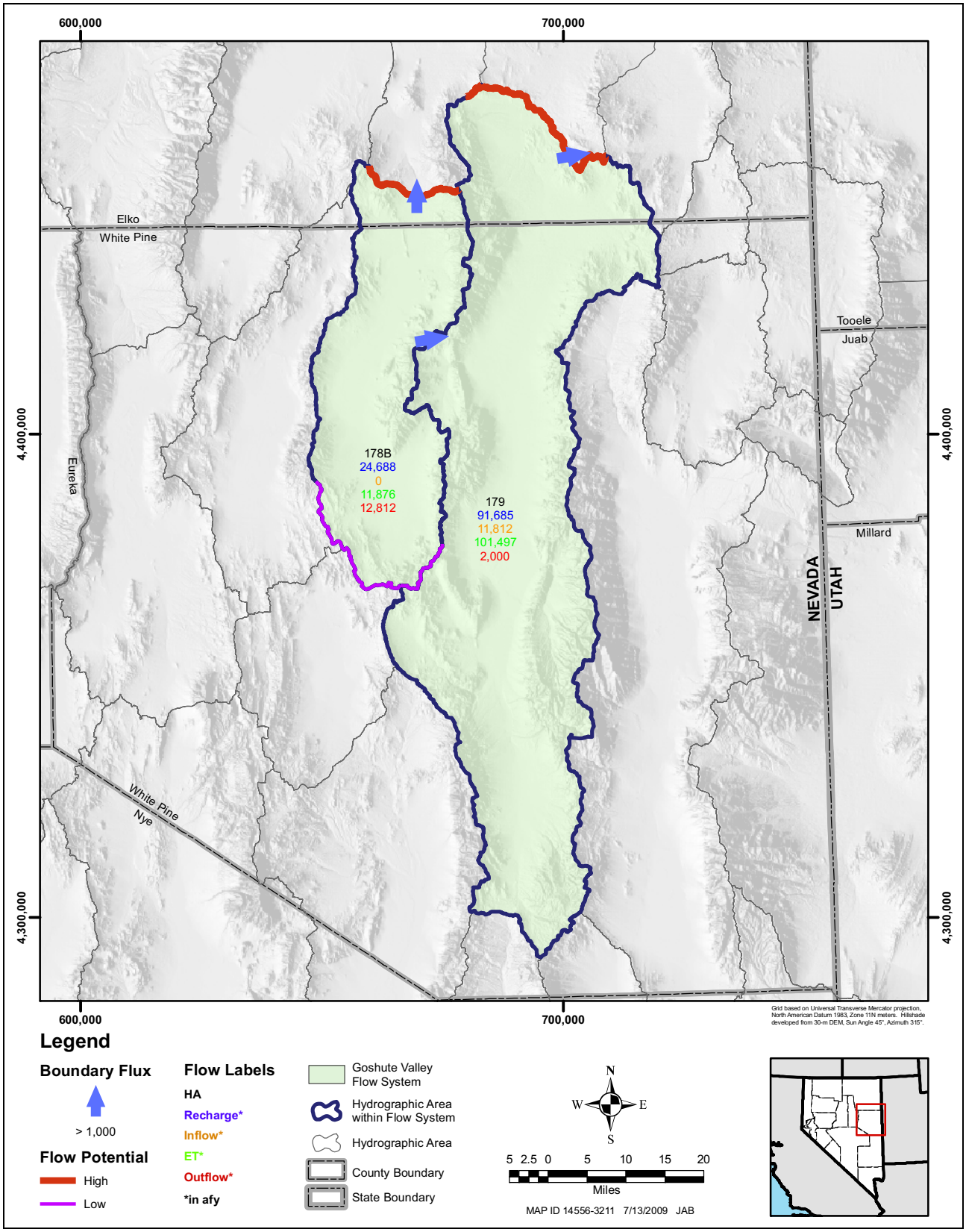

Figure I-1
Regional Groundwater Flow in Goshute Valley Flow System

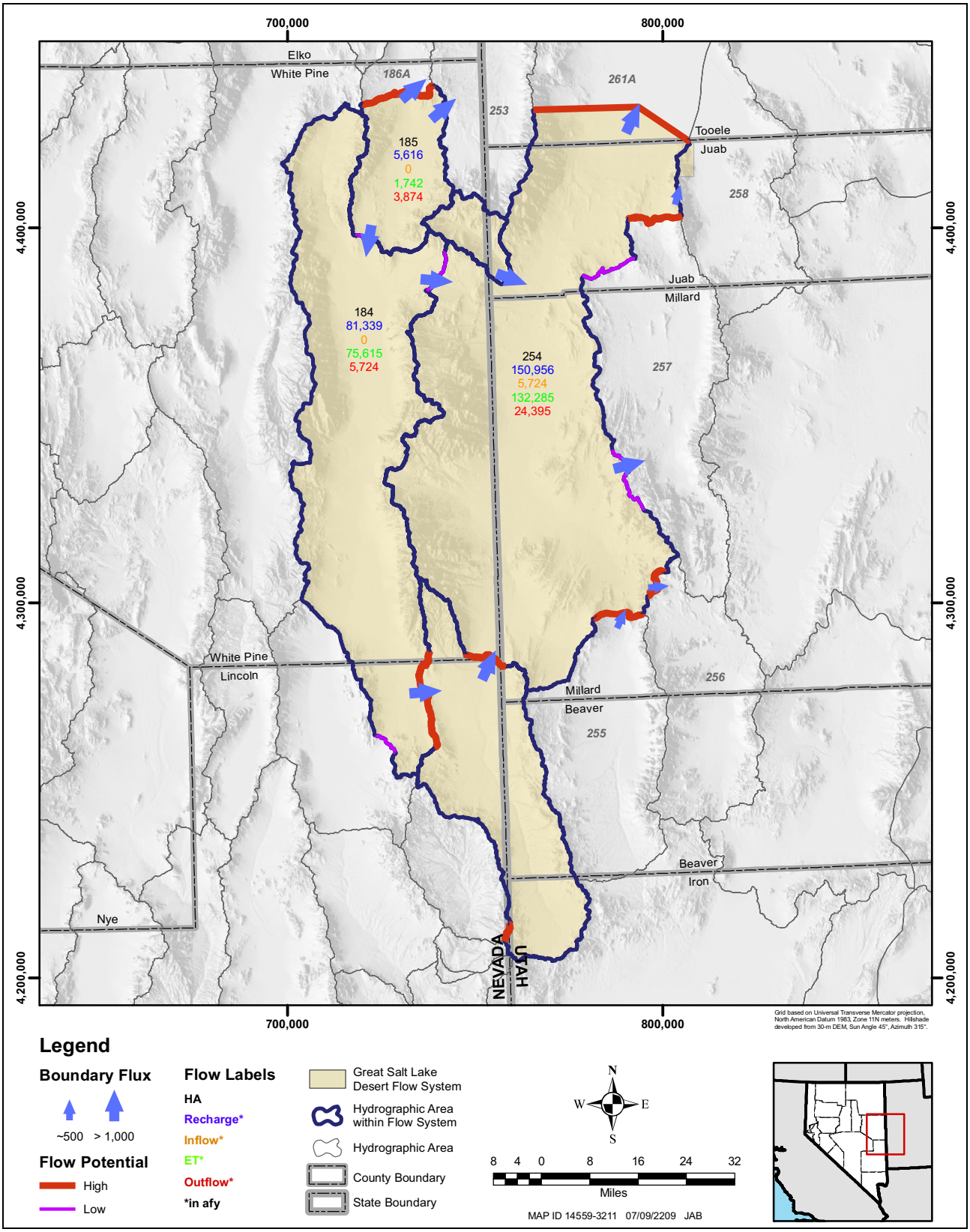

Figure I-2
Regional Groundwater Flow in the Great Salt Lake Desert Flow System

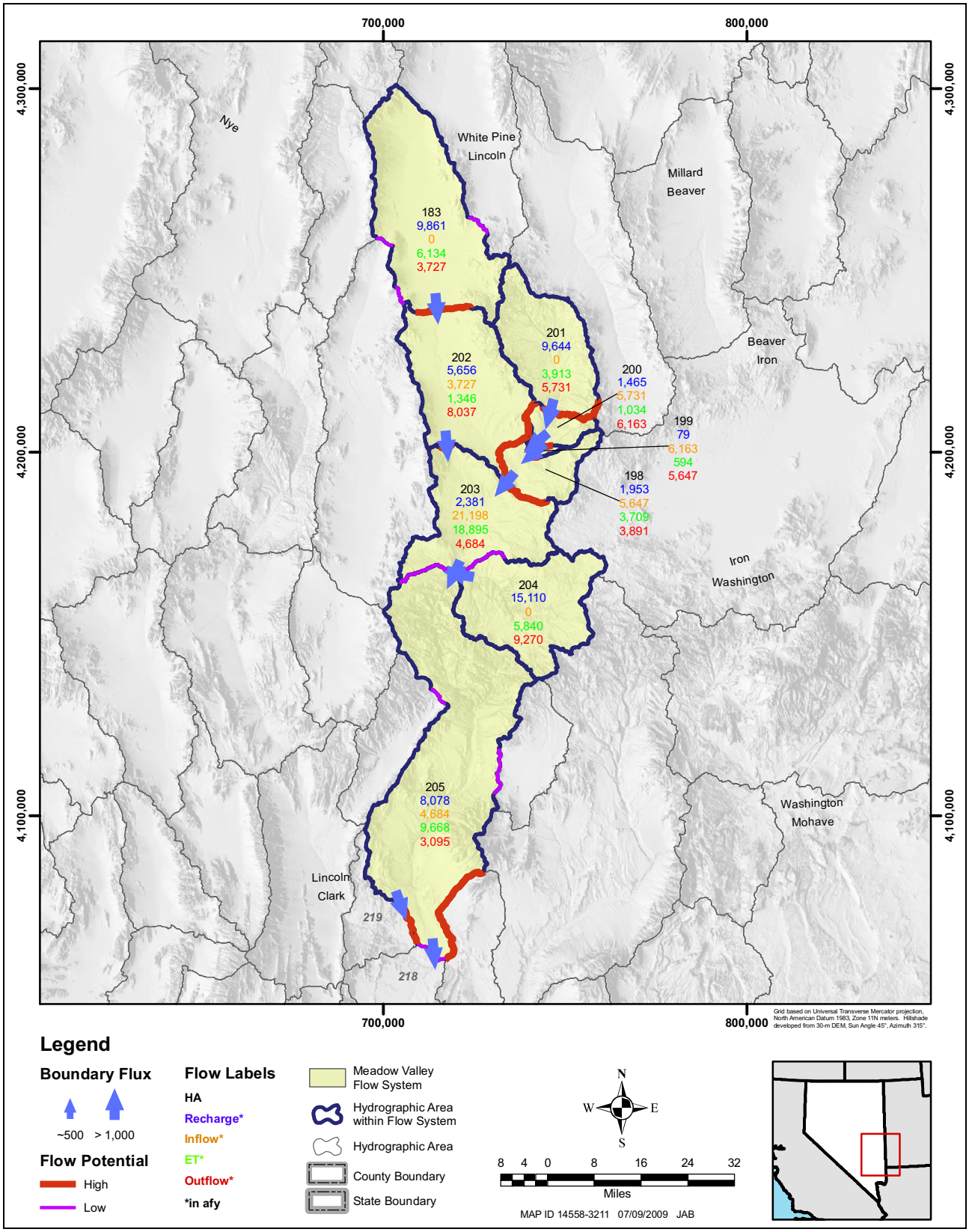

Figure I-3
Regional Groundwater Flow in Meadow Valley Flow System

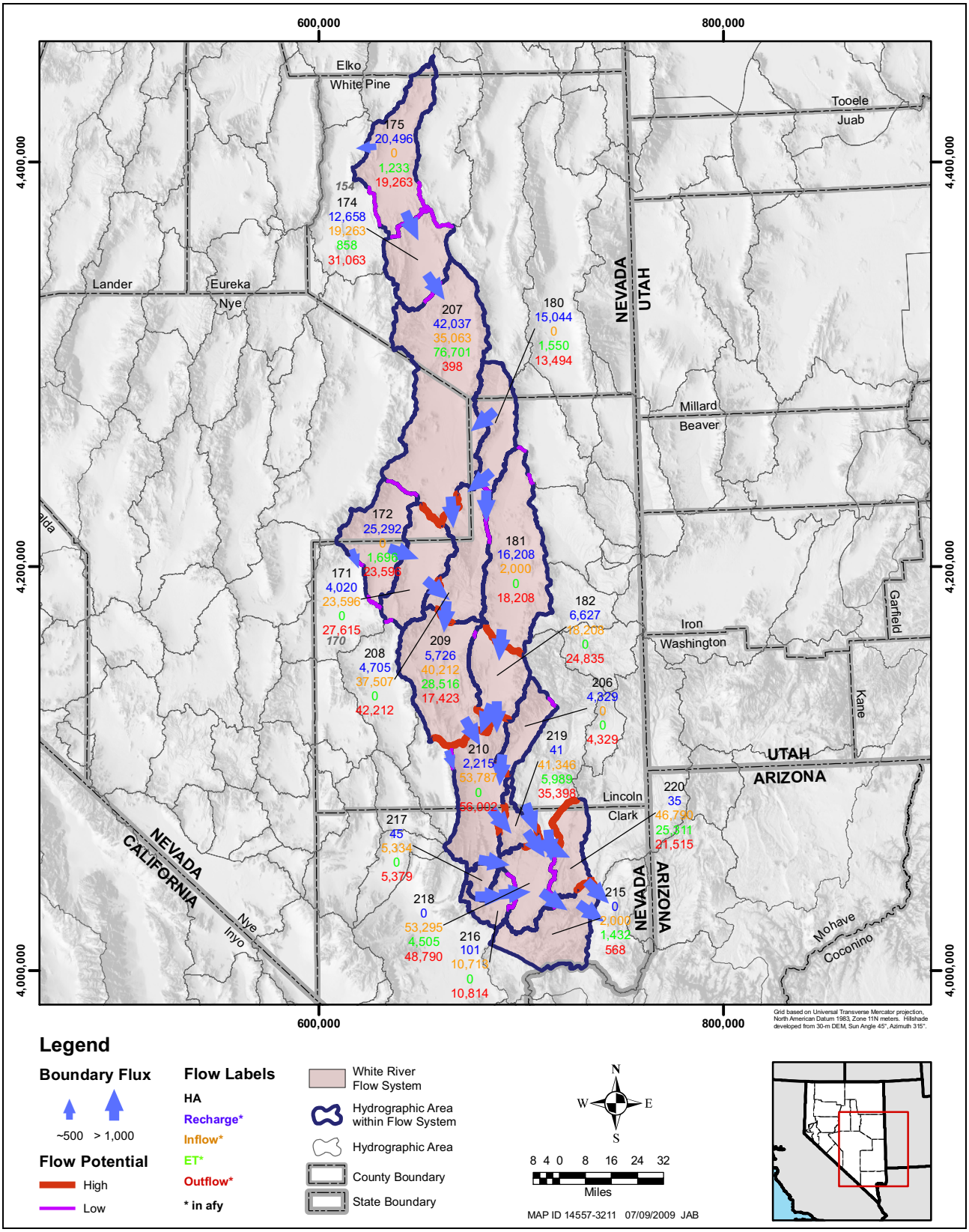

Figure I-4
Regional Groundwater Flow in White River Flow System

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Plates

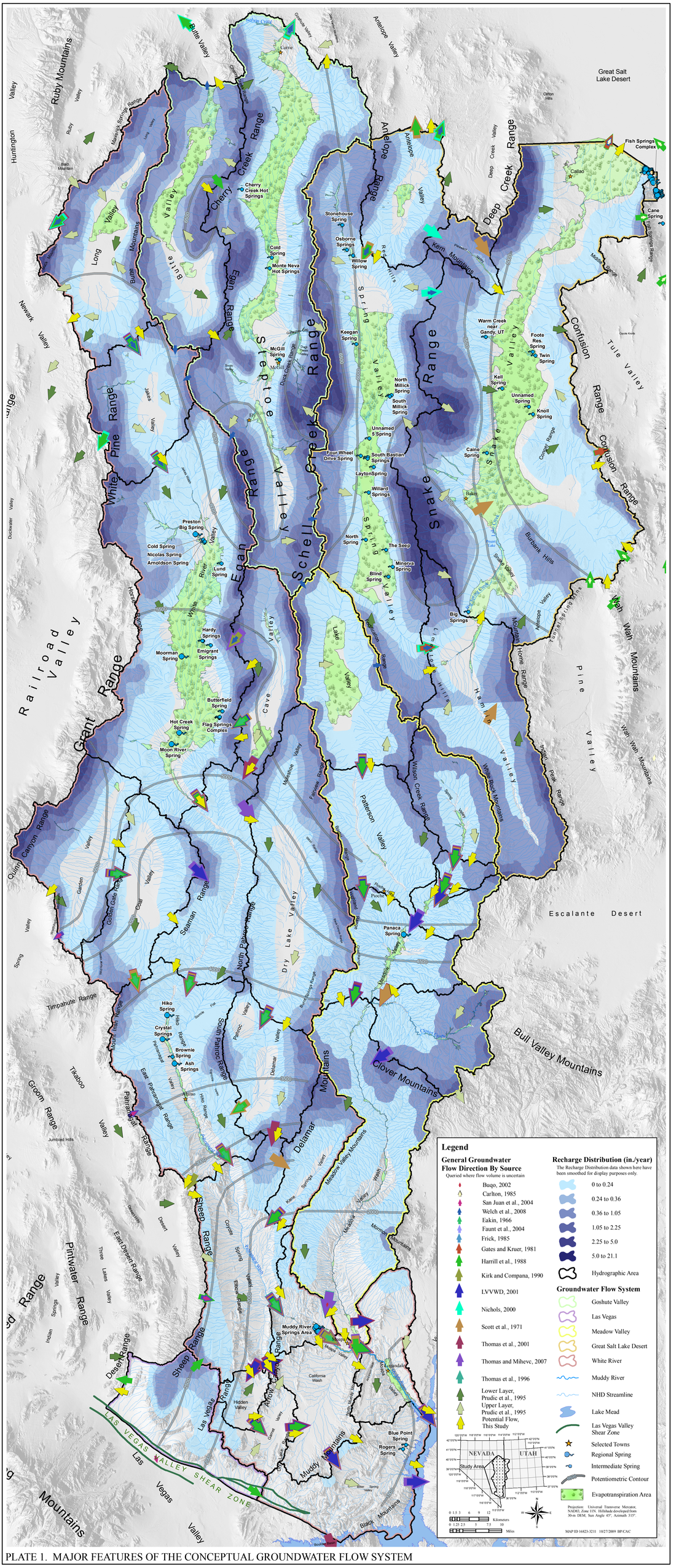


PLATE 1. MAJOR FEATURES OF THE CONCEPTUAL GROUNDWATER FLOW SYSTEM

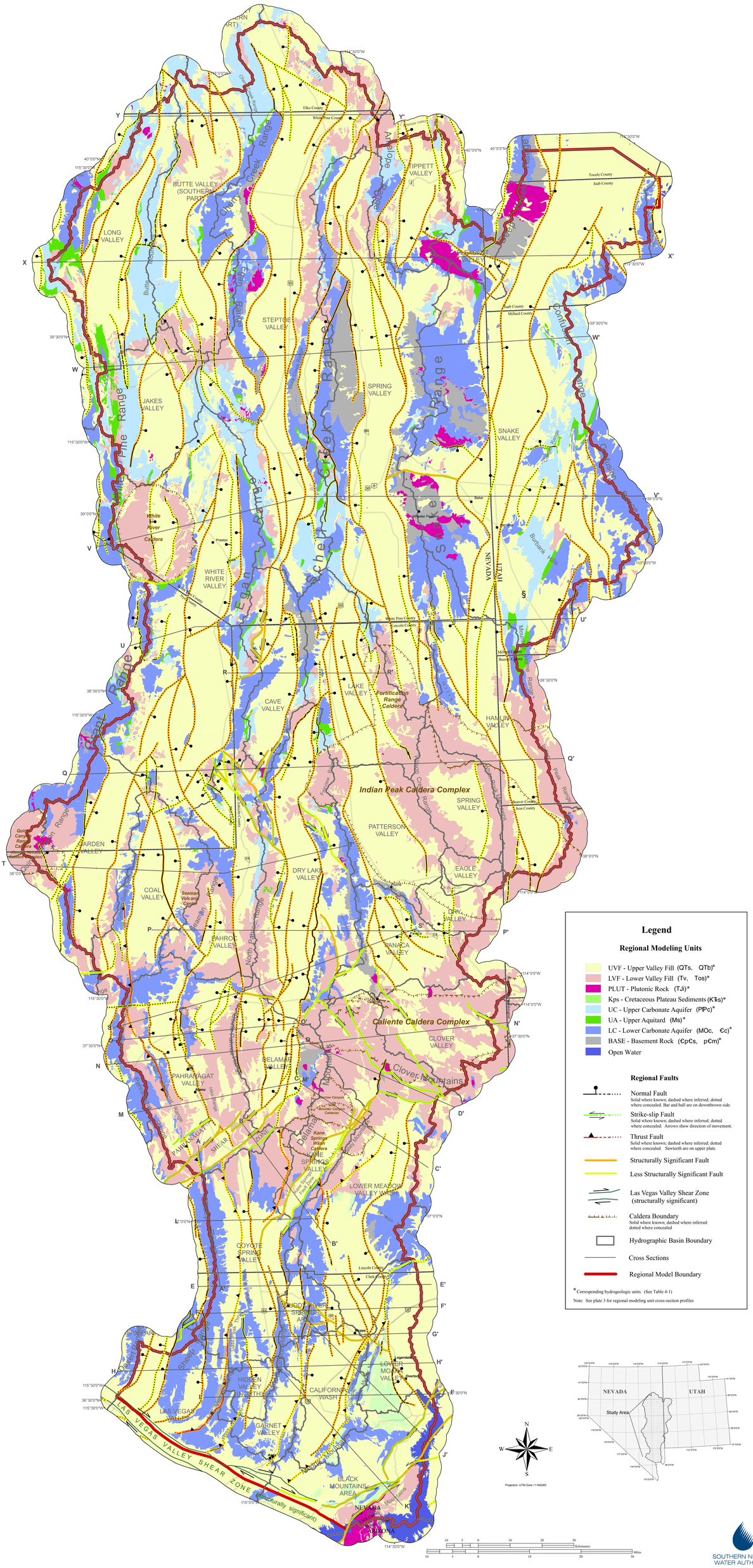


PLATE 2. SURFICIAL REGIONAL MODELING UNITS OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS, NEVADA, UTAH, AND ARIZONA

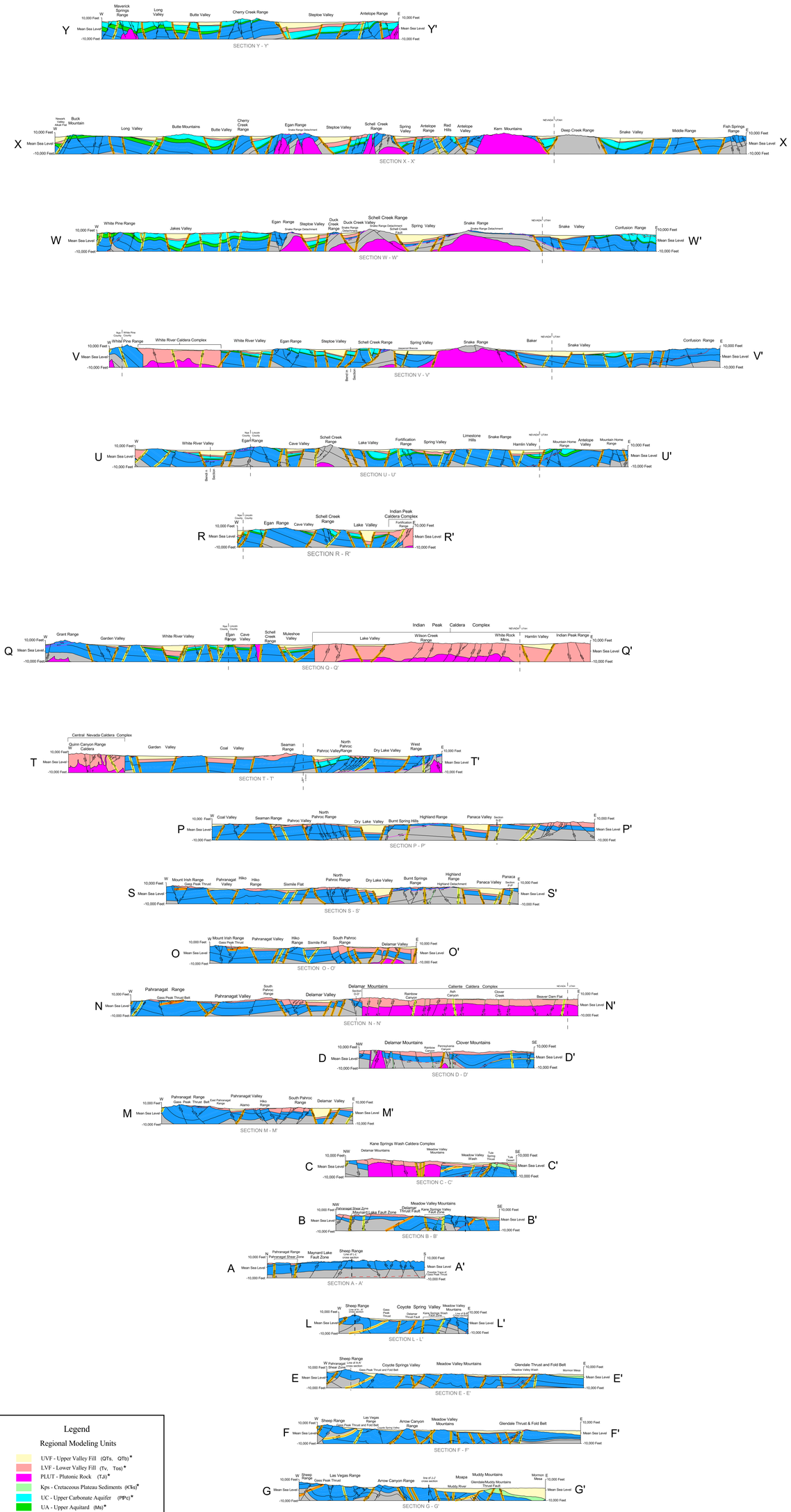
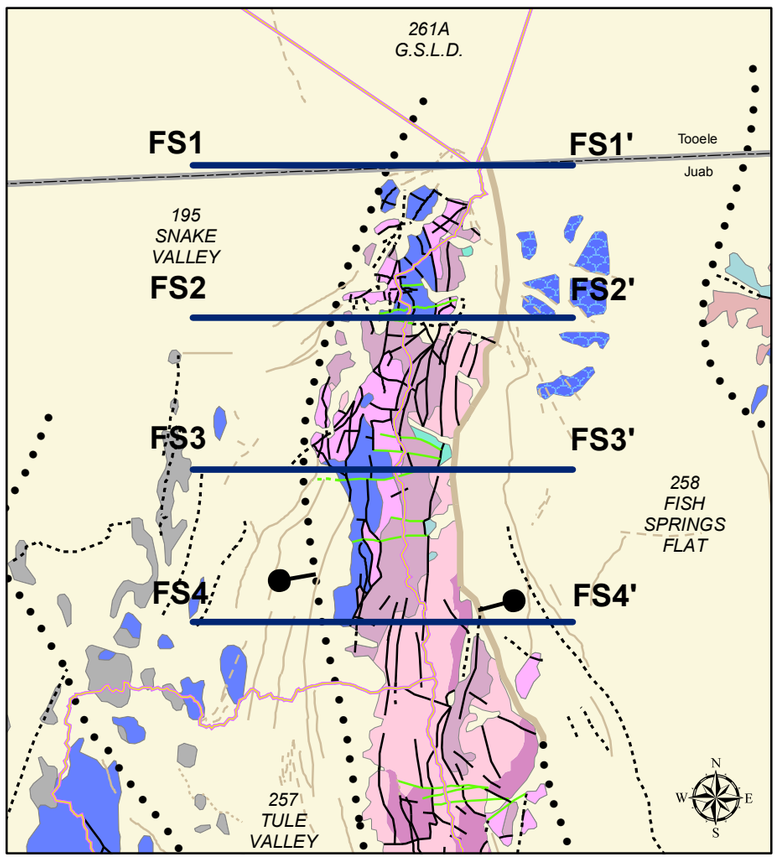


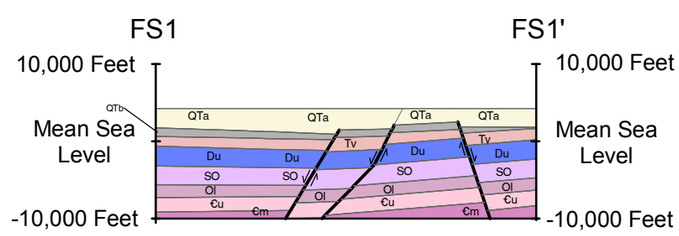
PLATE 3. CROSS SECTIONS SHOWING REGIONAL MODELING UNITS OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS, NEVADA AND UTAH

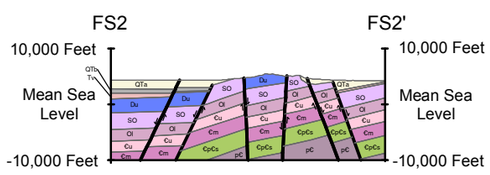
Southern Nevada Water Authority

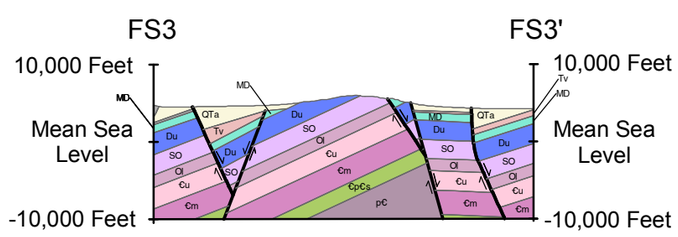
MAP ID 14956-3211 12/09/2008 JMB/JBB

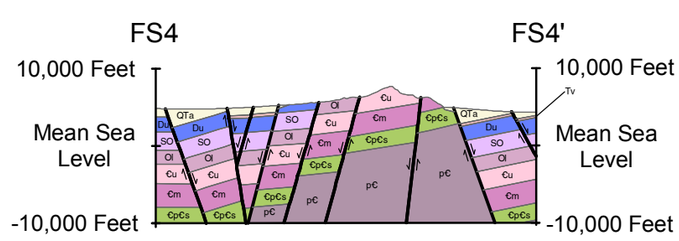
Geologic Units



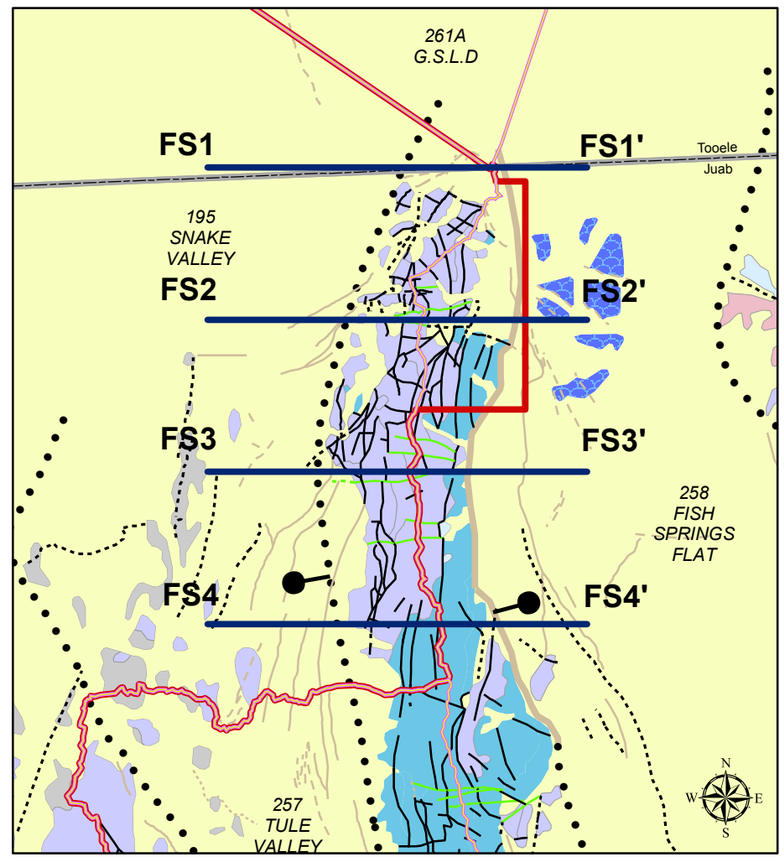


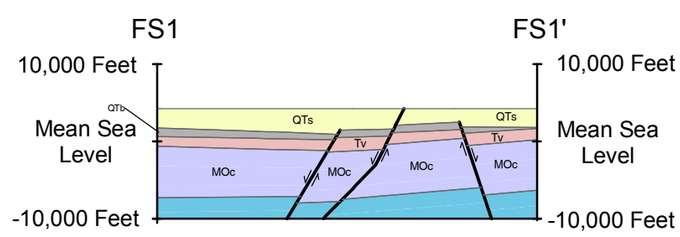


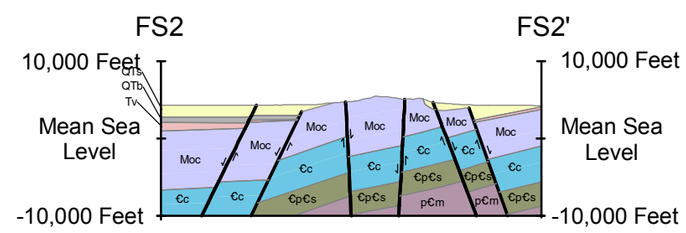


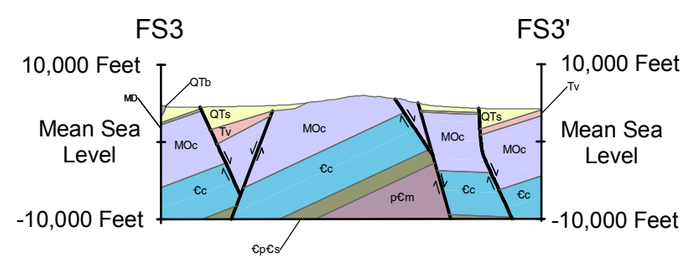


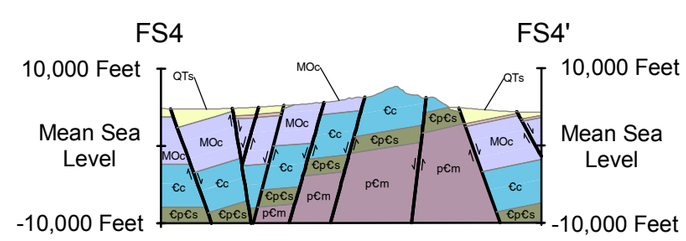
Hydrogeologic Units



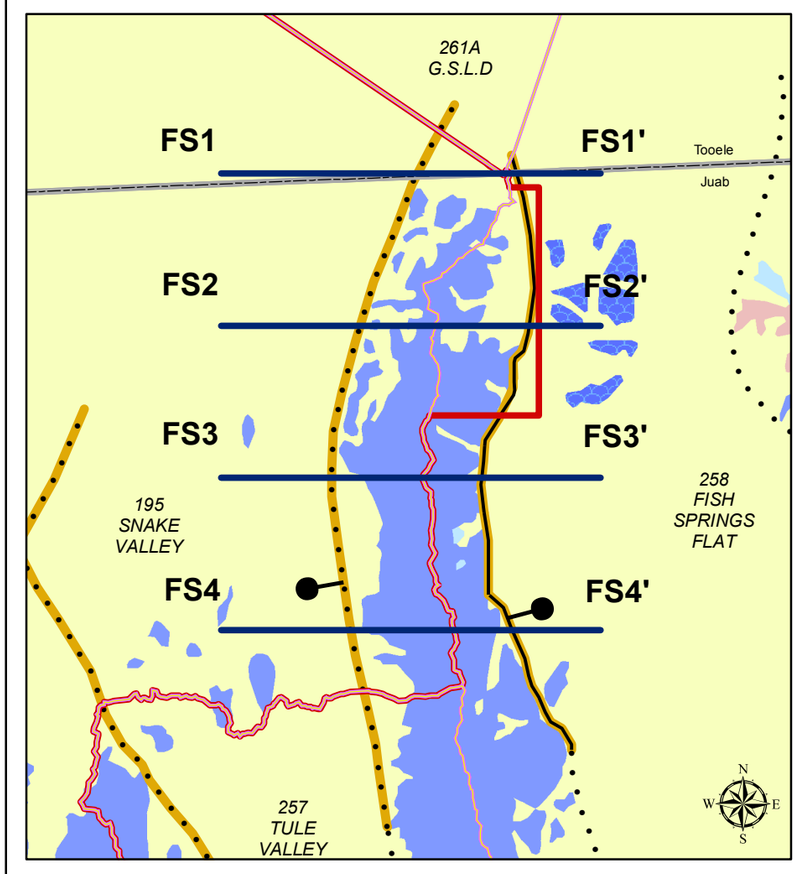


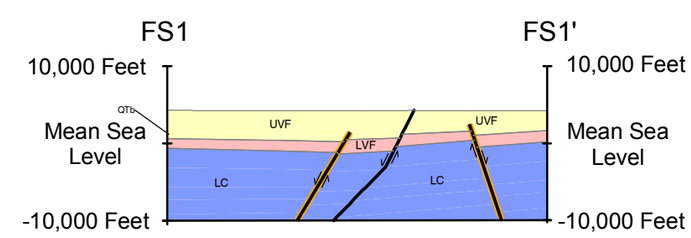


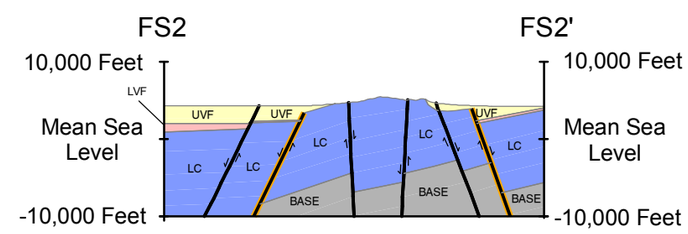


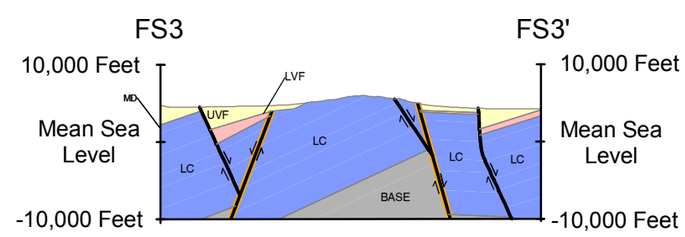


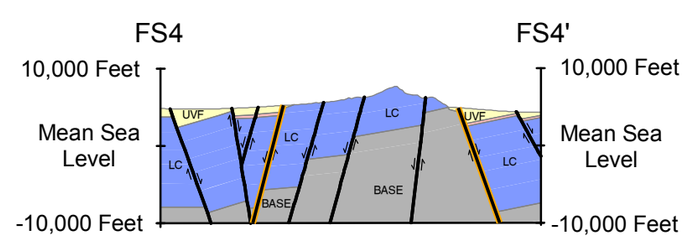
Regional Modeling Units











Geologic Units

- QTa — Quaternary and Tertiary basin-fill deposits
- QTb — Quaternary and Tertiary thin basalt flows and cinder cones
- Tv — Tertiary volcanic rocks
- Tt2 — Tertiary poorly-densely welded ash-flow tuff and interbedded airfall tuff
- IP — Pennsylvanian Ely limestone
- MD — Lower Mississippian to upper Devonian limestone and shale
- Du — Devonian carbonate sedimentary rocks, undivided
- SO — Silurian and Ordivician sedimentary rocks, undivided
- SOu — Silurian and Upper Ordovician dolomite, undivided
- Ol — Middle and Lower Ordovician, mostly eureka Quartzite and Pogonip Goup
- €u — Lower Ordovician? And Upper Cambrian limestone and shale, undivided
- €m — Upper and Middle Cambrian limestone
- €p€s — Middle Cambrian to late Proterozoic sedimentary rocks
- p€ — Late to Early Proterozoic metamorphosed and crystalline Precambrian basement rocks

Hydrogeologic Units

- QTs — Quaternary-Tertiary sediments
- QTb — Quaternary-Tertiary basalts
- Tv — Tertiary volcanic rocks
- PIPc — Permian-Pennsylvanian carbonate rocks
- MOc — Mississippian-Ordovician carbonate rocks
- €c — Cambrian carbonate rocks
- €p€s — Cambrian-Precambrian siliciclastic rocks
- p€m — Precambrian metamorphic rocks

Regional Modeling Units

(shown with corresponding Hydrogeologic Units)

- UVF — Upper Valley Fill (QTs, QTb)
- LVF — Lower Valley Fill (Tv, Tos)
- UC — Upper Carbonate Aquifer (PIPc)
- LC — Lower Carbonate Aquifer (MOc, €c)
- BASE — Basement Rock (€p€s, p€m)
- Open Water

Regional Faults

- Normal Fault — Solid where known; dashed where inferred; dotted where concealed. Bar and ball are on downthrown side of fault. Highlighted where structurally significant (RMU only).
- Quaternary Normal Fault — Solid where known; dashed where inferred; dotted where concealed.

Subsidiary Faults

- Normal Fault — Solid where known; dashed where inferred; dotted where concealed.
- Strike-Slip and Oblique-Slip Fault — Solid where known; dashed where inferred; dotted where concealed.
- Quaternary Normal Fault — Solid where known; dashed where inferred; dotted where concealed.
- Hydrographic Basin
- Regional Model Boundary
- County Boundary
- Cross Section

N W E S

0 2 4 8 12 16 Kilometers

0 2 4 8 12 16 Miles

MAP ID 15080-3211 12/09/2008 CAC/JBB

PLATE 4. SURFACE GEOLOGY, HYDROGEOLOGY, AND REGIONAL MODELING UNITS AND ASSOCIATED CROSS SECTIONS, FISH SPRINGS RANGE, JUAB COUNTY, UTAH