TETRA TECH

Development of a Numerical Groundwater Flow Model of Selected Basins within the Colorado Regional Groundwater Flow System, Southeastern Nevada

Version 1.0

Prepared For:

National Park Service

U.S. Fish & Wildlife Service

Bureau of Land Management

Prepared by:

Tetra Tech, Inc.
363 Centennial Parkway, Suite 210
Louisville, Colorado 80027

September 28, 2012

TABLE OF CONTENTS

1.0 BACKGROUND 1

1.1 Area of Investigation 2

1.2 Previous Department of Interior agency models 3

1.3 Approach 3

2.0 SOURCES OF INFORMATION 5

2.1 Geology 5

2.2 Spring and stream locations and flows 5

2.3 Evapotranspiration 5

2.4 Well Construction 5

2.5 Groundwater Production 6

2.6 Water Levels 6

3.0 GEOHYDROLOGY 8

3.1 Geologic Setting 8

3.1.1 Stratigraphy 8

3.1.2 Structural Features 9

3.2 Aquifer Parameters 10

3.3 Estimated inflow and outflow across study area boundaries 12

3.4 Precipitation/Recharge 13

3.5 Discharge 14

3.5.1 Springs 14

3.5.2 Evapotranspiration 15

3.5.3 Streams 16

3.6 Historical groundwater use 18

3.7 Potentiometric relations 18

3.7.1 Flow paths 18

3.7.2 Geologic control on gradients 19

4.0 DEVELOPMENT OF GEOLOGIC MODEL 20

4.1 Summary of Approach 20

4.2 Results 23

5.0 FLOW MODELING APPROACH 25

5.1 Development of flow-model computational grid 25

5.1.1 Grid refinement in Muddy River Springs area 25
5.1.2 Alignment with DVRFS model grid 25
5.1.3 Computational efficiency 26
5.1.4 Grid design 26
5.2 Boundary Conditions and Other Miscellaneous Datasets 28
5.2.1 Recharge 28
5.2.2 Springs 29
5.2.3 ET dataset 30
5.2.4 External boundary flux dataset 30
5.2.5 Production Well dataset 31
5.2.6 Stream-Routing Package 31
5.2.7 Faults as Hydrologic Flow Barriers 32
5.3 Calibration 32
5.3.1 Calibration Approach 32
5.3.2 Calibration Targets 33
5.3.3 Calibration Models 34
6.0 CALIBRATED MODEL 37
6.1 Hydrologic Properties of HGUs 37
6.1.1 Hydraulic Conductivity 37
6.2 Simulated water levels 42
6.2.1 Water-table map 42
6.2.2 Drawdown in Coyote Spring Valley and Muddy River Springs Area 43
6.3 Comparison of Simulated and Measured Spring Discharge 46
6.4 Comparison of Simulated and Measured Temporal Streamflows 46
6.5 Comparison of Simulated and Estimated Boundary Fluxes 48
6.6 Sensitivity Analyses 50
6.6.1 Pre-Production 50
6.6.2 Order 1169 Model 57
7.0 SUMMARY AND CONCLUSIONS 60
8.0 REFERENCES 64

LIST OF TABLES

Table 2-1. Sources of data on groundwater production 6
Table 3-1. Summary of Aquifer Test Data within the Study Area.....11
Table 3-2. Summary of boundary flux estimates 13
Table 3-3. Original Hardman Precipitation Zones and Corresponding Maxey-Eakin Recharge Efficiencies. 14
Table 3-4. Average annual ET discharge by Hydrographic Area 15
Table 5-1. Model Layer Thicknesses 27
Table 6-1. Hydraulic Conductivity Values by HGU in the Calibrated Model.....38
Table 6-2. Hydraulic Conductivity at Pilot Points used in Interpolation of PC4 Hydraulic Conductivity Field 39
Table 6-3. HUF Parameters by HGU 40
Table 6-4. Calibrated Storage Parameters by HGU 40
Table 6-5. Conductances assigned to the Horizontal Flow Barriers 41
Table 6-5. Mass Balance from the Pre-Development Model.....49
Table 6-6. Simulated discharge into Lake Mead.....49
Table 6-7. Scaled sensitivities of simulated water levels to selected parameters 52
Table 6-8. Scaled sensitivities of spring discharge rates to selected parameters. 53
Table 6-9. Scaled sensitivity of total range of water levels for selected parameters, Order 1169 simulation.....58

LIST OF FIGURES

Figure 1.1-1 Location of Study Area.
Figure 1.1-2 Physiographic Features of Study Area.
Figure 3.1-1 Geologic Map.
Figure 3.1-2 Major Faults.
Figure 3.3-1 Location of Harrill's Boundary Segments.
Figure 3.4-1 Estimated Annual Precipitation.
Figure 3.4-2 Estimated Annual Recharge Rate.
Figure 3.5-1 Locations of Wells, Springs, Stream Reaches, and Gauging Stations.
Figure 3.5-2 Designated Areas of Evapotranspiration.
Figure 3.5-3 Annual Evapotranspiration Cycle.
Figure 3.5-4 Discharge at Muddy River near Moapa.
Figure 3.5-5 Streamflow-Measurement Locations, Muddy River Synoptic Study.
Figure 3.5-6 Streamflow-Measurement Locations, Virgin River Synoptic Study.
Figure 3.6-1 Locations of Production Well Groups Used in Figure 3.5-3.
Figure 3.6-2 Annual Groundwater Pumping in Different Areas.
Figure 3.6-3 Location of Production Wells and Springs in Muddy River Springs Area.
Figure 4.1-1 Stacking of Hydrostratigraphic Units.
Figure 4.1-2 Locations of Geologic Sections, Drill-Hole Control, and Gravity Interpretation.
Figure 4.1-3 Kriging-Interpolated Thickness, PC4.
Figure 4.2-1 Estimated Unit Extents by Major Lithology.

Figure 4.2-2 Locations of Geologic Sections.
Figure 4.2-3 Comparison of Selected USGS and Geologic Model Sections.
Figure 4.2-4 Examples of Geologic Model Sections between USGS Sections.
Figure 5.1-1 Flow-Model Grid.
Figure 5.1-2 Example of Depth-Decay Relationship with and without Kmin
Figure 5.2-1 Locations of Springs, Stream-Flow Targets, and Spring-Discharge Targets.
Figure 5.2-2 Designated Areas of Evapotranspiration.
Figure 5.2-3 Stream-Routing Package Cells.
Figure 5.2-4 Faults Simulated Using HFB Package.
Figure 5.3-1 Ephemeral and Perennial Stream Segments.
Figure 5.3-2 Pre-Production Water-Level Target Locations.
Figure 5.3-3 Locations of Drawdown Target Wells.
Figure 6.1-1 Zonation of CAU.
Figure 6.1-2 Zonation of TVC and XLB.
Figure 6.1-3 Hydraulic Conductivity of PC4
Figure 6.2-1 Pre-Production Simulated Water Table.
Figure 6.2-2 Pre-Production Water Level Residuals.
Figure 6.2-3 Correlation Between Measured and Simulated Water Levels, Pre-Production Model
Figure 6.2-4 Order 1169 Pumping July 2010 – December 2011 for MX-5.
Figure 6.2-5 Comparison of Observed and Simulated Drawdown Order 1169 Simulation.
Figure 6.2-6 Drawdown from MX-5 Pumping, October 2009 – December 2011.
Figure 6.2-7 Simulated Drawdown, December 2011.
Figure 6.3-1 Observed and Simulated Spring Discharge.
Figure 6.3-2 Observed and Simulated Rogers and Blue Point Spring Discharge.
Figure 6.4-1 Observed and Simulated Ephemeral and Perennial Stream Segments.
Figure 6.6-1 Simulated Changes in Water Level, 100 Percent Increase in Horizontal Hydraulic Conductivity of CAU
Figure 6.6-2 Simulated Changes in Water Level, 100 Percent Increase in Horizontal Hydraulic Conductivity of PC1
Figure 6.6-3 Simulated Changes in Water Level, 100 Percent Increase in Horizontal Hydraulic Conductivity of PC4_1
Figure 6.6-4 Simulated Changes in Water Level, 25 Percent Increase in Regional Recharge

ATTACHMENTS

I Distributions and Top Elevations of Hydrogeologic Units

II Sensitivity Testing – Simulated Drawdowns

1.0 BACKGROUND

Continued population growth in southern Nevada is increasing the demand for water. Historically, the Colorado River and groundwater in Las Vegas Valley have met the water needs of the populace of much of southern Nevada. However, the volume of water available from these sources is limited, and groundwater resources outside of Las Vegas Valley are increasingly being targeted for development. A regional carbonate-rock aquifer has the potential for being a large and productive source of water. However, this is the regional aquifer that is the source of several large-volume warm springs that discharge on Federal lands and provide baseflow to streams. The properties that make it a productive aquifer also result in the effects of pumping the aquifer being transmitted over long distances, with eventual capture of the water that discharges from springs and thus depletion of their flow. Reduction or cessation of spring discharge on Federal lands would likely have an adverse effect on sensitive habitat and species. Development of a tool for predicting the future effects of pumping groundwater from the regional aquifer system is needed to help manage and protect the water-dependent resources on Federal lands.

Large-scale groundwater development of the regional aquifer is planned by Southern Nevada Water Authority (SNWA) and other water purveyors. The Nevada Division of Water Resources, the agency that regulates water rights within the State of Nevada, is also seeking information through studies that assist the agency in groundwater development decisions. In 2001, the National Park Service (NPS), the U.S. Fish and Wildlife Service (FWS), and the U.S. Bureau of Land Management (BLM), collectively the DOI bureaus, participated in an administrative hearing held by the Nevada State Engineer concerning proposed development in Coyote Spring Valley, about 40 miles northeast of Las Vegas Valley. As part of their preparations for hearing, the DOI bureaus cooperated in the development of a preliminary numerical groundwater flow model, prepared by GeoTrans, Inc., to simulate groundwater flow in the area and to evaluate and demonstrate the potential effects of groundwater pumping on water levels in the aquifer and on nearby spring flows. This preliminary model was constructed in a short period of time based on geologic information compiled in the early 1990's for a much larger area.

In 2002, the Nevada State Engineer issued an order (Order 1169) holding all pending groundwater applications in Coyote Spring Valley and selected nearby hydrographic areas in abeyance for at least five years, until further evaluation of the effects of groundwater pumping under existing permits is completed. Since 2000, some or all of the DOI bureaus also have interacted and negotiated with parties seeking large quantities of groundwater rights in several hydrographic areas north and northeast of Las Vegas, including Coyote Spring Valley, California Wash, Garnet Valley, Black Mountains Area, Lower Meadow Valley Wash, Kane Springs Valley, Clover Valley, Virgin River Valley, and Tule Desert. In some cases, negotiated settlement agreements were reached. Additionally, Environmental Impact Statements (EIS's) or Environmental Assessments (EA's) were conducted by the BLM pursuant to the National

Environmental Policy Act (NEPA) in some of these valleys regarding right-of-ways for proposed groundwater conveyance structures (i.e., pipelines), and consideration was given to the effects on the environment of groundwater withdrawals to supply the conveyance structures. The negotiated settlement agreements, EIS's, and EA's all contain language that requires some cooperation among the parties to develop hydrogeologic information to facilitate future water-resource management decisions. Order 1169 required that at least half of all existing groundwater rights in Coyote Spring Valley must be pumped for at least two consecutive years, before the Nevada State Engineer would consider the applicants' pending applications for additional groundwater rights. Water-level and spring discharge monitoring during the two-year "test pumping" would provide additional information on the response of the groundwater system to pumping. During the Nevada State Engineer's abeyance period and as these agreements are implemented, the DOI bureaus have participated in several scientific investigations with the goal of producing information that will enable refinement of the numerical model and improve the model's accuracy in predicting the effects of groundwater development on nearby Federal water resources.

1.1 AREA OF INVESTIGATION

The area of investigation for the expanded, updated model comprises all or portions of 13 contiguous hydrographic areas within the regional aquifer system of eastern and southeastern Nevada known as the Colorado Regional Ground-Water Flow System (CRGWFS). The area of this investigation (Figures 1.1-1 and 1.1-2) is located in southeastern Nevada and small parts of northwestern Arizona and southwestern Utah, and includes the following hydrographic areas: Clover Valley (hydrographic area #204), Lower Meadow Valley Wash (#205), Kane Springs Valley (#206), Coyote Spring Valley (#210), Garnet Valley (#216), Hidden Valley (North) (#217), California Wash (#218), Muddy River Springs Area (#219), Lower Moapa Valley (#220), Tule Desert (#221), Virgin River Valley (#222), the part of Black Mountains Area (#215) that is north and east of the Las Vegas Valley Shear Zone, and the part of Las Vegas Valley (#212) that is north of the Las Vegas Valley Shear Zone and east of the crest of the Sheep Range (see Figure 1.1-2). Hereinafter, this area is referred to as the study area. The study area is bounded on the north by the Pahranagat Shear Zone and the Caliente Caldera Complex; on the east by the Beaver Dam Mountains, the Virgin Mountains, and the Overton Arm of Lake Mead; on the south by the Las Vegas Valley Shear Zone and Lake Mead; and on the west by the Sheep Range. The principal aquifers in the study area are the regional Paleozoic carbonate-rock aquifer and basin-fill aquifers.

The NPS, FWS, and BLM each have lands under their jurisdiction within the study area. The FWS's Moapa Valley National Wildlife Refuge (NWR) is located within the study area (see Figure 1.1-2). The Moapa Valley NWR comprises an area of several large-volume warm springs (referred to collectively as the Muddy River Springs) inhabited by the endangered Moapa dace, a small desert fish. These springs, and other nearby springs (collectively referred to as the Muddy

River Springs, form the headwaters of the perennial stretch of the Muddy River. In addition, the FWS has responsibility for threatened and endangered species at other locations within the study area, including the Virgin River. The NPS's Lake Mead National Recreation Area (NRA) also occupies a portion of the study area. The Virgin and Muddy Rivers discharge into Lake Mead within the Lake Mead NRA. An area of several warm springs exists in the Overton Arm area of Lake Mead NRA (Figure 1.1-2), including Rogers Spring and Blue Point Spring, which have a combined discharge of approximately 1,000 gallons per minute. The BLM manages most of the land within the study area and has resource concerns associated with the water-dependent riparian habitat and species along the Lower Meadow Valley Wash, and several smaller springs at various locations throughout the study area. The source of the Muddy River Springs is the regional carbonate-rock aquifer. The source of Rogers and Blue Point springs is not yet completely understood; however, the majority of their recharge probably is also from the regional aquifer system. The Muddy River is sustained by regional groundwater discharge at the Muddy River Springs located in the upper Moapa Valley. The Virgin River also probably interacts with groundwater from the regional aquifer system.

1.2 PREVIOUS DEPARTMENT OF INTERIOR AGENCY MODELS

A three-dimensional model of part of the study area was developed by GeoTrans, Inc. in 2001 using an available geologic model and hydrologic information. This model was used to develop preliminary estimates of the effects of pumping in Coyote Spring Valley on springs in the Muddy River Springs area. It was revised and recalibrated in 2003 (GeoTrans, 2003) to include the addition of head-dependent flux boundary conditions, updating of land surface elevations, modification of boundary condition parameters, minor modifications to the model grid, and incorporation of newly identified and updated pumping and water-level data. While this model was an improvement on the 2001 model, the results of this model indicated that additional refinement of the model was necessary to improve its predictive ability.

1.3 APPROACH

The current model expansion and refinement involved:

1. Adding the lower Virgin River Valley and Clover Valley hydrographic areas to the model domain;
2. Construction of a new 3-D geologic framework of the study area based on recent studies and reports;
3. Incorporation of the results from recent evapotranspiration (ET) studies conducted by the USGS providing spatial and temporal distributions of ET rates;
4. Inclusion of new geologic, hydrologic, and geochemical information gathered from the drilling, construction, and sampling of several new production and monitoring wells in the study area by the Southern Nevada Water Authority (SNWA), by Vidler Water Company, Inc. (VWC), a private water-development firm, and others; and

5. Calibration of the model developed using MODFLOW-2000 (Harbaugh, et al., 2000) to observed water levels, streamflow and spring discharge information, and responses to temporally varying evapotranspiration and pumping rates.

2.0 SOURCES OF INFORMATION

2.1 GEOLOGY

Model refinements included constructing a new 3-D geologic framework model of the study area based on recent: (1) geologic mapping conducted cooperatively by consultants for the SNWA and by the U.S. Geological Survey (USGS), in cooperation with the NPS, FWS, SNWA, and the Virgin Valley Water District(VVWD); (2) geologic cross sections constructed by the USGS in cooperation with the NPS (Page et al., 2011) and by Dixon and Katzer (2002) in the Virgin Valley basin; and (3) geophysical studies by the USGS of the 3-D extent of Tertiary-aged basins within the study area in cooperation with the NPS.

2.2 SPRING AND STREAM LOCATIONS AND FLOWS

Information concerning spring and stream discharge was obtained from several different sources. The USGS maintains the National Water Information System database which provided data on spring and stream discharge gaging sites maintained by the USGS. The Southern Nevada Water Authority performed an inventory of wells and springs (SNWA, 2003, 2005) which included information on springs in the Muddy River Springs area. The USGS, with support by the NPS, performed synoptic streamflow surveys on the Muddy River (Beck and Wilson, 2006) and Virgin River (Beck and Wilson, 2005) which provided streamflow measurements on these rivers at many locations at a given point in time.

Locations for small springs that did not have surveyed locations were determined from locating them with on topographic maps followed by observing their locations on Google Earth. The locations and elevations were determined from the Google Earth coordinates.

2.3 EVAPOTRANSPIRATION

The spatial and temporal distributions of evapotranspiration rates were determined during recent evapotranspiration (ET) studies conducted by the USGS and the U.S. Bureau of Reclamation (USBR). The National Park Service funded the United States Geological Survey to delineate the distribution of and to quantify the amount of annual discharge from ET for the study area (DeMeo et al., 2008). These estimates were based on a combination of satellite mapping of plant communities and measurement of evaporation rates at different locations in southern Nevada using energy-balance techniques. In addition, the energy-balance studies provided information on ET rates during the year, across the growing and non-growing seasons.

2.4 WELL CONSTRUCTION

Well-construction data have been assembled and entered into a database for the development of modeling datasets. These data include surveyed coordinates, surveyed top of casing, ground surface elevation, and well depth. Sources of these data include USGS National

Water Information System (NWIS, 2012) and SNWA websites, references listed in Table 3-1 below, personnel from USGS, NPS, FWS, and BLM, and the reports listed in the Water-Level Data section. Additional reports that contain well construction information include Hess (1986), Berger et al. (1988), SNWA and the Las Vegas Valley Water District (LVVWD) (2003), Lincoln County Water District (LCWD) and VWC (2005), SNWA and LVVWD (2005).

2.5 GROUNDWATER PRODUCTION

Data on groundwater production were obtained from the sources listed in Table 2-1.

Table 2-1. Sources of data on groundwater production

Source	Years	Wells
SNWA	1987-2007, 2010-2011	Behmer, Lewis, LDS, Arrow Canyon, Garnet (GV), LMVW, CSI, MX, Cogen, RW-1
Desert Research Institute (DRI)	1987-1995	Lewis, LDS, Behmer, LMVW
Moapa Valley Water District (MVWD)	1993-2007	Arrow Canyon, MX
Vidler Water Company (VWC)	2001-2007	MW1-10 and FF1 and 2B
Coyote Springs Investment (CSI)	2005-2007, 2011	CSI, MX
VVWD (from Nevada Department of Water Resources (NDWR))	1999-2011	VVWD, Bunkerville
Las Vegas Valley Water District (LVVWD)	1949-1986, 2008-2009	Behmer, Lewis, GV
NDWR	1999-2011	GV, Arrow Canyon, Behmer, CSI, CSV-RW2, LDS, Lewis, MX, Cogen, Paiutes, Perkins, Republic, RG

2.6 WATER LEVELS

A data set consisting of water-level information (i.e., depth to water or static water level elevation measurements) for the model area has been developed for this study. The primary data sources were the NWIS, SNWA website, and the Nevada Division of Water Resources (NDWR, 2011). The NWIS, SNWA, and NDWR data have been supplemented by the following reports: Eakin (1964), Rush (1964), Mifflin and Zimmerman (1984), Pohlmann et al. (1988), Mifflin et al. (1989), Pohlmann and Wert (1989, 1990, 1991, and 1992), Black and Rascona (1991), Buqo et al. (1992), Brothers et al. (1993), Pohlmann (1993, 1994, 1995, and 1996), Enright (1996), MVWD (1997, 1998, 1999, and 2000), Converse (2000, 2001, 2004, and 2005), Kleinfelder (2000), LVVWD (2001), Johnson et al. (2001), VVWD and Entrix (2006), LCWD and VWC

(2007), and SAHRA (2008). These data were used as calibration targets in the steady-state and transient groundwater flow models.

3.0 GEOHYDROLOGY

This section describes the geologic setting of the study area and then provides information pertaining to the movement of water in the groundwater system. A key component of the groundwater hydrology is the rate at which water enters and leaves the study area. Thus, much of this section relates to the water budget for the area and the locations where water enters and leaves the study area. Additional information is provided in Section 5, which provides information on the groundwater flow model.

3.1 GEOLOGIC SETTING

In 2005, the Nevada Bureau of Mines and Geology published Map 150, Geologic Map of Parts of the Colorado, White River, and Death Valley Groundwater Flow Systems, prepared by Page, Dixon, Rowley, and Brickey (Figure 3.1-1). This work, which was supported by the SNWA, National Park Service, FWS, and Virgin Valley Water District, summarized the results of many investigators over several decades. Accompanying text describes the stratigraphic and structural features within the current study area, and provides the basis for the discussion below.

3.1.1 STRATIGRAPHY

Rocks and sediments range in age from Early Proterozoic through Holocene. For purposes of this discussion, they have been grouped according to their age and role in the movement of groundwater in the study area.

Early Proterozoic – The Early Proterozoic rocks are low-permeability metamorphic gneiss and schist, and intrusive granite. They are located in the Beaver Dam and Virgin Mountains along the eastern side of the study area, and in the core of the Mormon Mountains. They act as groundwater barriers where present.

Late Proterozoic and Lower Cambrian – Late Proterozoic sedimentary rocks are primarily quartzite, conglomerate, sandstone, siltstone, and shale that may contain limestone and dolostone. They are well-cemented and have low permeability. These rocks are located in the Desert and Sheep Ranges in the western part of the study area, and in the Delamar Mountains in the northern part. The younger Lower Cambrian are similar in lithology to the Late Proterozoic clastic rocks. The combined Late Proterozoic and Lower Clastic rocks are thickest in the Desert Range on the west side of the study area. The Late Proterozoic rocks thin to the east, and are absent in the Mormon, Virgin, and Beaver Dam Mountains. The Lower Cambrian rocks are represented by the Tapeats sandstone and Bright Angel shale in the eastern part of the study area.

Middle Cambrian through Lower Permian – These rocks are predominately limestones and dolostones, and form the widespread regional carbonate-rock aquifer in the study area, and in areas to the north and west of the study area. These rocks can be very permeable because of faulting, fracturing, and dissolution. As discussed below, low-angle thrust faults have resulted in

repeated stacking of these rocks, resulting in thickness of the aquifer greater than the original stratigraphic thickness of the sequence. The younger rocks contain higher proportions of clastic material (Dunderberg Shale, Eureka Quartzite, Chainman Shale, Indian Springs Formation, and Lower Permian redbeds), which can serve as confining units in local areas.

Lower Permian through Cretaceous – These rocks include the Lower Permian Kaibab and Toroweap Formations; Triassic Chinle and Moenkopi Formations; Jurassic Aztec and Navajo Sandstones, Kayenta and Moenave, Carmel, and Temple Cap Formations; and Cretaceous sandstones, conglomerates, siltstones, mudstones, and shales. Generally these rocks are much less permeable than the underlying carbonate rocks, although the Navajo serves as an aquifer in southeastern Utah and northeastern Arizona because of its thickness there. The Lower Permian through Cretaceous rocks are present in the southeastern part of the study area, especially the Muddy and Virgin Mountains.

Upper Cretaceous through Miocene intrusive rocks – These low-permeability rocks are locally present near Lake Mead, beneath the Clover Mountains, near the Caliente caldera complex, and north and west of Kane Springs Wash.

Tertiary Volcanic Rocks – The northern part of the study area contains several caldera complexes, the largest being the Caliente complex, which deposited ash-flow and air-fall tuffs. The ash-flow tuffs can serve as local aquifers. The calderas are likely floored by lower-permeability intrusive rocks. Volcanoes are also present in the study area north of Lake Mead.

Tertiary through Quaternary sedimentary rocks and deposits – Extensional tectonics created several deep basins which have been filled with fluvial and lacustrine deposits of variable lithology. The older deposits are more consolidated than the younger deposits, and would thus tend to be less permeable. Deposits of tuffaceous sandstones, tuff, conglomerates, limestones, siltstones, mudstones, gypsum, and halite are present. The Miocene and Oligocene-aged Horse Spring Formation is at least 8,500 feet thick beneath the Muddy Mountains, and may be more than 10,000 feet thick in deeper basins. The younger Muddy Creek Formation is less well consolidated. It is widespread, and is at least 3000 feet thick in some areas, and may be thicker in deep basins. It contains halite and other evaporite minerals near the Overton Arm of Lake Mead. The Muddy Creek Formation is hydrologically significant near the Muddy River Springs area; where thin or absent, water can discharge from the underlying carbonate aquifer as springs and seeps near and beneath the Muddy River. Further downstream, its presence above the carbonate rocks prevents substantial discharge into the Muddy River.

3.1.2 STRUCTURAL FEATURES

There are several different styles and times of faulting, ranging from Mesozoic through the present (Figure 3.1-2). The Sevier deformation, beginning during the Cretaceous and continuing through the Paleocene, produced eastward movement of sheets of the late Proterozoic

and Paleozoic rocks creating repeated stratigraphic sections. The Gass Peak thrust (present near the western edge of the study area in and north of the Las Vegas Range) and the Muddy Mountain thrust (along the east side of California Wash and extending north-north-eastward through the Mormon Mountains) are the most significant of these Sevier faults.

During the Tertiary, normal-style Basin-and-Range faulting created the north-trending basins and mountain ranges observed today. Examples include the west-dipping unnamed fault on the western side of the Arrow Canyon Range and extending northward beneath Coyote Spring Valley, and the west-dipping Piedmont fault on the east side of the Virgin Valley. The East Arrow Canyon Fault system on the east side of the Arrow Canyon Range appears to be significant in the development of the groundwater discharge zone in the Muddy River Springs area. Both east- and west-dipping normal faults are likely to be present buried beneath the basin-fill deposits. Page et al. (2005) mapped hidden normal faults forming a graben beneath the Tule Desert.

Some of the basins are very deep (the USGS interpretation is presented below in Figure 4.1-1). Gravity and seismic data indicate that the Virgin River basin might exceed 8,000 meters (26,000 feet) in the northwestern corner of Arizona, and more than 6,000 meters in Nevada. California Wash has two sub-basins, separated by a high near the Muddy River and Lower Meadow Valley Wash.

Additionally, more recent right- and left-lateral faulting has occurred. The right-lateral faults strike approximately northwest to southeast, and the conjugate system left-lateral faults strike to the southwest. The most apparent nearby example is the right-lateral Las Vegas Valley shear zone which strikes northwest to southeast, and borders the study area on the south. To the west of the study area, movement along this fault has caused rotation of Basin-and-Range mountain blocks along the fault. The left-lateral Pahranagat shear zone forms the northwestern boundary of the study area. Left-lateral faults within the study area include the Kane Springs Wash fault zone, which extends to the southwest to Coyote Spring Valley and merges with the unnamed normal fault on the west side of the Arrow Canyon Range, and several faults in the Lake Mead fault zone near the southeastern edge of the study area.

3.2 AQUIFER PARAMETERS

Within the study area, there have been few aquifer tests conducted to measure transmissivity or hydraulic conductivity and storativity. The tests that have been conducted to date were located in the basin fill and carbonate units only. However, there is a high variability of values obtained even for wells located close together. For example, carbonate wells Arrow Canyon and Arrow Canyon #2 have transmissivities that vary by a factor of about 3 even though the wells are located about 25 feet apart. Table 3-1 summarizes aquifer test results within the study area.

Table 3-1. Summary of Aquifer Test Data within the Study Area

Well ID	HSU	T (ft^2/d)	K (ft/d)	S (-)	Date	Reference
MX-4	Carbonate	40,000 200,000	-	-	12/1980 1985	Bunch and Harrill (1984) Dettinger et al. (1995)
MX-5	Carbonate	250,000 250,000	-	- 0.14	7-9/1981 1985	Bunch and Harrill (1984) Dettinger et al. (1995)
MX-6	Carbonate	13,000	-	-	12/1986	Dettinger et al. (1995)
Arrow Canyon	Carbonate	310,880	-	-	12/1993	Buqo (1994)
Arrow Canyon #2	Carbonate	92,940	-	-	6/2004	Buqo (2002)
EH-4	Carbonate	360,000	-	-	6/2004	Buqo (1994)
CSV-2	Carbonate	1,600	-	-	6/1986	Dettinger et al. (1995)
CE-VF-2	Basin Fill	3,000	-	-	2/1986	Dettinger et al. (1995)
ECP-2	Carbonate	109,500	-	0.0081	7/2000	Johnson et al. (2001)
TH-2	Carbonate	53,820	-	0.00031	7/2000	Johnson et al. (2001)
TH-1	Carbonate	80,110	-	0.039	7/2000	Johnson et al. (2001)
Breedlove North	Basin Fill	24,120 72,360	- -	- -	2000 2001	Buqo (2000) URS (2001)
Breedlove South	Basin Fill	87,100	-	-	2000	Buqo (2000)
KPW-1	Carbonate	4,313 to 11,667	-	0.00019	1/2006	URS (2006)
CSI-2	Carbonate	18,000	28	-	2005	Johnson (2005a)
CSI-1	Carbonate	16,000	34	-	2005	Johnson (2005b)
CSI-3	Carbonate	12,000	19	-	2006	Johnson (2007)
CSI-4	Carbonate	130,000	190		12/2007	Johnson (2008)
RW-2	Carbonate	308,200 to 415,400	-	-	2002	Converse (2002)
Well #3	Basin Fill	4,824 to 23,584	-	-	2001	URS (2001)
MW-1A	Basin Fill	5,494 to 12,998	-	-	2001	URS (2001)
RW-1	Carbonate	64,000 to 530,000	-	0.00015 – 0.0068	2001	SRK (2001)
PW-1	Carbonate	1554 to 2117	-	0.005	2001	Hydrosystems (2002)
PW-2	Carbonate	683.4	-	0.00038	2007	BLM (2009)
WL31	Basin Fill	4,844 to 19,900	9.8 to 17.7	.0012 to .107	2003	Burbey et al., 2005

Aquifer test data outside the study area has also been compiled to support multiple versions of the Death Valley Regional Flow System model (Belcher, 2001; IT, 1996) and the NTS regional model (IT, 1997). Another study by Maurer et al. (2004) presents a summary of hydraulic conductivity values by rock type in Nevada.

3.3 ESTIMATED INFLOW AND OUTFLOW ACROSS STUDY AREA BOUNDARIES

Table 3-2, modified from Harrill (2007) gives Harrill's estimated groundwater flux value across different segments of the external boundary of the study area. Figure 3.3-1 shows the locations of these boundary segments. There is a net inflow into the area, most water coming into Coyote Spring Valley from Tikapoo Valley on the west side of the Sheep Range (CSV-2) and from Pahranagat Valley (CSV-3). Harrill estimated that the flow into or out of the model was low along most of the study-area boundary.

Table 3-2. Summary of boundary flux estimates

Boundary Segment	Flux (ac-ft/yr)	Comments
LVV-1	0	No flow
LVV-2	0 to -500	Outflow. Water for Corn Creek discharge area, use only if model performance is improved.
LVV-3	0	No flow
CSV-1	0	No flow
CSV-2	2,600 to 7,300	Includes up to 2,200 acre-ft/yr from Pahranagat Valley
CSV-3	32,300	35,000 less 2,200 to CSV and 500 that flow directly from Delamar Valley
CSV-4	250	Flow directly from Delamar Valley
KSV-1	250	
KSV-2	0	No flow
LMVW-1	0	No flow
LMVW-2	100 to 300	Shallow flow in alluvium. May be some deep flow in carbonate rocks not estimated here.
CV-1	0	No flow. May be some deep flow in carbonate rocks not estimated here.
VRV-1	0	No flow
VRV-2	2,123	Calculated from streamflow measurements and recharge estimates
VRV-3	8,700	Subsurface flux, 8,700 af/yr plus recharge E flank of BDM plus drainage from north and south areas.
VRV-4	254	Calculated from streamflow measurements and recharge estimates
VRV-5	0	No flow
VRV-6	-2,000 to -4,000	Rough estimate by author. Estimate in Reconnaissance Report 51 is probably high.
LMV-1	-1,100	Subsurface outflow
BMA-1	Less than -30	From local recharge
BMA-2	-2,000 to -3,000	Primarily discharge from carbonate rocks
BMA-3	Less than -30	From local recharge
BMA-4	Less than -30	From local recharge
BMA-5	Less than -50	From local recharge.

[Estimates in acre-ft/yr unless otherwise indicated; positive values indicate flow into the study area. Abbreviations: LVV-Las Vegas Valley; CSV-Coyote Spring Valley; KSV-Kane Springs Valley; LMVW-Lower Meadow Valley Wash: CV-Clover Valley: VRV Virgin River Valley; BDM-Beaver Dam Mountains; BMA-Black Mountains Area]

3.4 PRECIPITATION/RECHARGE

For this model, recharge was estimated based on a modification of the Maxey-Eakin method (Maxey and Eakin, 1949). The Maxey-Method method identified five precipitation

zones, and assigned a recharge factor, or efficiency, to each of the zones. The recharge was then calculated by multiplying the precipitation rates by the correct recharge efficiency, and summing the values. In the Maxey-Eakin method, recharge was calculated using the precipitation zones defined by the Hardman map (1965), and the recharge efficiencies from Maxey-Eakin (Table 3-3).

Table 3-3. Original Hardman Precipitation Zones and Corresponding Maxey-Eakin Recharge Efficiencies.

Hardman Precipitation Zone	Recharge Efficiencies
< 8 in	0.00
8-12 in	0.03
12-15 in	0.07
15-20 in	0.15
> 20 in	0.25

In this study, the Maxey-Eakin method was modified by using a different source of information to estimate the annual precipitation (Figure 3.4-1, PRISM dataset), and a polynomial equation based on Table 3-3 to represent the recharge efficiencies, rather than the actual values in Table 3-3. The estimated annual recharge is presented in Figure 3.4-2. Additional information is provided in Section 5.2.1.

3.5 DISCHARGE

3.5.1 SPRINGS

There are three major groupings of springs within the study area (Figure 3.5-1). The greatest discharge occurs from springs located along the Muddy River on the east side of the Arrow Canyon Range upstream from Moapa. Water from the carbonate aquifer discharges either as discrete springs or as diffuse seepage into the Muddy River. The discharge rate prior to significant development of wells and pumping of groundwater from the shallow basin fill sediments or from the carbonate aquifer was approximately 34,000 af/yr, as measured at the stream gage 09416000 “Muddy River near Moapa”. With development, pumping had decreased the discharge to approximately 22,000 af/yr in 2004. The discharge increased to approximately 27,000 af/yr in 2011.

The second group of springs are Rogers and Blue Point Springs, located within the Lake Mead National Recreation Area. The springs, which discharge at rates of 1,200 and 400 af/yr, respectively, are located on the upgradient side of the Rogers Spring Fault. The temperature and chemistry of the water, and the limited (but present) variation in discharge rate, indicate that the discharge is a mixture of deep carbonate aquifer water and a smaller amount of shallower water that is recharged locally.

The third group includes the remaining springs, which are small springs that discharge water that is believed to be locally recharged. Nearly all are located in the higher elevation areas. Many of the springs may be perched.

3.5.2 EVAPOTRANSPIRATION

Evapotranspiration (ET) is a process by which water from the earth's surface is transferred to the atmosphere. ET, for the purposes of this model, includes evaporation from open water and soils, and transpiration from plants. Recently, the NPS funded the USGS to delineate the distribution of and to quantify the amount of annual discharge from ET for the study area (DeMeo et al., 2008). Seven ET units were identified: dense meadowland vegetation (200 acres), dense woodland vegetation (7,000 acres), moderate woodland vegetation (6,000 acres), dense shrubland vegetation (6,000 acres), moderate shrubland vegetation (21,650 acres), agricultural fields (3,000 acres), and open water (280 acres). Figure 3.5-2 shows the location of these ET units within the study area. The ET units are typically located on valley floors and usually include naturally vegetated areas. Annual total ET was computed using micrometeorological field stations in four ET-unit areas and estimated based on previous ET studies in southern Nevada at the other 3 ET-unit areas. Annual groundwater discharge from ET totaled 98,000 acre-feet for the entire study area. These areas are fed entirely or largely by groundwater discharge. The ET rate varies throughout the year, because water usage by plants increases during the summer growing season (Figure 3.5.3). Table 3-4 lists the average-annual ET discharge for each hydrologic basin within the study area.

Table 3-4. Average annual ET discharge by Hydrographic Area

Hydrographic Area	Total ET discharge (acre-feet/year)
Black Mountains Area (215)	2,000
California Wash (218)	6,000
Muddy River Springs Area (219)	4,000
Lower Moapa Valley (220)	11,000
Virgin River Valley (222)	52,000
Lower Meadow Valley Wash (205)	17,000
Clover Valley (204)	6,000
Coyote Spring Valley (210), Kane Springs Valley (206), Tule Desert (221), Hidden Valley North (217), Garnet Valley (216)	0
TOTAL	**98,000**

3.5.3 STREAMS

The principal streams in the study area are the Muddy River and the Virgin River. These rivers flow into northern part of the Overton Arm of Lake Mead. They are perennial in their downstream portions, but upstream segments are intermittent.

Muddy River – The channel of the Muddy River enters the study area from Pahranagat Valley. The channel passes to the south through Coyote Spring Valley. The confluence with Kane Springs Wash (an intermittent stream) is in the northern part of Coyote Spring Valley. The channel continues to the south until near where Highway 168 enters Coyote Spring Valley northwest of Moapa, where the channel turns to the southeast through the Arrow Canyon Range. In Coyote Spring Valley, there is no baseflow in the river. However, limited groundwater discharges into the river within the Arrow Canyon Range approximately 5 miles further downstream. Approximately four and one-half miles further to the southeast, the Muddy River leaves the higher relief area of the Arrow Canyon Range and enters a more open, lower relief area. At this point, significant groundwater discharge into the river begins, creating the Muddy River Springs area, and turning the Muddy River into a perennial stream. The Muddy River continues to flow to the southeast to Lake Mead. At the location of the USGS stream gage at Moapa, the baseflow in the river was approximately 40 cfs in the early 1970s.

Near Moapa, Meadow Valley Wash enters the Muddy River. Meadow Valley Wash is fed by groundwater at different points downstream of where it enters the study area (near Caliente) and its confluence with the Muddy River. Meadow Valley Wash is fed by groundwater within the lower 5 to 6 miles above the confluence, but is intermittent for about 8 or 9 miles above that.

Downstream from the confluence with Meadow Valley Wash, water is diverted from the Muddy River to the extent that flow in the river is so greatly diminished that the flow at the gage at Lewis Avenue is only about 4 cfs.

Virgin River – The Virgin River enters the study area at an area known as the Virgin River Narrows, where Interstate 15 passes through the Virgin Mountains. It is perennial where it enters the study area. At Littlefield, AZ, Beaver Dam Wash joins the Virgin River. Beaver Dam Wash is intermittent over most of its course, but is fed by groundwater near Littlefield. There is a group of springs known as Littlefield Springs that is located on the east side of the Virgin River where Interstate 15 crosses the river. The highest springs are tens of feet higher than the river.

Downstream to Mesquite, NV, groundwater is shallow and provides discharge to the river in areas. From Mesquite downstream to Lake Mead, groundwater is discharged by evapotranspiration, and perhaps by discharge to the river. Several dry tributary channels, including Toquop Wash, enter the Virgin River between Mesquite and Lake Mead.

3.5.3.1 GAGING STATIONS

Stream gaging stations at different stretches along the Muddy River provide information on the spatial and temporal changes in stream flow. (See Figure 3.5-1 for the locations of washes, streams, gaging stations.) Their periods of record differ, and do not provide information over the entire timeframe of interest. The gage identified as Muddy River at Moapa has the longest period of record, and provides information at a critical location with respect to groundwater discharge into the Muddy River (Figure 3.5-4). The earliest measurements (approximately 47 cfs, or 34,000 af/yr) were made in 1914. Groundwater pumping and surface-water diversions upstream of the gage have caused measureable declines in the streamflow, beginning in approximately 1960.

3.5.3.2 SYNOPTIC STUDIES ALONG THE MUDDY AND VIRGIN RIVERS

The U.S. Geological Survey conducted two synoptic ("Snapshot-in-time") studies of discharge of the Muddy River in February 2001 (Beck and Wilson, 2006) and of the Virgin River in February 2003 (Beck and Wilson, 2005).

The study of the Muddy River Springs Area and the Muddy River (Figure 3.5-5) focused on streamflow at different locations on a single day, February 7, 2001. In particular, by compiling flow data, the USGS was able to quantify the rate at which the Muddy River was gaining or losing water over the measured reach on that particular day. Above the Moapa gage, the river gains nearly all of its flow over about a 2-mile reach. Below the Moapa gage, there is almost no gain. The discharge measured at the Muddy River at Anderson Wash near Logandale (09419490), approximately one-half mile upstream of the Bowman Reservoir diversion, is nearly the same as measured below the refuge. Beck and Wilson concluded that the difference is less than the measurement error. Further downstream, at Lewis Avenue, the discharge had decreased to 4.17 cfs because of diversion downstream of the measurement near Anderson Wash.

The study of the Virgin River provided flow measurements between the Virgin River Narrows and Lake Mead, Nevada (Figure 3.5-6). Evaluation of 14 discharge measurement locations and 3 diversions suggests that while the Virgin River gains significantly between the Narrows and Littlefield Springs (nearly 70 cfs), streamflow decreases between Littlefield Springs and Bunkerville by approximately 30 cfs and then remains relatively consistent between Bunkerville and Lake Mead, with some stretches that gain and others that lose. The study indicates that the Virgin River is hydraulically connected to the saturated Muddy Creek Formation, and that groundwater is supplying water for evapotranspiration between Bunkerville and Lake Mead, but is not discharging into the river at rates high enough to increase its baseflow within this reach. Together, DeMeo, et al. (2008, p. 19) and Beck and Wilson (2005, p. 7) showed that the total ET is almost identical to the loss from Littlefield to Overton on the Virgin River. This shows that there is not a large net gain or loss to/from the river to/from the aquifer system over this reach.

3.6 HISTORICAL GROUNDWATER USE

Figure 3.6-1 shows the locations of major production wells within the study area, and indicates groupings of wells based on location. Figure 3.6-2 provides the estimated or measured annual production for these groupings. In the Muddy River Springs area, groundwater withdrawal within the study area has occurred since the Lewis Well field began production in the late 1940s, ranging from 500 af/yr to nearly 2,000 af/yr until the early 1980's. Pumping increased to values of approximately 5,500 af/yr over the next 20 to 25 years. Groundwater production was from the surficial materials until 1991, when the Arrow Canyon well was drilled to produce water from the carbonate aquifer.

Figure 3.6-3 shows the locations of springs and production wells in the Muddy River Springs area. The discrete springs are located on the southwest side of the valley, at elevations higher than the nearby Muddy River. Diffuse groundwater discharge also occurs throughout the Muddy River Springs area, and collects in spring-brooks and rivulets that contribute to the flow of the Muddy River. The production wells are not located near the discrete springs, but upstream of, across the river from, or downstream of them.

Water production in the Virgin Valley has been increasing in the last decade. The earliest reported production was in 1998, but data for earlier years are not available. The production reached nearly 7,400 af/yr in 2005, but has decreased slightly in recent years. Production is from basin-fill materials, primarily the Muddy Creek formation.

Another area where groundwater production has been significant is in the Apex area and vicinity in Garnet Valley. Pumping in this area began in in the early 1960's. In 1993, the rate of production increased to provide water for several industrial operations, reaching rates of about 3,200 af/yr in the 2000's. This production is from the carbonate aquifer.

The Moapa Band of Paiutes have installed several wells into the carbonate aquifer on their reservation. However, there has been only limited production from these wells to date.

Water production in Coyote Spring Valley began in 2005. In 2010, the Order 1169 pumping began; the pumping rate was approximately 5,800 af/yr in 2011.

3.7 POTENTIOMETRIC RELATIONS

3.7.1 FLOW PATHS

Groundwater flow generally begins as recharge in the Clover Mountains, the Delamar Mountains, and the Sheep Range where precipitation infiltrates and moves through the carbonate aquifers discharge areas at streams and springs. In the Virgin River Valley, the groundwater table intersects the land surface at the southern end of Beaver Dam Wash, where it gradually increases in flow and merges with the Virgin River. The Virgin River enters the Virgin Valley

on the east side, and flows until it enters Lake Mead. Although groundwater likely flows toward the Virgin River throughout its path to the lake, these potential gains are lost to evapotranspiration along the way, and the Virgin River does not gain substantially in flow, other than in the stretch upstream from Littleton.

Flow in Meadow Valley Wash generally is parallel to the valley itself, infiltrating into the basin fill and carbonates at the northern end, then discharging to Meadow Valley Wash west of the Mormon Mountains.

Flow in Coyote Spring Valley comes from a combination of recharge in the Delamar Mountains and underflow at the northern-most end of Coyote Spring Valley where most of the groundwater enters from Pahranagat Valley and/or Tikapoo Valley. Flow continues south through carbonate rocks. Some of the groundwater flow discharges into the Muddy River either through the Muddy River Springs, or into the Muddy River upstream of the gaging station at Moapa. Some regional groundwater flow likely continues southeast into California Wash in an extensive area of highly permeable carbonate rock. This water moves under the influence of a very mild hydraulic gradient in the area until it eventually makes its way northeast back to the Muddy River, or flows generally southeastward through the California Wash fault and discharges at Rogers and Blue Point Springs. A small amount likely discharges into Lake Mead. Additional contributions to groundwater along this flow path include recharge in the Sheep Range, and minor amounts in the Muddy Mountains.

3.7.2 GEOLOGIC CONTROL ON GRADIENTS

Gradients are generally controlled by a combination of highly permeable carbonates, relatively low-permeability basin fill including the Muddy Creek Formation, and structural features which have formed thrust sheets of large areal extent, as well as localized impediments to flow. In particular the Kane Springs Wash Fault and the Las Vegas Valley Shear Zone play influential roles in channeling groundwater flow.

4.0 DEVELOPMENT OF GEOLOGIC MODEL

A three-dimensional geologic model was constructed in order to provide information on the spatial distribution of hydrogeologic units (HGUs) to the flow model. This geologic model was developed to be compatible with MODFLOW's Hydrologic Unit Flow (HUF) package, which allows the assignment of hydrologic properties to specified HGUs for calculation of hydrologic properties of the individual model cells. The geologic model was developed using a regular grid with a spacing of 250 meters (820 feet). The flow model was developed using a variable grid; properties for the flow-model cells were sampled from the geologic model grid using the locations of the center points of the flow-model grid cells.

4.1 SUMMARY OF APPROACH

Twenty-seven different HGUs were defined to account for the stratigraphy and the effect of thrust faults (Figure 4.1-1). Geologic sections developed by Page and others (2011) and Dixon and Katzer (2002) were used to provide information on the effects of faulting on the three-dimensional distribution of the different HGUs (Figure 4.1-2). The sections were also used to provide information on the tops of the different HGUs. Drill hole and geophysical information was also used.

The lateral extents of the 27 HGUs were estimated using the geologic mapping by Page and others (2005) and the cross sections mentioned above. Where HGUs were bounded by faults, the interpretation of fault locations presented in Figure 4 of Page and others (2005) was adopted. The three-dimensional locations of HGU surficial contacts were used in development of the geologic model to provide information on where the HGU thicknesses were zero and on their elevations. Elevations of the contacts were determined by finding the intersection of the contact lines with the land surface, using ArcGIS and a Digital Elevation Model (DEM) downloaded from the USGS Seamless on-line database. The DEM database used in this project had cell dimensions of approximately 28 m on a side. Stratigraphic information provided from drillholes was also used to determine the elevations of HGU contacts.

Interpreted structural contour maps of the tops of the HGUs were prepared by a geologist using the information discussed in the previous paragraph. Because of the number of HGUs and the structural complexity and resulting high relief of the HGU contacts, these structural contour maps were sometimes inconsistent with each other. In other words, the thicknesses of the HGUs (calculated by subtracting the elevations of superjacent contacts) were quite variable and sometimes negative. Because of the number of stacked HGUs, manual adjustment of the structural contour maps to correct inconsistencies the HGU elevations was untenable.

A methodology based on PEST (Doherty, 2011) and pilot points was developed to calculate the elevations of the tops of the HGUs based on the available geologic mapping information, structural interpretations provided by the cross sections (in which the HGU

elevations were consistent), and drillhole data. PEST is a software package designed for calibration of models to data (observations) using non-linear multiple regression techniques. These techniques involve multiple estimations of model parameters to improve the goodness of fit between values of model-calculated values and observed values of the variables of interest. For this application, the estimated parameters were chosen to be the thicknesses of HGUs at specific locations. The variables of interest (calibration targets) were the interpreted elevations of the tops of the HGUs, as expressed in the interpreted structural contour maps. In addition, the combined thickness of the basin-fill units at different locations, as estimated by Morin (2006) and Scheirer et al. (2006) based on gravity and seismic-survey data , were also used as calibration targets.

The pilot-point technique is one in which a grid of values is calculated based on values assigned to "pilot points" using a kriging approach. Kriging is an estimation tool originally developed for interpolating between measurements of ore grade, and has since been widely adapted for interpolating between other types of measurements. The technique takes into account the spatial correlation among measurements (expressed as a semi-variogram) and the locations of the measurements. For the geologic model, it was assumed that the correlation between HGU thicknesses at different locations could be described with a exponential semi-variogram, using a characteristic length of 6,000 meters, and a sill (half variance) of 36,000 meters. These values were derived by evaluating the thicknesses of several HGUs determined from Page's cross sections, and selection of representative values that appeared representative of all HGUs. Interpolation between pilot points was performed to a 250-meter uniform grid.

Three categories of pilot points were developed for this process:

- PPK – These pilot points (Pilot Point Known) were developed from HGU thicknesses determined from the geologic sections developed by Page and others (2010) and from drillhole lithologic information. Even though the geologic sections are interpretive, it was assumed that they were accurate representations of the subsurface geology, as they incorporated both stratigraphic and structural information.
- PPK0 – These pilot points (Pilot Point Known Zero) represent the locations of contacts between HGUs, where the thickness of the subject HGU was mapped as zero. The PPK0 pilot points are located along the unit extent boundaries of the respective HGUs.
- PPE – These pilot points (Pilot Point Estimated) represent locations within the Unit Extent of an HGU where PEST would develop estimates of the HGU thickness for that HGU. These locations were selected to be somewhat distant from PPKs and PPK0s to provide control for the kriging process in other areas. The geologic modeling process involved using PEST to estimate the thicknesses of each HGU in order to develop an acceptable agreement with the structural contour maps and basin-fill thickness map. Thicknesses at the PPEs were constrained using a process called "regularization" by Doherty; this technique will be discussed in more detail below.

These three categories of pilot points were developed for each HGU. At each pilot-point location, information on the thickness (either known or being estimated) of each HGU was used in the kriging process to develop the HGU-thickness datasets. The thickness datasets were then used to calculate the elevations of the top of the HGUs.

Doherty (2003) described the use of pilot points and regularization to estimate hydraulic conductivity during calibration of a MODFLOW model. The same approach was used for developing the geologic model for the flow model. The use of pilot points was discussed previously. Regularization is an approach to increasing the stability of the iterative regression process by adding additional constraints or information on the estimated parameters (HGU thickness, in this case). For the geologic modeling performed here, the regularization equations that were used were based on the idea that the stratigraphic thickness of an HGU at a PPE should be similar to that at a nearby PPE. Stated differently, the regression process should attempt to make an HGU a uniform thickness if the agreement between the model-calculated HGU elevations and the structural contour maps is good. The manner in which regularization is implemented in PEST ensures that the agreement is given higher priority than having uniform thickness.

The parameter estimation software package PEST, in combination with a FORTRAN program (gmcalc) that was written for this project, was utilized to create estimated tops and thicknesses of each HGU based on regularized thicknesses. Briefly, this involved the following steps:

1. Create PPEs, PPK0s, and PPKs for each HGU for use in developing a grid of HGU thickness values.
2. Calculate kriging factors for use in interpolating values at pilot points to the 250-meter geologic model grid, and a reduced set of kriging factors (using PPEs only) for use in developing the regularization equations, based on the locations of the pilot points.
3. Develop an input data set for PEST which provides PEST control parameters, initial estimates for the HGU thicknesses at each PPE, calibration targets (based on the structural contour maps and basin-fill thickness map), and regularization equations.
4. Run PEST, which performs the following steps
    a. Develop estimates for HGU thicknesses for all of the PPEs
    b. Calculate thickness arrays for each HGU using thickness values for PPKs, PPK0s, and PPEs. Figure 4.1-3 is an example of the kriging-calculated thickness of one of the carbonate thrust sheets, PC4.
    c. Execute a FORTRAN program (gmcalc) to calculate the tops of the HGUs, based on the land surface elevation from the DEM, and arrays (one for each HGU) of the thickness of the HGUs. For each geologic model cell location, the elevations of the top of the HGUs were calculated by sequentially subtracting the HGU thicknesses from the elevations of the overlying HGU. The subtraction process was performed

from the top downward (shallowest HGU to the deepest HGU). In addition, the program calculates the sensitivity of the HGU elevation to the thickness of other HGUs, for use by PEST.

d. Compare model-estimated elevations and basin-fill thicknesses with structural-contour map values and basin-fill thickness map values, respectively
e. Based on these comparisons and parameter-sensitivity information, develop new estimates of HGU thicknesses at PPEs
f. Repeat steps b through e until convergence criteria are satisfied

5. Compare results of the PEST optimization with cross sections and structural contour maps, and adjust or add PPEs, and repeat the process, as necessary.

4.2 RESULTS

Examples of the extents and reliefs of the tops of four stratigraphic units are shown in Figure 4.2-1. These represent combined HGUs. For example, all of the thrust sheets of the Paleozoic Carbonates (PC) are shown. The surfaces shown are based on a 250 m by 250 m grid. Units are absent where the surface is gray. In the northern parts of Meadow Valley Wash and Beaver Dam Wash, the QCD is thin (only tens of feet) and was thus omitted from the geologic model.

The widespread occurrence of Cenozoic basin fill relative to the higher elevation ranges (gray areas) is apparent. The Tertiary volcanics are prevalent in the northern part of the study area, and also present adjacent to Lake Mead in the south. The Mesozoic rocks are present primarily in the eastern part of the study area, where the Paleozoic carbonates are present throughout most of it. On the carbonate depiction, the gray areas are where either Tertiary or Proterozoic crystalline rocks are present and the carbonate rocks were either intruded or eroded.

A comparison of sections by Page et al. (2011) (see figure 4.2-2 for locations) with sections derived from the digital geologic model (developed using EVS) is shown in Figure 4.2-3. The underlying crystalline rocks are not shown in the EVS sections. In general, the correspondence between the geologic model and original sections is quite good, with some smoothing of the detail in the original sections. This would be expected, as PPKs were used along the original section lines.

Sections are also presented in locations between the Page et al. sections (figure 4.2-4). The section labeled “North of A’A’” show the dominance of the crystalline basement (white areas) with a “relative” thin layer (greater than 1000 m thickness in most areas) on top. The sedimentary rocks are present in the eastern part of the section, but are thinner than in section A-A’.

A section was drawn using EVS between the Page et al. (2011) sections C-C’ and D-D’. It shows the effect of the Gass Peak thrust on the west side (at approximately 5,000 to 8,000 m

from the left end of the section), the great thickness of carbonate rocks between distances of 10,000 to 50,000 m from the left end, and the great thickness of basin-fill deposits beneath the Virgin Valley.

The next section, which crosses the Black Mountains, is similar to the one above it, but shows the effect of the Muddy Mountain thrust, the presence of the Mesozoic units (in yellow), and the faulted and overturned section in the Muddy Mountains (depicted by the Permian red beds both underlying and overlying the Kaibab/Toroweap (in light green) and Mesozoic rocks (in yellow). The last section ("Between F-F' and G-G'") shows the effects of the Gass Peak and Muddy Mountain thrusts, and the thick section of carbonates present between them.

These sections are constrained by the location of contacts on the geologic map and on the Page et al. (2011) cross sections, by gravity and seismic reflection data, as well as by geologic interpretations that were expressed in the structural contour maps. They indicate that the procedure used to develop the geologic model produces reasonable interpretations of the geology in a structurally complicated area.

Attachment I contains maps (ordered from top to bottom) which show the distribution of each of the HGUs in the geologic model, and the elevations (in meters) of their tops. The color gradation is the same for each map. The outline of the model is shown as a red line, which is not visible when the HGU is mapped to the edge of the model. The dots represent the pilot points (PPE) that were used to estimate the thickness of the HGU shown.

5.0 FLOW MODELING APPROACH

The flow model was developed using MODFLOW-2000, a widely used finite-difference flow-modeling code developed by the USGS. This section describes the development of the flow model, and how rock-property and water-budget information was provided to the model. Section 6 provides the results.

5.1 DEVELOPMENT OF FLOW-MODEL COMPUTATIONAL GRID

In order to conduct hydrologic simulations of groundwater flow within the geologic framework, a separate grid was constructed for use with MODFLOW. Although the geologic framework model was based on a regular spacing (250 meters) between nodes, the flow-model grid was telescoped to permit focus on the specific areas of interest while remaining computationally efficient. The flow-model grid consists of model layers of uniform cell thickness, each deeper layer being approximately 25% thicker than the layer above it. The top of the upper-most layer was assigned at the water table, permitting the model to be run in a fully confined manner.

In designing the flow-model grid, multiple factors were taken into account with specific consideration for where the model needed to be most accurate, how to allow it to potentially be used in conjunction with other models in the area, and how to make the model computationally efficient.

5.1.1 GRID REFINEMENT IN MUDDY RIVER SPRINGS AREA

The primary factor of concern in designing the model lay in ensuring the highest level of confidence in the model results for the area in and around the Muddy River Springs. Due to the intention of using the model to simulate pumping impacts on the springs, and because of the greater amount of information in the Muddy River Springs Area, Coyote Spring Valley, and California Wash on the hydrology and the effects of pumping, a fine grid was warranted in these areas.

5.1.2 ALIGNMENT WITH DVRFS MODEL GRID

The Death Valley Regional Flow System (DVRFS) model (Belcher, 2004) was created to simulate groundwater flow for the area immediately adjacent to this model, and to the west. 1500-meter cells were employed in construction of the DVRFS model. Model cells were therefore aligned to be consistent with the model cells of the DVRFS model, to provide the option for potentially linking the models in the future.

5.1.3 COMPUTATIONAL EFFICIENCY

Computational efficiency was a factor in deciding how the model grid was developed because of concerns that an 18-layer model with more than 300 stress period model with maximum cell dimensions of 250 meters on a side would become unwieldy to run. A variable-grid was judged the most effective way to minimize the number of model cells while preserving the reduced model cell size in the Muddy River Springs area.

5.1.4 GRID DESIGN

The model domain and horizontal discretization is shown in Figure 5.1-1. The model grid consists of 314 rows, 209 columns, and 18 active model layers. The active portion of the model grid consists of Hydrographic Areas (HA) 204-206, 210, 215-222, and part of HA 212 that is north of the Las Vegas Valley Shear Zone and east of the crest of the Sheep Range. The horizontal grid shaping is spatially variable, telescoping from 1,500 m x 1,500 m cells in the corners to 250 m x 250 m cells in the vicinity of Muddy River Springs. The grid spacing was chosen to be identical to the Death Valley Regional Flow System (DVRFS) Model (Belcher, 2004), or to be as easily translated to the DVRFS grid as possible. (Note: the horizontal grid spacing is specified in meters, because the UTM coordinates system was used in GIS; the units of the flow model are in feet and days). Future versions of this model could include grid refinement in other areas of interest and linking this model to the DVRFS model.

The model grid vertical discretization is based on an approach used in the development of the regional groundwater flow model for the Underground Testing Area Project of the Environmental Restoration Program at the Nevada Test Site (IT Corporation, 1996). This approach has been incorporated into the Hydrogeologic Unit Flow (HUF2) package for MODFLOW-2000 (Anderman and Hill, 2003), and was used by the USGS in the development of the Death Valley Regional Flow System model (Belcher, 2004). The complex structural geology in the region imposes a need to use an approach that can effectively incorporate the effects of fault displacement. The approach uses model layers that are not defined on the basis of geology, but on a vertical spacing from an arbitrary two-dimensional surface, such as sea level or the elevation of the water table. The HSUs present within a model cell are identified, and their hydraulic properties are used to calculate the hydraulic property values assigned to that cell. A large number of model layers is required to accurately represent the geology. For this model, eighteen layers are used, resulting in a total thickness of 15,630 feet. Table 5-1 shows the thicknesses of each model layer and their corresponding depths below the approximate elevation of the water table.

Table 5-1. Model Layer Thicknesses

Model Layer	Thickness (ft)	Depth (ft below water table)
1	100	100
2	125	225
3	150	375
4	180	555
5	230	785
6	275	1,060
7	350	1,410
8	450	1,860
9	550	2,410
10	650	3,060
11	720	3,780
12	825	4,605
13	950	5,555
14	1,175	6,730
15	1,500	8,230
16	1,900	10,130
17	2,400	12,530
18	3,100	15,630

The thicknesses of the model layers increase with depth, which allows for inclusion of greater detail near the top of the groundwater system. The top of layer 1 is an approximation of the water table, as initially developed by gridding of static water-level elevation data from wells and springs. When lack of data caused the interpolated water table to be above land surface, an elevation that was 10 feet below the land surface elevation was used as the top of the model.

One of the capabilities of HUF2 is the ability to simulate the decrease in hydraulic conductivity with increasing depth caused by the weight of overlying rocks. In studies of hydraulic conductivity values in southern Nevada (IT Corporation, 1996; D'Agnese et al., 1997, Belcher, 2001, Belcher, 2004) it has been found that there is an identifiable trend of decreasing hydraulic conductivity with depth, although there is considerable uncertainty with respect to the rate at which the hydraulic conductivity decreases. The decrease in hydraulic conductivity has been found to be describable by an exponential decay function. At great depth, this function results in unrealistically low values, as pointed out by Belcher (2004). The MODFLOW source code was modified for this model to incorporate a minimum hydraulic conductivity value to prevent unrealistically low k values in this model according to the modified exponential decay function:

$$K_{Depth} = \left(K_{Surface} - K_{\min}\right)10^{-\lambda d}\Big) + K_{\min}$$

where K_{Depth} is the hydraulic conductivity at depth d; K_{min} is the minimum hydraulic conductivity; $K_{Surface}$ is the hydraulic conductivity projected to land surface; λ is the depth-decay

coefficient; and *d* is the depth below land surface. Figure 5.1-2 shows an example of how the hydraulic conductivity changes with depth as calculated by the equation above. In this model, the depth-decay coefficients derived from IT Corporation (1996) for several different lithologies were used as initial values in the calibration process.

The USGS Hydrogeologic-Unit Flow (HUF) package (Anderman, E.R. and Hill, M.C., 2000) allows the model to be run in a fully-confined format, removing the necessity for MODFLOW to solve unsaturated flow equations and thereby significantly reducing model run times. A later modification of the initial HUF package (HUF2) allows for the use of the specific yield term for the upper-most mode layer (Anderman, E.R. and Hill, M.C., 2003)). The model was constructed using this option for computational efficiency, while allowing use of both specific yield and specific storage terms for individual HGUs or zones within HGUs.

5.2 BOUNDARY CONDITIONS AND OTHER MISCELLANEOUS DATASETS

Besides the datasets that describe the geometry of the HGUs and their hydraulic properties, there are other modeling datasets that describe how water moves into and out of the groundwater system (called Boundary Condition datasets) and where Horizontal Flow Barriers (representing zones of reduced permeability perpendicular to faults) are present and their properties. These are described in this section.

5.2.1 RECHARGE

Recharge was implemented using the MODFLOW Recharge package (RCH). Recharge was applied to the model as a constant flux. No seasonal or climatic variation was integrated. This may represent a place where future model refinement would be appropriate.

Groundwater recharge to the model starts as precipitation. The most important source of recharge is snow, but summer storms can also contribute appreciable amounts of water. Recharge was estimated using a modification of the original Maxey-Eakin approach. The first modification was in the use of the PRISM (Parameter-elevation Regressions on Independent Slopes Model) precipitation dataset in place of the Hardman map, as it represents a more recent interpretation using a longer period of record and more measurement locations. PRISM-precipitation datasets are developed by the PRISM Group at Oregon State University (PRISM Group, 2008). PRISM is designed to map climate, such as precipitation, in difficult locales, such as mountainous locations and rain shadows. This model uses the mean monthly precipitation data from 1971-2007 provided on an 800 m by 800 m grid. Figure 3.4-1 shows the precipitation distribution over the model area. As expected, higher altitude locations, such as the Clover Mountains, have greater precipitation than lower elevations.

Second, a polynomial equation was developed from the original Maxey-Eakin coefficients to produce a continuous, rather than step-wise, function between precipitation and

recharge rate. A cubic equation was derived using the Solver Add-in in Microsoft Excel to obtain with the amount of recharge in each model cell based on precipitation:

$$Percentage = -0.60551 + 1.0117P + 0.06572P^2 - 0.00175P^3$$

where *Percentage* is the percentage of precipitation that becomes recharge, and P is precipitation minus 7(in/yr). This equation thus does not calculate any recharge occurring when the annual precipitation is less than 7 inches per year. The precipitation values were sampled onto the variably-spaced model grid, and a weighted average precipitation value was calculated for each model grid cell using ArcGIS. Figure 3.4-2 shows the calculated recharge for each model cell.

It should be noted that the Maxey-Eakin method was developed to estimate basin-wide estimates of recharge, and has several simplifications that can affect the estimated distribution and rates of recharge. First, it assumes that recharge occurs at or very near to where the precipitation occurs. It does not consider runoff processes with the recharge occurring in downstream locations such as alluvial fans or beneath stream channels. Second, it does not consider the hydrologic properties of the materials at a location. It may calculate a recharge rate that is greater than the vertical hydraulic conductivity of the surface and create unrealistically high water levels in the model at that location. These simplifications are incorporated into the modified approach used in this model.

The average annual precipitation in the Muddy Mountains is below the minimum amount needed to yield appreciable recharge, but the data from Rogers and Blue Point springs, and the presence of small springs in the eastern part of the Muddy Mountains, indicate that part of the discharge is from local recharge. The recharge dataset developed using the modified Maxey-Eakin approach was modified to add local recharge to the Muddy Mountains through the use of MODFLOW's matrix arithmetic capabilities. The local recharge rate was adjusted during model calibration.

Because of the use of a different precipitation dataset and use of a polynomial for the recharge efficiency, the rate of recharge was different than the value that would be calculated using the original Maxey-Eakin approach. The basin water budget information was used to estimate a factor by which to reduce the calculated recharge rates to be consistent with discharge rates.

5.2.2 SPRINGS

Discharge from springs was simulated using two approaches:

- DRAIN package – Springs that did not cause significant surface water flow were simulated using the DRAIN package. The largest springs simulated with DRAIN package were Rogers and Blue Point Springs. Discharge from these springs was simulated by defining DRAIN

cells in all 18 layers, reflecting a conceptual model that water could travel upward along the Rogers Spring fault. Both springs were located in the same model cell. Numerous small springs in the Clover and Delamar Mountains were also simulated with this boundary-condition package. These were simulated using a DRAIN cell only in layer 1. The combined discharge at Rogers and Blue Point Springs are calibration targets for the steady-state and transient flow models.

Figure 5.2-1 shows the locations of the springs simulated in the model. Horizontal coordinates for some of the springs were adjusted hundreds to thousands of feet based on aerial photography. The USGS NWIS web site gives horizontal accuracy for each spring location and some springs were specified with an accuracy of 6,000 ft.

- Stream-Routing Package – Springs in the Muddy River Springs area, which result in surface-water discharge, were simulated with SFR2. SFR2 was also used to simulate surface-water/groundwater interactions in other areas. The Muddy River Springs complex has several springs that create tributaries that flow into the Muddy River: Muddy Spring (or Big Muddy Spring), Baldwin, Pipeline-Jones (or Apcar), Pederson and Pederson-East, and Plummer (Iverson). The Pederson and Iverson spring complexes flow into Refuge Stream, which then flows into the Muddy River. These five springs were classified at separate segments in the SFR2 dataset.

5.2.3 ET DATASET

The ET units were sampled onto the model grid and an ET rate for each model cell was calculated based on the area occupied by the ET unit multiplied by the calculated or estimated ET rate from DeMeo et al. (2008) (Figure 5.2-2). The well package was used to remove groundwater from the subsurface as ET on an annual or monthly basis. Since ET is the only water budget component that can be measured with some level of confidence, it was explicitly used in the model to remove groundwater instead of using the ET package. Also, ET was not applied to model cells that contained springs (e.g., Rogers and Blue Point) so the model could remove groundwater via discharge from the springs and not ET.

5.2.4 EXTERNAL BOUNDARY FLUX DATASET

The external boundaries in each model layer are specified using the well package, except for Lake Mead. The flow rate for each individual boundary cell was calculated based on the estimated flow rate for the boundary segment containing the cell, the conductances for the cells in the boundary segment, and the conductance for the individual cell.

Early in the calibration process, the Multinode-Well (MNW) Package was being used to distribute the estimated boundary-segment flow rate, but caused model-stability problems. When these stability problems became apparent, the steady-state calibration process had progressed to the point that the hydraulic-conductivity parameters were not changing

significantly. These conductivity values were used to calculate the cell conductances used to develop the well-package dataset for the boundary fluxes.

Lake Mead was simulated as a constant-head boundary in this model to allow the model to estimate the discharge into the lake and to determine the impact of changes in lake stage. The elevation of the lake was set to the mean lake stage for each stress period. Constant heads were set in model layers 1, 2, 3, and/or 4 depending on the floor elevation of the lake (Twichell et al., 2003).

5.2.5 PRODUCTION WELL DATASET

Groundwater production (see Figure 3.6-1) was simulated using the MNW Package. This package distributes the pumping from individual model cells that are contained within the screened interval for a well, based on the cell conductances and the water-level calculated for each cell. For example, if the well penetrates two different cells, one with a high conductance (because the rock represented by the cell is very permeable) and another with low conductance, most of the water pumped from the well will be simulated as being produced from the high-conductance cell.

Estimates of annual pumping amounts presented in LVVWD (2001) are used prior to 1987 in this model. If water production information for a well field was given (rather than for individual wells), it was assumed that all wells in the well field pumped an equal amount for that stress period. Beginning in 1987, monthly withdrawal amounts are available from a number of data sources listed in Table 2-1. Monthly stress periods are used in the model beginning in 1987 because of the availability of monthly pumping data from that time on.

5.2.6 STREAM-ROUTING PACKAGE

Streams in the model are simulated using the Streamflow-Routing (SFR2) package (Figure 5.2-3). The gaging station on the Muddy River at Moapa is used at a calibration target for the steady-state and transient flow models. In addition, stream segments in which there was not surface flow except in response to storms were identified, and calibration targets (with a streamflow rate of 0 cfs) were established at appropriate locations for use in model calibration.

Parameters for the streamflow-routing package were determined using ArcGIS. The length and width of each reach were estimated using satellite and aerial photography. Slopes and stages in the rivers and streams were estimated from the 9.8-m digital elevation model (DEM) of the study area. The hydraulic conductivity and thickness of the streambeds were set to 2 and 10 ft, respectively and modified during the calibration process. The five springs mentioned above were classified at separate segments so they could be given higher hydraulic conductivities to simulate spring flow from the aquifer into the stream, because the SFR2 package performs an

interpolation of parameter values from the uppermost location to the lowermost location along a segment.

5.2.7 FAULTS AS HYDROLOGIC FLOW BARRIERS

Several of the mapped faults within the model domain may impede groundwater flow across them. The following faults were implemented in the flow-model utilizing the MODFLOW Horizontal Flow Barrier (HFB) package: Tule Desert Fault system, Kane Springs Wash Fault, Glendale Thrust, California Wash Fault, and the Las Vegas Valley Shear Zone where it runs within the model domain between the Muddy Mountains and Lake Mead (Figure 5.2-4). An additional fault has been inferred based on water levels in the vicinity of the Muddy River Springs. This fault was placed at the White Narrows of the Muddy River and represents a north-south oriented expression of the East Arrow Canyon Range Fault Zone as shown on Figure 3.1-2.

5.3 CALIBRATION

Development of groundwater models is a two-step process. The first step is setting up the modeling datasets providing information on the geometry of the system and how water moves into and out of the groundwater system. This process was described in section 4 of this report. The second step is called model calibration. During model calibration, the values assigned to the hydrologic properties of the HGUs and other modeling parameters (such as recharge rates) are adjusted so that output variables calculated by the model reasonable agree with observations. These observations can include water levels, changes in water levels, spring discharge rates, and streamflow measurements.

It is important for users of a model to recognize that models are approximations of the natural groundwater system. The natural system is more complex than can be represented in a computer model, and information on the natural system is incomplete. As a result, a model should be considered to be non-unique (i.e., other models can be developed for the system which may match observations equally well, but use different system geometries and properties). A model should also be considered to produce modeling results that are uncertain. Uncertainty in model predictions will be greater in areas where data are limited. For example, in this model, considerably more data are available in near the Muddy Springs area than in other part of the model domain. Thus, the model will provide predictions with less uncertainty near the Muddy Springs area than in other areas.

5.3.1 CALIBRATION APPROACH

Calibration of the flow model was performed using a combination of manual and automated calibration approaches. Information used to constrain (or guide) calibration included water-level information, changes in water levels in response to pumping and seasonal changes in

ET rates, and streamflow and spring discharge measurements. Commonly, groundwater flow models are calibrated to steady-state and pumping conditions, assuming that adequate information on the effects of pumping is available, in separate steps because of the longer simulation time for a transient model. A similar approach was used for calibration of this model, except that one "steady state" model and two different transient models were developed. The "steady-state" model included a simulation for steady-state conditions plus a 38-year period of limited pumping, primarily near the Muddy River springs area. The pumping was included to account for changes in the groundwater system that occurred prior to the time that observation data generally became available. One of the transient models covered the timeframe from 1949 to 2011, and the second covered the much shorter period (October 2008 through December 2011) including pumping and data collection associated with Order 1169 .

The calibration approach consisted of iteratively using manual calibration to test different model configurations, such as different applications of boundary conditions and parameter zonations, and automated parameter estimation methods (PEST, see Doherty, 2010) to estimate values of model parameters. PEST (which was also used to develop the three-dimensional geologic model) is a computer program which is designed to develop parameter estimates which minimize the value of an objective function using regression procedures. The objective function is the sum of the squared weighted residuals, where a residual is the difference between a measured value (observation) and the corresponding model-calculated value. For example, water-level measurements can be used as observations, and the residuals would be the differences between the measured and simulated water levels. Other types of measurements can also be used, such as calculated drawdown and measurements of spring discharge.

5.3.2 CALIBRATION TARGETS

Information used to calibrate the model included:

- 15307 observed water-level elevations in wells throughout the model domain
- 186 combined discharge measurements at Rogers and Blue Point Springs
- 179 discharge measurements in the Muddy River at Moapa
- 70 spring-flow discharge measurements at Baldwin Spring
- 71 spring-flow discharge measurements at Big Muddy Spring
- 173 combined spring-flow discharge measurements at Pederson and Pederson East Springs
- 65 spring-flow discharge measurements at Pipeline-Jones (Apcar) Spring
- 25 spring-flow discharge measurements at Plummer (Iverson) Spring
- 178 discharge measurements in the Muddy River at Glendale
- One-time measurements of stream flow at different locations along the Muddy and Virgin Rivers

For the transient models, individual measurements were used, reflecting conditions at specific times. However, for the steady-state model, values representative of conditions prior to significant groundwater production were selected, if possible.

There are both ephemeral and perennial stretches along the stream channels. These are depicted in Figure 5.3-1. Sections of Meadow Valley Wash below Rainbow Canyon and above the confluence with the Muddy River at I-15, Muddy River segments in and upstream of Arrow Canyon, and Beaver Dam Wash segments downstream between the Clover Mountains and the confluence with the Virgin River were observed in aerial photographs to be dry. They also lacked phreatophyte vegetation indicative of shallow groundwater. These sections represent segments in which water probably only flows ephemerally. Cells within these sections of the rivers were selected and used as zero-flow targets for calibration.

5.3.3 CALIBRATION MODELS

The pre-production model was developed to use develop estimates of hydraulic conductivity for HGUs throughout the domain of the model. Simulation time for this model was considerably shorter than for the transient models, allowing more parameters to be estimated. This simulation did not include any groundwater production. Types of observations relied on for calibrating this model included water-level data at selected wells throughout the model domain (Figure 5.3-2), locations of perennial and ephemeral streams, discharge rates at the larger springs, and "pre-development" streamflows, where possible.

A map of the locations of stream-flow and spring discharge targets was presented in Figure 5.2-1. Measured discharges at the Muddy River near Moapa (09416000), Muddy River at Glendale (09418890), Muddy River at Lewis Avenue (09419507), and discharges estimated during the Muddy River Synoptic study before the power plant diversion provided information on groundwater interactions with the stream. Additional discharge targets were placed to simulate the USGS gage on Meadow Valley Wash at Caliente Spring, a gaging location used in the USGS synoptic study located downstream on Muddy River from where Baldwin Spring enters (MR above Upper Confluence, 09415880), the USGS gage on the Virgin River at Littlefield (09415000), and the Virgin River gage site (09415240) located near Overton.

Because data on streamflow are generally unavailable for pre-development conditions, the streamflow data are considered to be approximate. For example, diversions of water from the Muddy and Virgin Rivers have been occurring for decades, but the synoptic streamflow studies were only conducted in the past few years. This model included diversions upstream from Moapa, but did not include diversions between I-15 on the Muddy River at Lewis Avenue. As a result, the simulated streamflow at Lewis Avenue was many-fold larger than measured, and a low weighting factor was applied at the Lewis Gage to minimize the impact on the PEST-estimation process.

Spring Discharge targets were placed at Baldwin Springs, the Warm Springs weir which monitors flow from Pederson and Pederson East Springs, Pipeline-Jones/Apcar Spring, Plummer/Iverson spring, and the Big Muddy Spring.

Prior to construction of Hoover Dam (1931- 1936), a topographical survey of Black Canyon and the Overton Arm was performed as part of a dam siting and impact evaluation. No observations of substantial-volumetric-rate springs were noted during the resulting maps developed as part of the study, suggesting that very little, if any groundwater originating within the Lower Colorado Flow System discharges to Lake Mead, other than where it contributes to flow in the Muddy River or Virgin River prior to entering the Lake, or from Rogers and Blue Point Springs. This pre-development observation was also used to constrain the calibration of the model through a mass-balance calculation of water entering the model cells used to simulate Lake Mead, and attempting to maintain minimal discharges.

The pre-production model included three stress periods. The first stress period was set up to be steady state. However, the model would not consistently satisfy convergence criteria because of the use of head-dependent boundary conditions, specifically the stream-routing package. Therefore, a second stress period was added with identical boundary conditions and material properties as the first, steady-state, stress period. For the model calibration process, this stress period was 400 years long. However, for the final model, the length of the stress period was increased to 10,000 years to ensure that water levels and discharges were stable. Differences of a few feet in water levels occurred between the 400-year and 10,000 year simulations in areas that were distant from flowing stream segments. The third stress period in the "pre-production" model incorporated average pumping rates from non-carbonate wells in the Muddy River Springs area for a 39-year period ending in 1987.

A transient model for the period October 2008 through December 2011 (the Order 1169 Model) was the primary model used to refine the groundwater model in the vicinity of the Muddy River Springs and Coyote Spring Valley, and to provide estimates of aquifer storage parameters. This time period included the effects of pumping near the springs, pumping in Coyote Spring Valley, and changing rates of evapotranspiration near the springs. This model is termed the Order 1169 model, because it focuses on the time period in which pumping and data collection pursuant to Order 1169 occurred. The carbonate aquifer (HGU PC4) is the primary aquifer in this area. In order to account for spatial variability of the hydraulic conductivity of this HGU, a pilot-point approach was used. There were 24 pilot points defined over the extent of PC4, and kriging was used to interpolate hydraulic-conductivity values at each of the pilot-point locations to other cells in the model grid. The pre-production model was used to estimate hydraulic-conductivity values for the PC4 at these pilot points, and the Order 1169 model was used to refine the pilot-point values near the Muddy Springs area and in central Coyote Spring Valley.

A map of the locations of drawdown targets is presented in Figure 5.3-3. These targets were based off of the water level measured in each well as close to the beginning of the model run (October 2008) as possible. However, in some cases transient seasonal effects from pumping during the summer of 2008 were apparently still dissipating. Drawdown values in these wells were adjusted so that zero drawdown coincided with water levels measured during the winter months when pumping and evapotranspiration effects would have subsided.

The Order 1169 model used water levels calculated from the pre-production model as initial heads. Monthly stress periods were used in the Order 1169 model so that changes in ET rates and pumping rates could be incorporated. The Order 1169 model began in October 2008, allowing approximately two years of monthly changes in ET and pumping to be simulated prior to the increase in pumping in Coyote Spring Valley. The simulation was conducted with monthly stress periods through the end of December 2011.

The longer-term transient model (1949 through 2011) was not used in PEST, but was run separately to confirm that the model provided results consistent with the longer term observations. This model used 38 year-long stress periods, using different estimates of the pumping for each year, before switching to monthly stress periods for the remainder of the simulation.

6.0 CALIBRATED MODEL

6.1 HYDROLOGIC PROPERTIES OF HGUS

The primary properties of HGUs that affect groundwater flow are hydraulic conductivity and storage parameters. In MODFLOW, the user has the ability to provide hydraulic conductivity information in the x-, y-, and z-directions relative to the model grid for each cell, if desired. In this model, the model layers were defined to be parallel to an estimate of the water table, which was determined from previous model results developed after extensive model calibration had already been performed. The model assumes that the hydraulic conductivity in the x- and y-directions are equal to each other, but different than in the z-direction. In addition, because of the vertical thickness of the modeled system and the effects of the weight of the overlying rock on the hydraulic conductivity, the KDEP capability of the HUF package was used. Thus, parameters needed to be provided to describe the reduction in hydraulic conductivity that results from increasing depth of burial.

When water levels change, water is released from or put into storage in the aquifer, through (1) draining or refilling pore space at the water table, or by (2) de-compressing or compressing the water and aquifer beneath the water table. The amount of water released from or put into storage, from these two different processes, is described by the parameters specific yield and specific storage, respectively.

6.1.1 HYDRAULIC CONDUCTIVITY

Table 6-1 contains the calibrated values for horizontal hydraulic conductivity and horizontal-to-vertical anisotropy for each of the HGUs, except for the hydraulic conductivity of the HGU termed PC4. The technique used to calculate the hydraulic-conductivity field for PC4 is presented below. The distribution of the property zones for the CAU is shown in Figure 6.1-1, while the zones of the TVC and XLB are provided in Figure 6.1-2.

Table 6-1. Hydraulic Conductivity Values by HGU in the Calibrated Model

HGU	Kx and Ky	VANI	HGU	Kx and Ky	VANI
QCD	150	10	PR4	0.1	100
CAU Zone 1	3.0	100.0	PC4 (See Table 6-2 below)	Varies	40
CAU Zone 2	10.0	100.0	PC3	15.16	100
CAU Zone 3	66.0	100.0	PR3	0.1	100
CAU Zone 4	7.13	100.0	KT3	5	100
CAU Zone 5	18.0	100.0	MU3	5	30
CAU Zone 6	40.0	100.0	MU2	5.59	30
CAU Zone 7	40.0	100.0	KT2	5	100
THS	0.1	60	PR2	0.1	100
TAU	1.0	60	PC2	200.0	100
TVC North	2.0	10	MU1	0.5	100
TVC Black Mtns	0.1	10	KT1	70.81	100
PC6	500	2.0	PR1	0.5	100
LC6	50	2.6	PC1	80.0	100
PC5	200	2.0	LC1	10.0	1.0
LC5	50	3.0	XLB North Zone	200	0.5
MU4	3.71	100	XLB South Zone	0.1	0.5
KT4	8	100			
Note: **Kx, Ky: Horizontal Hydraulic Conductivity (feet per day) projected to land surface (no overburden)**					
Vani: Horizontal to Vertical Anisotropy Ratio					

The hydraulic conductivity dataset for PC4 was developed using Pilot Point techniques and utility programs provided as part of PEST. Spatial variation in hydraulic conductivity of an HGU is expected to be present because of differences in depositional environment, in structural setting, and in alteration history, among other factors. In most models, there is insufficient information with which to estimate properties in different area, and either homogeneity is assumed, or parameter zones (in which it is assumed that the properties in each zone are homogeneous) are used. For the PC4 HGU (in the western part of the model), it was anticipated that results from the Order 1169 pumping in Coyote Spring Valley might allow the hydraulic conductivity to be estimated in different locations.

The pilot point technique (which was previously used in the development of the geologic model to estimate thicknesses of the HGUs) uses kriging to interpolate values provided for

values specified at “pilot points”. The goal is to develop a spatially varying distribution of hydraulic conductivity that reflects the average hydraulic conductivity near a location. Because there is limited information on the distribution of hydraulic conductivity with which to calculate a semi-variogram, a semi-variogram was assumed that resulted in a smoothly varying hydraulic-conductivity field constrained by the estimated values at the pilot-point locations.

Table 6-2 provides the estimated hydraulic-conductivity values at the 24 pilot-point locations. The locations of the pilot points, and the resulting hydraulic-conductivity field, is shown in Figure 6.1-3. The most striking feature is the high hydraulic conductivity estimated for pilot point #1, near the location of the Muddy River Springs. The PEST-estimated value for that pilot point was approximately 19,500 ft/day. Other hydrologists have postulated that there is a northwest-trending zone of increased permeability extending from the area of the Muddy River Springs into Coyote Spring Valley. Pilot point #2 is near MX-5, and the PEST-derived estimate of its hydraulic conductivity was approximately 4600 ft/day.

Table 6-2. Hydraulic Conductivity at Pilot Points used in Interpolation of PC4 Hydraulic Conductivity Field

PC4 Pilot Point	Kx	PC4 Pilot Point	Kx
1	19488.9	13	24.4
2	4560.3	14	1500.0
3	1000.0	15	421.0
4	679.1	16	300.0
5	1500.0	17	56.7
6	5.0	18	50.0
7	6.5	19	100.0
8	141.7	20	1500.0
9	134.3	21	1500.0
10	5.0	22	20.0
11	15.5	23	1836.4
12	23.2	24	200.0

Table 6-3 provides the values of lambda and Kmin used by HUF in the model. The Kmin value is the smallest value assigned to the HGU. For example, the QCD has a hydraulic-conductivity value of 150 ft/day at land surface, and the value decreases exponentially to a minimum value of 0.0001 ft/day. The value of lambda is 0.0017/ft, meaning that the hydraulic conductivity decreases by an order of magnitude every 588 ft. The minimum value assigned for the carbonate HGUs is 0.0003 ft/day; their hydraulic conductivity decreases by an order of magnitude every 1,333 ft in the model. The values of lambda were obtained from studies of the relationship between hydraulic conductivity and depth in the Death Valley flow system to the

west of this study area. While these studies determined that there were definite trends of reducing hydraulic-conductivity values with increasing depth of burial, there was considerable uncertainty for the rate at which hydraulic conductivity declined with depth because of the high degree of variability in hydraulic conductivity in the rocks.

Table 6-3. HUF Parameters by HGU

HGU	Lambda (1/ft)	Kmin (ft/d)
QCD/CAU/THS/TAU	1.70E-03	1E-04
TVC	7.10E-04	1E-06
MU	4.57E-04	5E-04
KT	4.57E-04	3E-04
PR	4.57E-04	5E-04
PC	7.50E-04	3E-04
LC	4.57E-04	1E-05
XLB	1.00E-03	1E-04

Table 6-4 provides the calibrated values for specific storage and specific yield (SYTP) for each HGU. The SYTP values are only applied to layer 1 in the model, the layer which contains the water table. With the exception of the storage parameters for PC, these values were estimated from literature values. The PC values were based on pumping tests for ECP-2.

Table 6-4. Calibrated Storage Parameters by HGU

HGU	SS (1/ft)	SYTP
QCD	1.0E-05	0.25
CAU	1.0E-05	0.2
THS/TAU	1.0E-05	0.10
TVC	1.0E-05	0.10
MU	1.0E-05	0.10
KT	1.0E-05	0.10
PR	1.0E-05	0.10
PC	1.1E-06	0.02
LC	1.0E-05	0.05
XLB	1.0E-05	0.05

Table 6-5 provides the values given to the HFBs. The values for all but two of the HFBs were set to 1.0E-06 ft/d, in spite of efforts to estimate their values using PEST. With the available information, PEST was not able to develop consistent estimates of these parameters. When lower values were initially provided to PEST, they were commonly increased by PEST.

The values provided for Kane Springs Wash fault and the Tule Desert fault are those values being used by PEST at the time that calibration efforts were concluded. These values are similar in magnitude to values being used in the SNWA model for their Clark, Lincoln, and White Pine Counties groundwater development project.

Table 6-5. Conductances assigned to the Horizontal Flow Barriers

Fault	Parameter	HFB conductance (ft/d)
White Narrows fault	hf_wnf	1.00E-06
Kane Springs Wash fault	hf_kswf	4.74E-06
Tule Desert fault	hf_tdf	1.31E-06
Glendale thrust	hf_glent	1.00E-06
California Wash fault (north)	hf_cwf_n	1.00E-06
California Wash fault (south)	hf_csf_s	1.00E-06
Rogers Spring fault	hf_rsf	1.00E-06
LVVSZ (west)	hf_lvvsz_w	1.00E-06
LVVSZ (east)	hf_lvvsz_e	1.00E-06

During model calibration, two changes to the boundary conditions were implemented.

1. The calibrated hydraulic conductivity for the northern Tertiary volcanics was low enough to cause hydraulic heads to mound above land surface in the Delamar Mountains. Based on evaluation of aerial photographs from the area, several drains were added and set to the land surface elevations of the bottom of several steep-walled valleys which appeared to contain vegetation patterns suggestive of a spring flow source, allowing part of this recharge to leave the model.
2. In evaluating flow contributions to the Muddy River in the vicinity of the Muddy River Springs complex, significant budgetary shortfalls were discovered. To address part of this, the Cardy-Lamb spring, whose flow was historically used for irrigation, was added to the springs complex, and assumed to contribute to flow in the Muddy River at approximately the same confluence as Baldwin Springs. For calibration purposes, the flow at Cardy-Lamb springs was estimated to be 3340 af/yr, or approximately 4.6 cfs, and assigned a spring discharge elevation of 1797.16 ft. The spring was implemented in the same way as the rest of the Muddy River Springs complex, using reaches of the stream-flow routing package, extending vertically downward to model layer 8.

6.2 SIMULATED WATER LEVELS

6.2.1 WATER-TABLE MAP

Figure 6.2-1 shows a map of simulated pre-production water levels for the model area. This represents water-level conditions for the steady-state simulation used as initial conditions for the long-term simulation. Figure 6.2-2 shows the residuals for pre-production water levels in comparison to the target locations used in calibration. The correlation between measured and simulated water levels is presented in Figure 6.2-3. The correlation coefficient is 0.961.

The simulated water-table map is characterized by areas of low hydraulic gradient (parts of Coyote Spring Valley, Hidden Valley, Garnet Valley, and California Wash), high gradients (Sheep Range, Delamar Mountains, Clover Mountains, Tule Desert and Tule Springs Hills), and intermediate gradients (Mormon Mountains, Virgin River Valley, Muddy Mountains, and Black Mountains). These gradients reflect the underlying geology and amounts of recharge. The lowest gradients occur where the carbonate aquifer (PC4 sheet) is relatively shallow. The highest gradients occur where significant precipitation falls on areas of low permeability rock.

The areas where there is interaction between the simulated groundwater system and the streams are apparent in the water-table contours. For example, along the Virgin River, the flow converges toward the river, and the groundwater system discharges into the river. [Near the downstream end of the Virgin River, there is a closed contour (1200 ft) that is the likely result of the removal of water by ET.] Beaver Dam Wash is simulated as a gaining stream over most of its length, although the southern and middle parts of Beaver Dam Wash are ephemeral, not perennial.

In the upper stretches of Meadow Valley Wash, groundwater is simulated as discharging into the river. Further downstream, where the simulated water-table elevation is between 2600 and 2700 ft, the stream begins to lose water into the groundwater system for a short distance. Approximately 15 miles upstream of the confluence of Meadow Valley Wash and the Muddy River, Meadow Valley Wash becomes a gaining stream again.

The contour lines also reflect the discharge of water into the Muddy River in the Muddy River Springs area, but the amount of contour-line deflection (considering the volume of discharge) is not as pronounced as in some areas, because of the high transmissivity of the carbonate aquifer in the Muddy River Springs area.

The impacts of some of the HFBs are very apparent in the spacing of some contour lines. The most apparent impacts are along the HFBs representing the Rogers Spring Fault, the Glendale Thrust, and the Tule Desert Fault System. In these three examples, there are high gradients or obvious deflections of the contour lines simulated by the model. More subtle

examples occur along the Lake Mead Fault System, the southern part of the California Wash Fault, parts of the Kane Springs Wash Fault, and the White Narrows Fault.

There are three closed contour lines (1800 ft) in the northwestern part of the Muddy Mountains. These result from the application of a small amount of recharge in this area.

The model matches water levels in the basins reasonably well, given the complex geology, but tends to simulate water levels in the Clover Mountains that are too low. The water-level data in the high relief areas may represent perched conditions. In these areas, it is likely that interbedding of fine-grained sediments, and/or detail of individual flows within a volcanic sequence are sufficient to perch water independently of the regional groundwater flow system.

6.2.2 DRAWDOWN IN COYOTE SPRING VALLEY AND MUDDY RIVER SPRINGS AREA

The Order 1169 pumping provided an opportunity for calibrating the parameters of the groundwater flow model based on the observed impacts associated an increase in the amount of pumping in Coyote Spring Valley that occurred as a result of Order 1169. Limited pumping began in well MX-5 with pumping in August and increased to approximately 50% of production capacity pumped in September of 2010 (Figure 6.2-4). The pumping rate was increased again in October 2010. Pumping associated with the test was simulated through the end of December 2011.

During this period, changes in groundwater discharge at other locations also occurred, specifically water supply for irrigation, increased evapotranspiration and power generation during summer months. These changes complicate the analysis of the effects of the Order 1169 pumping but have been incorporated into the model. There are other changes that are not accounted for in the model, notably changes in recharge rates related to climatic variability, and changes in boundary flows. In short, a part of the variation that affects water levels in the area is not accounted for.

Figure 6.2-5 shows the comparisons between measured and simulated drawdowns for the Order 1169 simulation. The locations for these wells were shown on Figure 5.3-3. The drawdown figures show the observed (in red) and simulated (in blue) drawdowns from the start of the simulation (October 1, 2008). For carbonate wells that were pumped significantly during the simulation period, the monthly pumping is shown in green. The larger plot at the bottom of the figure also shows the monthly pumping from these wells on a single plot. In addition to the time-varying pumping associated with the Order 1169 pumping in Coyote Spring Valley, pumping and ET from the valley fill in the Muddy River Springs area also varied monthly.

Pumped Carbonate Wells – The model simulates in increases in drawdown when these wells are pumped at higher rates. However, the simulated increase in drawdown is less than measured. This model behavior should be expected, because the drawdown in the well results

partially from the convergence of flow lines to the wells, which have diameters of approximately 1 foot, where as the model cell has a dimension of 820 feet. Even though this cell dimension is small for a regional model, the model is not capable of accurately simulating the drawdown in pumped wells.

Coyote Spring Valley – The non-pumped wells in Coyote Spring Valley are, approximately from north to south, CSVM-3, CSVM-7, KMW-1, CSVM-4, CE-VF-2, DF-1, CSI-4, CSVM-6, CSI-3, CSI-2, CSI-1, CSV-RW2, MX-4, CSVM-1, CSV-3, and CSVM-2. For the wells to the north (CSVM-3, CSVM-7, KMW-1, CSVM-4, CE-VF-2, and DF-1) the model calculates a small amount of drawdown (which increase to the south), and the measurements (although noisy) suggest a comparable amount of drawdown occurred.

Wells that are closer to the pumping wells in Coyote Spring Valley (primarily MX-5, CSI-3, and CSI-4) include CSVM-6, CSV-RW2, and CSVM-1. The total amount of simulated drawdown at these wells is, in general, slightly less than observed, and the shorter term temporal variations (responses to changes in pumping rates) are smaller than observed. The observation-well data indicate short-term temporal changes during the first two years of the simulation that are not reflected in the model results. Simulation results at CSVM-1 show little seasonal response (but do show a downward trend of water levels) while the model response at CSVM-6 (which is further from the seasonal ET and groundwater pumping near the Muddy River Springs area) shows a greater seasonal response. This difference suggests that the source of the seasonal response in SCVM-6 is not the Muddy River Springs area, but is likely pumping in Coyote Spring Valley, such as at CSI-4. When pumping starts in MX-5 (approximately at the end of the second year of the simulation) the effects of the pumping are quite discernible in CSV-RW2 and CSVM-1, but less so in CSVM-6.

The measured responses in CSVM-2 and CSV-3 are similar to those observed in Paiutes M-1, Paiutes M-3, and Paiutes ECP1, as well as wells closer to the Order 1169 pumping, showing both general declines in water level and the presence of shorter term temporal changes. The simulated results show less overall decline and essentially no short-term variation. These differences suggest that the model is using hydraulic conductivity values that may be too high in some areas, too low in others, storage coefficients that are too high, or combinations of these.

Muddy River Springs Area – These wells are closer to the Arrow Canyon wells, shallower wells that pump from the alluvial material and Muddy Creek, and the areas where ET occurs. The model simulates the approximate overall decline in water levels in EH-4, EH-5B, and Cardy-Lamb, and simulates the short-term changes reasonably well. In the Battleship Wash well, the simulated drawdown is approximately one-third of that observed.

Eastern Wells – Measurements in EH-3 and EH-7 indicate that there has not been a consistent trend in water levels, or short-term changes that appear to be caused by changes in ET

or pumping rates. The water-level changes observed in EH-3 appear to be local and short-lived. The simulation has little change in water levels in these two wells.

Summary – The simulated drawdowns during the Order 1169 simulation period agree reasonably well with the overall drawdown observed in the wells, but typically have lower amplitude short-term responses than were observed. In some wells, no short-term variability is simulated. Thus, the model results appear to be better suited to evaluating the longer-term average response than the short-term variability.

Figure 6.2-6 shows the drawdown from simulation of the pumping from MX-5 only for the time period covered by the Order 1169 model. MX-5 was the primary production well in Coyote Spring Valley during the time period. The figure indicates that the simulated drawdown was less than 0.8 ft except for the immediate vicinity of MX-5, where a drawdown greater than 3 feet was simulated. Because of numerical "noise", the outer boundary of the extent of drawdown should be considered as approximate. The model estimates that drawdown has occurred more than 10 miles from the pumping well, but the magnitude of the drawdown will be too low to measure over much of the area that is affected.

Figure 6.2-7 is a map of the simulated drawdown at the water table that considers pumping over the period of 1949 through December 2011. In the western part of the model, the effects of pumping in three different areas are evident. Pumping from both basin-fill and carbonate aquifers has occurred. Near the Muddy River Springs area, the model-simulated drawdown is greater than 5 feet, and greater than 10 feet near Arrow Canyon 1 and 2. There is also drawdown associated with pumping along the I-15 corridor northeast of Las Vegas. The third pumping area in the western part of the model is in Coyote Spring Valley, associated with the pumping of MX-5. The model predicts that drawdown is greater than 2 feet over most of this area. The simulated drawdown nearly reaches the western boundary of the model west-northwest of MX-5. This model does not use a head-dependent boundary condition anywhere except at Lake Mead, and thus does not simulate the increase in flow across the boundary that would occur when water levels change along the boundary. Adding a head-dependent boundary condition would likely decrease the amount of drawdown calculated by the model as water was captured from outside the model area.

A second area of pumping is in the Virgin River valley, near Mesquite. This pumping is from basin-fill sediments, and therefore the drawdown is greater and does not extend laterally as far as pumping from the carbonate aquifer in the western part of the model.

There is a third area of simulated drawdown along Meadow Valley Wash. This is a location that flow in the wash was simulated as occurring prior to any groundwater pumping, but that dried up at later time. When the wash was flowing, water was lost from the stream and recharged the groundwater. With the loss of the recharge water, water levels declined. It is not

clear whether the drying of the stream was caused by pumping effects, or numerical oscillations in the model.

6.3 COMPARISON OF SIMULATED AND MEASURED SPRING DISCHARGE

Figure 6.3-1 shows the observed and simulated spring discharges in the model domain. The agreements between the simulated and observed discharges are good. The simulated discharge from Pederson Combined agrees well with the sum of the Pederson and Pederson East discharge values. There is a significant, sudden decline in the measured values for Iverson Flume. During calibration of the model, it was assumed that maintenance was performed at the gaging site and that the later measurements were more accurate.

Simulated values decline through the simulation period. Significant increases in simulated pumping do not occur in the model until 1987. Although observed spring flow in Muddy Spring does not significantly change between 1960 and 1990, simulated flows do decrease. Spring flow is highly dependent on groundwater elevations, and the simulated pumping in the Lewis wellfield prior to 1987 causes declines in groundwater elevations (approximately 5 feet at EH-4, slightly upgradient of the Muddy River Springs). These simulated spring discharge declines are relatively minor (less than 10%), and may reflect the need for more detailed evaluation of recharge variation over time, or localized detail in the geology that is not being simulated.

Rogers and Blue Point spring flow are simulated as a combined-flow single spring. Flow at the spring is caused by a combination of elevated heads in the deep Paleozoic carbonates (PC1) and local recharge in the Muddy Mountains. The combined discharge from these two springs is approximately 2.35 cfs; the simulated value was 2.25 cfs (Figure 6.3-2).

6.4 COMPARISON OF SIMULATED AND MEASURED TEMPORAL STREAMFLOWS

Figure 6.4-1 shows a comparison between the locations of the simulated perennial reaches with the observed locations. On average, the model simulates that the perennial reaches are more widespread than observed. Beaver Dam Wash is simulated as flowing all the way to its confluence with the Virgin River but only the upper part is perennial. The uppermost stretch of Meadow Valley Wash is also simulated as perennial but is ephemeral. The wash does become perennial further downstream, but has an ephemeral stretch at the approximate latitude of the upper part of Kane Springs Wash; the model simulates the wash as perennial in this location. Further to the south, the model simulates the wash as perennial for approximately 15 miles above the confluence with the Muddy River. Aerial photographs suggest that the wash may be perennial through much of this stretch.

The model simulates that Kane Springs Wash and Pahranagat Wash are ephemeral, and that the Muddy River becomes perennial a short distance upstream from where it actually

becomes perennial near the Muddy River Springs. Aerial photographs show that there is an short reach of the Muddy River where groundwater discharge occurs as it cuts through the Arrow Canyon range that was not mapped as perennial, but that the Muddy River is not perennial between that discharge location and the much more significant discharge area approximately four miles downstream.

Figure 6.3-1 also shows the observed and simulated streamflow discharges for the gaging locations for the Muddy River at Moapa. Not shown is the information for the gage on the Muddy River at Overton. Uncertainty in pumping and diversion information between Glendale and Overton makes simulation results of flow for the Muddy River at Overton inaccurate, as the Overton gauge is consistently overestimated.

Simulated flow in the "Muddy River at Moapa" gage is 20,324 af/yr, around 70% of observed flow. Approximately 50% of observed flow originates in the Muddy River Springs. As noted above, the spring flow contribution is accurately represented by the model in simulation. The other 30% is believed to come from a combination of irrigation return flow, unidentified spring flow, and groundwater contributions to what is a gaining reach of the Muddy River.

Evaluation of aerial photography of the Muddy River between Arrow Canyon and a stream gage located below the confluence of the Muddy and Baldwin Springs (09415880) suggests that although groundwater is shallow in the river alluvium, indications of gains in flow as suggested by the consistent phreatophytic vegetation around the stream channel and/or visible width of stream, do not occur until approximately 1,100 feet above the gage. What appears to be a return flow ditch is visible entering the stream channel to the north of the gaging station. The source of this water may represent a significant portion of the un-simulated stream flow at the Moapa Gage.

Observed flow at the Muddy River at Glendale stream gage averages approximately 31,400 acre-feet per year. Stream flow during the pre-development simulation at the Glendale gage is simulated at 48,046 af/yr, or 153% of observed flow. This likely reflects overestimated heads along the Muddy River between the springs area and Glendale, and inflow from Meadow Valley Wash (8,325 af/yr) that is too high. Water levels simulated in Well EH-2A, located along this reach, are overestimated by approximately 90 feet at the end of the pre-development simulation. Overestimated water-level elevations in this area may indicate that a combination of higher carbonate hydraulic conductivity values in the vicinity of EH-2A, and flow restriction in the form of fault-barriers or zones of reduced conductivity between EH-2A and the Muddy River Springs may exist beyond what is currently implemented in the model as the White Narrows Fault.

Simulated flow at the Virgin River gage near Overton, Nevada (09415240) is generally within 10% of observed flow. Simulated groundwater elevation contours indicate convergent

flow and a gaining reach of the Virgin River; however these influxes of water are essentially balanced by the removal of water due to evapotranspiration processes, and pumping near Mesquite, Nevada.

6.5 COMPARISON OF SIMULATED AND ESTIMATED BOUNDARY FLUXES

Information on the water balance for the overall model prior to any groundwater development is provided in Table 6-5. These results are from the transient part of the pre-production model at 10,000 years, prior to pumping of groundwater in the model.

Fixed boundary fluxes in the groundwater model include influx of water at the basin edges, estimated by retired USGS hydrologist Jim Harrill (Harrill, 2007) (Table 3-2), and seasonal estimates of evapotranspiration, based on estimates performed by the USGS. These fluxes were assumed to be known and were not varied in calibration. Other elements of boundary flux in the simulation include recharge, groundwater-surface water interaction along streams, and discharge of groundwater to Lake Mead constant head cells.

Stream fluxes and spring discharges are discussed in earlier sections. Table 6-5 provides information at the external boundaries. The volume of water leaving the model by the Muddy River is much higher than is actually occurring, because the diversions downstream of I-15 are not measured.

Applied recharge was simulated based on the approach described in the model development section of this report. Recall that the modification of the Maxey-Eakin approach employed in this model resulted in an increase in the recharge from the original Maxey-Eakin method. As a result, the recharge rates calculated by the modified Maxey-Eakin approach were reduced by 35% to be consistent with the overall water balance estimates based on more recent studies. Recharge in the Muddy Mountains was implemented at a rate of 0.5 inches per year in areas with elevations over 3000 ft.

Steady-state mass balance conditions reflect a distribution of water in the model such that approximately 50% of incoming water exits the model through streamflow, 40% exits through evapotranspiration, and the remaining 10% is divided between groundwater discharge to Lake Mead, and spring discharge including Rogers and Blue Point springs, as well as other springs placed in the areas in the Delamar Mountains to avoid simulated heads greatly above land surface. Table 6-6 provides information on where water is exiting the model into Lake Mead. The total discharge to Lake Mead is simulated to be approximately 4,500 af/yr.

Table 6-5. Mass Balance from the Pre-Development Model

Model Boundary Fluxes			
IN			
		ft^3/d	af/yr
	Model Boundary Segments	4542177	38086
	Recharge	13066496	109562
	Virgin River Inflow	7819200	65564
	Storage In	158	1
OUT			
	Lake Mead Outflow	535153	4496
	Evapotranspiration	10656596	89355
	Drains, including Rogers & Blue Point Springs	1064216	8923
	Muddy River Flow	5030900	42184
	Virgin River Flow	7115200	59661
	Diversions without Return Flow	786970	6599
	Model Boundary Segments	238240	1998
	Storage Out	822	7
TOTALS	IN		213223
	OUT		213223
	NET		-1

Table 6-6. Simulated discharge into Lake Mead

Zone	Lake Mead Inflow Zone	ft^3/d	af/yr
1	Muddy River	69363	582
2	Virgin River	169520	1421
3	East of Rogers Fault	30125	253
4	Rogers Fault to Black Mtns	67002	562
5	East of Black Mtns	5569	47
6	South of Black Mtns	152240	1277
7	Bottom of Lake	41254	346

TETRA TECH

6.6 SENSITIVITY ANALYSES

Sensitivity analyses were completed on the groundwater flow model for the pre-development and Order 1169 pumping model simulations. The objective of the sensitivity analyses was to provide an evaluation of how parameter changes impact simulated water levels, spring discharges, and drawdown resulting from pumping in Coyote Spring Valley.

A selected set of parameters were evaluated for their sensitivity to the resulting model simulation, including effects on hydraulic head distribution, drawdown, and spring flow. Parameters were selected based on observations of model responses during calibration. These parameters include five pilot points used in interpolating Kx for the PC4 thrust sheet, Kx-values for CAU in Zone 3, and Kx for the Paleozoic carbonate in the other extensive thrust sheet, PC1. They also include specific storage and specific yield for the Paleozoic Carbonate units, and for the Muddy Creek (CAU), fault conductance for the California Wash Fault fault (HFB), recharge rates, and spring conductances for the Muddy River springs. Sensitivity analysis was performed by simulating each parameter using multiples of the calibrated value of 2x and 0.5x for hydraulic-conductivity, specific storage, HFB conductance, and spring conductance parameters; 1.25x and 0.8x for recharge parameters; and 1.125x and 0.8x for specific-yield parameters.

Changes in the simulated heads and spring flow rates for the pre-development simulation were compared against pre-development observed measurements at the end of 10,000-year transient stress period implemented using non-pumping conditions. Because different factors were used for different types of parameters, sensitivities were expressed as the scaled sensitivity. The scaled sensitivity is the estimated change in the model output variable, such as water level or spring discharge, that would occur if the parameter were doubled, assuming that the model response to the change in the parameter value was constant. For the pre-production model, the output variables (water level and discharge rates) were evaluated directly. For the Order 1169 transient model, an estimate of drawdown at selected wells was developed by calculating the simulated range in heads (difference between the maximum head and minimum head). Scaled sensitivities for the range were calculated and tabulated. In addition, plots of measured and simulated drawdown were prepared for each sensitivity run. These are provided in Attachment II.

6.6.1 PRE-PRODUCTION

Table 6-7 provides the scaled sensitivities for the hydraulic heads at the indicated wells. These values are color coded so that the parameters which produce the largest changes in water level can be more readily identified. Green is used to indicate a positive scaled sensitivity (increase in water level as a result of an increase in the value of the parameter), and red indicates a negative scaled sensitivity.

The scaled sensitivities for the spring discharge rates and streamflow in the Muddy River at Moapa and at Glendale are provided in Table 6-8. These values are also color coded. Green indicates an increase in discharge or flow, and red indicates a decrease, as a result of increasing the value of the parameter.

The tables provide the scaled sensitivities calculated by increasing the parameter values (forward difference formulation). The sensitivities calculated by reducing the values were similar.

Table 6-7. Scaled sensitivities of simulated water levels to selected parameters

		Parameter														
Basin	**Well**	k_pc4_1	k_pc4_2	k_pc4_6	k_pc4_14	k_pc4_24	kx_cau_3	kx_pc1	sfac	sfacmm	ss_pc4	sy_pc4	sy_cau	hf_cwf_n	hf_cwf_s	MRS_cond
Clover Valley	W204	-0.009	-0.002	-0.002	0.000	0.000	-0.001	-0.270	11.831	0.000	0.000	0.000	0.000	0.000	0.000	-0.001
	W206	-0.314	-0.072	-0.195	0.000	-0.002	-0.031	-6.450	372.415	0.004	0.000	0.000	0.008	0.000	0.000	-0.013
Lower Meadow Valley Wash	LMVW-11	-3.905	-0.676	0.000	-0.077	-0.041	-5.544	-0.013	6.611	0.185	0.001	0.000	0.000	-0.004	-0.047	-2.333
	LMVW-20	-2.108	-0.493	-1.388	-0.004	-0.016	-0.206	-40.784	1132.636	0.008	0.001	0.000	0.037	0.001	-0.001	-0.085
	LMVW-42	-15.481	0.085	0.001	-0.036	-0.005	-2.735	0.008	2.752	0.091	0.000	0.000	0.000	-0.001	-0.023	-1.153
	Breedlove	-2.678	-0.470	0.000	-0.052	-0.028	-3.755	-0.014	4.650	0.126	0.001	0.000	0.000	-0.002	-0.031	-1.580
	W182	-0.440	-0.151	-0.002	-0.001	-0.004	-0.072	-0.222	5.156	0.000	0.000	0.000	0.000	0.000	-0.001	-0.030
Tule Desert	PW-1	-21.273	-4.506	-0.167	-0.029	-0.166	-1.777	-83.379	268.770	0.051	0.000	0.000	0.068	0.000	-0.012	-0.737
	FF-1	-14.668	-2.914	-0.104	-0.029	-0.111	-1.647	-40.071	219.669	0.052	0.000	-0.008	0.108	0.002	-0.012	-0.699
	W170	-22.325	-4.739	-0.174	-0.030	-0.174	-1.809	-78.963	263.708	0.047	0.000	-0.008	0.056	0.000	-0.013	-0.749
	W191	-5.343	-1.163	-0.518	-0.010	-0.042	-0.454	-108.078	1153.207	0.012	0.000	0.000	0.068	0.000	-0.003	-0.187
Kane Springs Valley	KMW-1	-19.004	-9.378	-0.004	-0.424	-0.218	-26.479	-0.131	28.764	0.888	0.002	0.000	0.004	-0.018	-0.231	-11.103
	KS-GEYSER	-36.701	-28.567	-0.152	-0.301	-0.187	-17.865	-1.273	375.756	0.598	0.002	0.000	0.136	-0.011	-0.156	-7.516
Virgin River Valley - Beaver Dam Wash	W168	-0.032	-0.005	0.000	0.000	0.000	-0.004	-1.917	6.002	0.005	0.000	0.000	0.005	0.001	0.000	-0.001
	W172	-0.268	-0.053	-0.005	-0.001	-0.002	-0.031	-0.243	29.377	0.000	0.000	0.000	0.004	0.000	-0.001	-0.013
	W175	-0.097	-0.019	-0.002	0.000	-0.001	-0.011	0.993	13.514	0.000	0.000	0.000	0.004	0.000	0.000	-0.005
	W185	-1.253	-0.253	-0.043	-0.002	-0.009	-0.124	-27.710	218.212	0.004	0.000	0.000	0.032	0.001	0.000	-0.051
	W188	-0.625	-0.127	-0.028	-0.001	-0.005	-0.061	-29.890	148.810	0.004	0.000	0.000	0.016	0.000	0.000	-0.025
	W190	-1.742	-0.358	-0.102	-0.003	-0.013	-0.164	-68.704	433.949	0.004	0.000	0.000	0.044	0.001	-0.001	-0.068
	MW-8	-8.775	-1.835	-0.157	-0.014	-0.067	-0.787	-48.617	461.081	0.024	0.001	0.010	0.137	0.001	-0.004	-0.326
Virgin River Valley	VVWD31	-0.611	-0.095	-0.005	-0.003	-0.005	-0.120	2.428	24.792	0.004	0.000	-0.008	0.016	0.000	-0.002	-0.053
	VV_OV	0.010	0.006	0.000	0.000	0.000	-0.007	0.139	0.790	0.008	0.000	0.000	0.000	0.002	0.001	-0.011
Coyote Spring Valley	CSI-2	-1.875	0.059	0.004	-0.406	-0.057	-27.517	-0.089	17.574	0.912	0.001	0.000	0.000	-0.020	-0.236	-11.550
	CSVM-1	-1.529	0.626	0.003	-0.400	-0.055	-27.541	-0.089	17.386	0.912	0.000	-0.008	-0.004	-0.020	-0.237	-11.562
	CSVM-2	0.130	1.464	0.003	-0.516	-0.054	-27.965	-0.106	17.937	1.014	0.000	0.000	0.000	-0.020	-0.267	-11.526
	CSVM-3	-24.144	-11.742	-0.009	-0.453	-0.257	-26.903	-0.116	30.877	0.904	0.002	0.000	0.008	-0.018	-0.236	-11.277
	CSI-3	-2.165	-0.567	0.003	-0.413	-0.060	-27.496	-0.090	17.750	0.912	0.000	0.000	-0.004	-0.020	-0.237	-11.539
Muddy River Springs Area	Behmer	2.193	0.936	0.002	-0.169	-0.008	-4.719	-0.045	9.000	0.503	0.000	0.000	0.000	-0.011	-0.128	-7.220
	EH-4	3.781	1.596	0.003	-0.287	-0.021	-27.191	-0.080	15.345	0.861	0.001	0.000	0.000	-0.019	-0.219	-11.767
	EH-5b	1.910	1.598	0.003	-0.330	-0.038	-27.434	-0.080	15.891	0.877	0.001	0.000	0.000	-0.019	-0.224	-11.656
	UMVM-1	0.093	1.498	0.003	-0.372	-0.046	-27.569	-0.085	16.772	0.904	0.000	-0.009	-0.004	-0.020	-0.233	-11.606
	CSV-2	1.216	1.584	0.003	-0.347	-0.039	-27.453	-0.078	16.318	0.884	0.000	-0.008	-0.004	-0.020	-0.228	-11.595
	S_CMW	1.792	0.905	0.001	-0.174	-0.014	-7.371	-0.044	8.837	0.488	0.000	0.000	0.000	-0.011	-0.126	-8.292
California Wash	MP_M1	5.068	1.881	0.003	-0.166	0.064	-30.181	-0.089	15.795	0.928	0.000	0.000	0.000	-0.023	-0.229	-11.275
	MPECP1	2.218	1.756	0.003	-0.068	-0.040	-28.899	-0.153	17.953	1.270	0.000	0.000	-0.004	-0.019	-0.321	-11.366
	MBTH1	2.202	1.764	0.003	-0.044	-0.040	-28.910	-0.158	18.068	1.305	0.001	0.000	0.000	-0.018	-0.328	-11.352
	MP-M2	1.978	1.725	0.003	-0.039	-0.046	-28.740	-0.173	18.423	1.376	0.000	0.000	0.000	-0.018	-0.361	-11.334
	MP-M3	1.820	1.696	0.003	-0.122	-0.047	-28.657	-0.159	18.423	1.301	0.001	0.000	0.000	-0.018	-0.349	-11.366
	EH-2a	4.587	1.894	0.003	-0.216	-0.145	-28.964	-0.076	16.262	0.967	0.000	-0.008	-0.004	-0.059	-0.232	-11.104
Hidden Valley	Sheep Range	-11.413	-4.799	0.004	-5.162	-0.117	-27.915	-0.154	929.021	1.152	0.003	0.025	0.053	-0.017	-0.347	-11.409
Garnet Valley	GV-1	1.452	1.668	0.003	-0.283	-0.060	-28.390	-0.188	19.819	1.442	0.000	-0.008	-0.004	-0.018	-0.467	-11.321
	CRYST1	1.894	1.715	0.003	-0.052	-0.047	-28.645	-0.176	18.551	1.395	0.001	0.000	0.000	-0.017	-0.375	-11.329
	MIRANT	1.426	1.659	0.003	-0.260	-0.059	-28.342	-0.194	19.951	1.474	0.001	-0.008	0.000	-0.017	-0.493	-11.310
Black Mountains Area	RB_S	0.194	0.035	0.001	0.200	0.030	-0.457	-0.058	0.371	1.738	0.000	0.000	0.000	0.002	0.240	-0.218
	RB_D	0.574	0.420	0.000	0.086	0.016	-0.631	-1.164	0.582	0.731	0.000	0.000	0.000	0.019	0.230	-0.369

Table 6-8. Scaled sensitivities of spring discharge rates to selected parameters.

	Parameter														
Discharge Location	k_pc4_1	k_pc4_2	k_pc4_6	k_pc4_14	k_pc4_24	kx_cau_3	kx_pc1	sfac	sfacmm	ss_pc4	sy_pc4	sy_cau	hf_cwf_n	hf_cwf_s	MRS_cond
Rogers and Blue Pt	-149571	-9113	1	-27754	-3451	33874	36845	-20926	-135868	-26	321	-260	-157	-18971	18566
Muddy River at Moapa	186600	80182	100	-13700	-1100	-827000	-3900	760859	41669	2100	1600	22800	-1000	-10800	455900
Muddy River at Glendale	-126900	-21495	700	-21800	-3300	219800	-57800	7022391	73117	3500	3200	38000	-1000	-17600	80600
Baldwin	13960	6988	10	-1240	-130	-110550	-340	66675	3695	190	160	2000	-80	-940	111490
Pederson	24516	9936	21	-1600	-109	-54379	-478	94166	5169	263	208	2780	-114	-1318	-51555
Pipeline-Jones	14660	6329	20	-1050	-80	-98137	-300	59537	3341	170	160	1800	-70	-840	54730
Plummer	23850	9068	20	-1440	-70	-143420	-430	84380	4717	240	240	2560	-100	-1200	201610
Cardy-Lamb	52660	29883	60	-5430	-600	-398594	-1440	286917	15803	810	640	8560	-350	-4050	-75490
Muddy Springs	51850	17256	40	-3010	-230	-229550	-810	164215	9081	470	400	4920	-190	-2310	251670

Water levels in the Muddy River Springs area, Coyote Spring Valley, California Wash, and Garnet Valley are very sensitive to the hydraulic conductivity of the Muddy Creek/CAU (kx_cau_3). Doubling of this hydraulic-conductivity parameter lowers simulated water levels in these areas by 5 to 10 feet (Figure 6.6-1). Because the vertical hydraulic conductivity is calculated from the horizontal hydraulic conductivity, the model sensitivity is to changes in both the horizontal and vertical conductivity parameters. Although water flows primarily through the high permeability Paleozoic carbonates to reach the springs area, its discharge to Muddy River is impeded by the presence of the CAU sediments. The CAU is several orders of magnitude less permeable than the carbonates, and acts as a hydraulic dam. Discharge to the individual springs is simulated as occurring through restricted conduits from the underlying carbonate aquifer (PC4) to the surface. Increasing the hydraulic conductivity for the CAU allows more water to discharge to the Muddy River (as indicated by the increase in discharge at the Glendale gage), lowers hydraulic heads in carbonate wells in the vicinity, and causes a discharge in the discharge of the individual springs. These effects also propagate away from the springs area to affect water levels in much of the surrounding area because of the high hydraulic conductivity of the Paleozoic carbonates.

Downgradient of the Muddy River Springs, water levels rise because of the net decrease in the discharge in the springs area, which causes an in increase in the hydraulic gradient needed to transmit the extra water to other discharge areas further downgradient.

Another parameter which has a large effect on simulated water levels is the hydraulic conductivity of the lowest carbonate thrust sheet, PC1. The greatest effect of increasing the conductivity is in the northern part of the model area, in the Clover Mountains and Tule Desert areas (Figure 6.6-2). Doubling the conductivity lowers the simulated water table by more than 100 feet in some areas. Waters levels increased in areas that were close to discharge areas (e.g., Beaver Dam Wash, Virgin River, and lower part of Meadow Valley Wash), in response to the increased flow toward these discharge points. Impacts on discharge from the springs above Moapa and flow in the Muddy River are minor. The largest volumetric effect was on the Muddy River flow at Glendale, which decreased about 1%. However, the greatest percentage change was for the combined discharge from Rogers and Blue Point Springs, which declined 308 af/yr (18%). The discharge into Lake Mead increased 376 af/yr (9.2%), slightly more than the decrease in discharge from Rogers and Blue Point Springs.

The hydraulic conductivity of the carbonate aquifer in thrust sheet 4 would also be expected to have a large impact on the model results. Because 24 pilot points were used to define its properties, the sensitivity to changes at individual pilot points was investigated rather than for the entire PC4 thrust sheet. Sensitivities to hydraulic conductivity at five pilot points were investigated. Three (2, 1, and 24) are located near a line running between central Coyote Spring Valley through the Muddy River Springs area (Figure 6.1-3). Pilot point 1 is in the area of the springs, and had the highest hydraulic conductivity value (19,486 ft/day) in the model.

Pilot point 2, in central Coyote Spring Valley, had the second highest (4,560 ft/day). Of the five pilot points investigated, the model was most sensitive to changes at pilot point 1. The greatest changes in head occurred in northern Coyote Spring Valley, Kane Springs Wash, and in the Tule Desert. Doubling the hydraulic conductivity value caused simulated heads to decline by more than 50 feet in some areas (Figure 6.6-3). However, in the Muddy River Springs area, simulated water levels increased by nearly 4 feet. Water levels in the downgradient part of the PC4 thrust sheet generally increased, and on the west side of the Glendale Thrust they increased by more than 20 feet. Smaller increases occurred beneath California Wash and further to the south and west. The discharge from the springs in the Muddy River Springs area increased. These responses indicate that increasing the hydraulic conductivity of the carbonates in PC4 near PP1 causes an increase in the volume of water captured by the carbonate aquifer from areas to the north. While the flow in the Muddy River at Moapa increased by 8%, the flow in the Muddy River at Glendale decreased by 2%. The discharge from the combined Rogers and Blue Point Springs increased.

Changes in the values of hydraulic conductivity at pilot point 24 had little effect on the water levels or flows. Changing the hydraulic conductivity at pilot point 6 (k_pc4_6), in the northernmost part of Coyote Spring Valley, also had very little effect on the model results. Neither did changing values at pilot point 14 (k_pc4_14), on the boundary of Garden and Hidden Valleys. Doubling the conductivity at pilot point 14 lowered simulated water levels in the Muddy River Springs area a few tenths of a foot, and therefore decreased streamflow a small amount. Because the PC4 thrust sheet extends to the Rogers and Blue Point Springs area, doubling k_pc4_14 increased the simulated discharge from these springs by 29 af/yr (14%), by diverting flow from central Coyote Spring Valley into the southern part of the valley.

The parameter with the greatest impact on water levels and discharge in the model is the recharge. In the model, the recharge has two parameters. The most important is a multiplier (Rech_sfac) for the recharge array, which was used to adjust the recharge over the entire model domain. The second parameter (sfacmm) is a value that was added to the recharge array in the area of the Muddy Mountains. Sensitivity testing was performed by increasing these by a factor of 1.25, and decreasing these by a factor of 0.8. Results were similar. Figure 6.6-4 shows the change in simulated water levels from increasing the value of Rech_sfac by 25%. The greatest increases in water levels are in the upland areas, as these are the areas with the greatest recharge and that are also distant from the areas where groundwater discharge occurs (springs, perennial reaches of streams, and Lake Mead). In the sensitivity simulation in which the regional recharge was increased by 25%, the simulated overall recharge increased by nearly 27,000 af/yr. The increase in discharge from all the springs was 3,337 af/yr, of which the combined Rogers and Blue Point Springs discharge accounted for only 44 af/yr. The discharge into Lake Mead was only 11 af/yr higher than in the base-case (calibrated model) simulation. The flow at the Muddy River near Moapa gage increased by 1,600 af/yr. On the other hand, the simulated flow in the Muddy River at the Glendale gage (which is below the confluence of the Muddy River and

Meadow Valley Wash) increased by 14,766 af/yr. The remaining 8,865 af/yr discharged into Beaver Dam Wash, the Virgin River, and the lower part of the Muddy River. Thus, approximately 88% of the increased recharge was through discharge into the streams [this percentage includes discharge from the springs in the Muddy River Springs area, which was simulated using the Stream Routing Package.]

The recharge added to the Muddy Mountains (2,011 af/yr) is a small component of the total recharge in the model (109,560 af/yr). Doubling this recharge is predicted to increase the water levels in California Wash nearly 1.5 ft, and approximately 1.7 feet at the Rogers and Blue Point Springs. In the sensitivity simulation, the recharge was increased by 503 af/yr. Simulated discharge from the combined Rogers and Blue Point Springs increased by 290 af/yr, approximately 2/3 of the increased recharge. Groundwater flow from other springs increased by about 7 af/y. The simulated discharge from the groundwater system into Lake Mead was 18 af/yr. Thus, not all of the increased recharge discharged near the Muddy Mountains. Figure 6.3-1 showed that some of the recharge on the Muddy Mountains flows to the northwest. The increase in water levels simulated to occur in California Wash causes discharge to increase in upstream areas as well. The discharge above the Muddy River near Glendale gage increased by 156 af/yr.

Groundwater flow discharge at Rogers and Blue Point springs is simulated as a combination of local recharge and distant-sourced waters. Flow occurs primarily through the California Wash Fault at depth where the fault barrier properties are less influential, eventually exiting through the springs at the Rogers Fault. Spring discharge is most sensitive to the conductance of the pilot point 1 for the PC4, and the recharge applied at the Muddy Mountains. Increasing the values of these parameters increases the simulated discharge at Rogers and Blue Point Springs. Increasing the hydraulic conductivity for zone 3 of the CAU and for the PC1 decreases the simulated discharge.

Water levels had little sensitivity to the values used for the conductances of the California Wash fault. The simulated discharges to the Muddy River at Glendale and at Moapa, and from Rogers and Blue Point springs were slightly sensitive to the value assigned to the southern part of the California Wash fault HFB. However, other parameters were much more important in determining these discharge rates.

A sensitivity evaluation was done in which the conductances for the springs in the Muddy River Springs area were changed, by factors of 2 and 0.5. When the conductances are increased, the simulated discharges for most springs increase, as do the simulated flows in the Muddy River near Moapa and Glendale. However, the discharges at Pederson and Cardy-Lamb springs declined. These springs have higher elevations than the others, and the decline in heads in the groundwater system that is also caused by increasing the conductances causes a decrease in the head difference (water level – spring elevation) that is proportionally greater than the increase in

conductance. When the conductances were decreased by a factor of 0.5, the spring discharge declined at all springs except Pederson, where it increased. At Pederson, the increase in water levels had a larger effect than the decrease in conductance, but at the lower elevation springs (including Cardy-Lamb) the decrease in conductance had a larger effect.

6.6.2 ORDER 1169 MODEL

Sensitivity analyses were also performed using the transient Order 1169 model to evaluate the effects of changing selected model parameters on drawdown calculations for wells in the vicinity of Coyote Spring Valley and the Muddy River Springs area. The sensitivities were determined for the same parameters as used for the pre-production model sensitivity analyses, with the exception that the spring-conductance parameters were not evaluated. The starting heads for each of the Order 1169 model simulations were obtained from the pre-production model results at the end of 2008, for the same parameter data set as used for the Order 1169 simulation. The effects on the simulated drawdowns were evaluated, in two different ways. As discussed above, the range of drawdowns at each of the wells was determined, and the sensitivity of the range to the changes in the model parameter was calculated. Table 6-9 gives the calculated scaled sensitivities to the parameters that were investigated. The values are estimates of the change in the range of drawdown for doubling of the parameter.

Results are also presented in a set of drawdown plots for each of the investigated parameters (Attachment II). The figures are similar in format to the figure that presented the results of the calibrated model. Drawdown values (using the scale on the left) are provided in feet. For each well, the calibrated, or base-case, model results are presented as a purple line. The results for the sensitivity simulation are shown as blue dots. Measured values are shown by a red line. For wells which were pumped during this time period, the pumping rate is provided by a green line, using the scale provided to the right (in cubic feet per day).

In the vicinity of the major pumping in Coyote Spring Valley (from MX-5), the simulated drawdown is most sensitive to the values for hydraulic conductivity at pilot points 1 and 2 (k_pc4_1 and k_pc4_2), and the specific yield of the CAU (sy_cau). Pilot point 1 is located in the Muddy River Springs area, and pilot point 2 is near MX-5. Increasing any of these values decreases the simulated drawdown in the observation wells close to the pumping well. The effects of changing k_pc4_1 and k_pc4_2 are observable not only in Coyote Spring Valley, but also in the Muddy River Springs area. As would be expected, pilot point 2 has a larger effect on drawdown at MX-4 and MX-5 than pilot point 1 does. Drawdown in other wells (e.g., CSI-1, CSI-2, CSV-RW1, and CSVM-1) close to MX-5 also decreases when the hydraulic conductivity at pilot points 1 and 2 are increased. In contrast, the drawdown at wells further away (e.g., Moapa Band of Paiutes' M-1, M-3, ECP1, and TH-2; CSVM-2, -3, -4; and CSV-3) increases when the hydraulic conductivity at these pilots points in increased. Larger hydraulic conductivities allow the drawdown to extend further.

Table 6-9. Scaled sensitivity of total range of water levels for selected parameters, Order 1169 simulation.

	Parameter													
Well	k_pc4_1	k_pc4_2	k_pc4_6	k_pc4_14	k_pc4_24	kx_cau_3	kx_pc1	sfac	sfacmm	ss_pc4	sy_pc4	sy_cau	hf_cwf_n	hf_cwf_s
eh-3	4.27E-03	-1.34E-03	-1.22E-04	-1.22E-04	0.00E+00	2.81E-03	-6.10E-04	1.02E-02	4.80E-04	1.10E-03	-1.86E-09	-5.86E-03	1.22E-04	1.22E-04
eh-4	-0.1363527	-2.98E-02	-1.22E-04	-4.52E-03	-1.83E-03	0.1732173	-1.19E-07	-2.43E-02	-2.40E-03	-3.82E-02	-4.20E-02	-0.431641	0.00E+00	4.88E-04
eh-5b	-0.286377	-3.54E-02	0.00E+00	-3.05E-03	-1.34E-03	0.12316883	4.88E-04	-6.28E-02	-4.32E-03	-3.82E-02	-4.79E-02	-0.4296905	2.44E-04	1.34E-03
eh-7	2.44E-04	3.66E-04	1.22E-04	1.22E-04	1.22E-04	-1.71E-03	1.22E-04	1.95E-03	9.60E-04	0.00E+00	0.00E+00	-4.35E-02	1.22E-04	0.00E+00
mbp_m-1	2.48E-02	-1.04E-02	0.00E+00	-1.10E-03	1.46E-03	-1.46E-02	0.00E+00	-5.35E-03	-9.60E-04	-2.99E-02	-3.12E-02	-0.3168948	0.00E+00	3.66E-04
mbp_m-3	5.00E-02	7.32E-03	-1.22E-04	1.79E-02	7.32E-04	-5.58E-02	-1.22E-04	1.56E-02	4.80E-04	-2.00E-02	-1.76E-02	-0.1914062	0.00E+00	-2.44E-04
mbp_ecp1	4.37E-02	5.86E-03	-1.22E-04	1.01E-02	7.32E-04	-4.87E-02	-1.22E-04	1.36E-02	4.80E-04	-1.54E-02	-1.37E-02	-0.1484375	2.98E-08	-2.44E-04
csi-2	-0.1472173	-0.1614636	-1.22E-04	-3.66E-03	-1.22E-03	-3.91E-03	0.00E+00	4.86E-04	-4.79E-04	-3.20E-02	-3.42E-02	-0.437501	1.19E-07	1.22E-04
csv-rw2	-0.306152	-0.4547344	0.00E+00	-4.52E-03	-2.20E-03	-1.73E-02	0.00E+00	3.41E-03	-4.79E-04	-3.80E-02	-4.00E-02	-0.5146486	0.00E+00	1.22E-04
csvm-1	-0.2387695	-0.2933926	-1.19E-07	-4.40E-03	-1.71E-03	-1.46E-02	1.22E-04	2.92E-03	0.00E+00	-3.81E-02	-4.10E-02	-0.5136701	1.22E-04	2.44E-04
csvm-2	4.91E-02	2.29E-02	1.22E-04	1.10E-03	2.44E-04	-3.85E-02	0.00E+00	1.22E-02	9.60E-04	-2.80E-02	-4.30E-02	-0.3129883	1.22E-04	0.00E+00
csvm-3	6.96E-03	3.91E-03	0.00E+00	-7.32E-04	-1.22E-04	-3.31E-02	-1.22E-04	1.07E-02	4.80E-04	-1.59E-03	-1.95E-03	-2.49E-02	-1.22E-04	-2.44E-04
csvm-4	3.15E-02	2.60E-02	2.98E-08	-1.46E-03	2.44E-04	-5.10E-02	-1.22E-04	1.85E-02	9.60E-04	-1.75E-02	-1.46E-02	-0.1552735	0.00E+00	-2.44E-04
csvm-5	-2.39E-02	4.74E-02	-1.22E-04	-9.77E-04	-4.88E-04	-3.75E-02	-2.44E-04	1.12E-02	0.00E+00	-3.37E-02	-4.39E-02	-0.4238285	-1.22E-04	-1.22E-04
csvm-6	-9.84E-02	-6.21E-02	0.00E+00	-3.54E-03	-1.10E-03	-2.25E-02	0.00E+00	5.84E-03	-4.80E-04	-3.50E-02	-3.52E-02	-0.4843765	0.00E+00	-1.22E-04
csvm-7	6.96E-03	4.15E-03	-1.22E-04	-6.10E-04	0.00E+00	-3.33E-02	-1.22E-04	1.12E-02	9.60E-04	-1.59E-03	-1.95E-03	-2.49E-02	-1.22E-04	-2.44E-04
umvm-1	-9.67E-02	-4.81E-02	0.00E+00	-4.15E-03	-1.10E-03	1.72E-02	1.22E-04	-9.73E-03	-9.59E-04	-3.98E-02	-4.30E-02	-0.4663092	1.22E-04	3.66E-04
csi-3	-0.1854247	-0.4106764	0.00E+00	-1.95E-03	-1.83E-03	-2.81E-03	0.00E+00	9.72E-04	0.00E+00	-1.66E-02	-1.56E-02	-0.337401	-1.22E-04	-1.22E-04
kmw-1	2.60E-02	1.62E-02	1.22E-04	-9.77E-04	2.44E-04	-4.58E-02	1.22E-04	1.70E-02	1.44E-03	-1.07E-02	-7.81E-03	-9.08E-02	0.00E+00	-1.22E-04
a_cn	-0.3278813	-3.43E-02	-1.22E-04	-3.66E-03	-1.22E-03	9.77E-02	2.44E-04	-3.21E-02	-3.36E-03	-3.85E-02	-4.79E-02	-0.4077168	0.00E+00	7.32E-04
a_cn_2	-0.2901617	-3.39E-02	-1.22E-04	-3.66E-03	-1.34E-03	9.44E-02	2.44E-04	-2.87E-02	-2.88E-03	-3.83E-02	-4.79E-02	-0.4038111	-1.19E-07	6.10E-04
c_l	-0.1773686	-7.55E-02	-1.22E-04	1.29E-02	7.32E-04	-0.2585444	3.78E-03	-0.4059792	-3.98E-02	-2.22E-02	-2.44E-02	-0.7641622	8.54E-04	1.11E-02
cry_mw1	-7.31E-02	-2.79E-02	-1.22E-04	0.00E+00	0.00E+00	-0.502686	1.22E-04	-0.2424181	-6.24E-03	-5.74E-03	-7.82E-03	-0.5219728	0.00E+00	2.44E-04
cox-mw1	-1.51E-02	-6.10E-03	-1.22E-04	6.10E-04	0.00E+00	-7.75E-02	1.22E-04	-2.97E-02	-1.92E-03	-3.30E-03	-3.91E-03	-0.6591817	1.22E-04	3.67E-04
csi-1	-0.1384282	-0.1556059	0.00E+00	-4.15E-03	-1.46E-03	-2.16E-02	-1.22E-04	5.36E-03	0.00E+00	-3.59E-02	-3.71E-02	-0.4946285	-1.22E-04	0.00E+00
csi-4	-0.1126713	-0.1199692	-1.22E-04	-2.56E-03	-1.59E-03	-3.30E-02	-1.22E-04	1.07E-02	4.80E-04	-2.92E-02	-2.54E-02	-0.4594739	1.19E-07	-1.22E-04
csv3011m	1.90E-02	1.68E-02	0.00E+00	-1.10E-03	1.22E-04	-3.81E-02	-1.22E-04	1.31E-02	9.60E-04	-1.14E-02	-5.86E-03	-8.20E-02	0.00E+00	-2.44E-04
mx-6	-8.85E-02	-3.41E-02	-1.22E-04	-3.30E-03	-9.77E-04	3.91E-02	1.22E-04	-1.17E-02	-1.92E-03	-3.70E-02	-4.79E-02	-0.4008785	0.00E+00	3.66E-04
coburn	-0.3177495	-0.1750109	-4.89E-04	3.50E-02	3.42E-03	-1.0389409	9.40E-03	-1.1750968	-0.1050918	-1.76E-02	-1.95E-02	-0.7153341	2.20E-03	2.69E-02
mbpth-2	5.87E-02	5.37E-03	5.96E-08	7.81E-03	9.77E-04	-4.41E-02	5.96E-08	1.07E-02	4.80E-04	-2.10E-02	-2.05E-02	-0.2182618	5.96E-08	5.96E-08
csv-3	3.06E-02	2.78E-02	0.00E+00	-7.32E-04	-1.22E-04	-3.13E-02	-1.22E-04	9.25E-03	4.80E-04	-3.25E-02	-4.69E-02	-0.359375	0.00E+00	-1.22E-04
bw-01	-6.24E-02	-2.09E-02	-1.22E-04	-3.05E-03	-9.77E-04	4.90E-02	5.96E-08	-1.46E-02	-1.44E-03	-3.12E-02	-3.71E-02	-0.3139644	5.96E-08	3.66E-04
csv-1	-0.1159667	-8.18E-02	0.00E+00	-4.15E-03	-1.10E-03	-1.95E-03	1.22E-04	-9.74E-04	-4.80E-04	-3.87E-02	-4.30E-02	-0.5019523	1.22E-04	2.44E-04
csv-2	-0.1051024	-3.42E-02	-1.22E-04	-3.78E-03	-1.22E-03	4.66E-02	1.22E-04	-2.00E-02	-2.40E-03	-4.10E-02	-4.39E-02	-0.4394527	0.00E+00	6.10E-04
mx-5	-0.4815664	-0.7833966	0.00E+00	-4.27E-03	-3.17E-03	-1.28E-02	-1.22E-04	2.92E-03	-4.80E-04	-3.72E-02	-3.91E-02	-0.5126916	0.00E+00	1.22E-04
mx-4	-0.5434577	-0.9106897	-1.23E-04	-4.39E-03	-3.54E-03	-1.70E-02	-1.23E-04	3.41E-03	-4.84E-04	-3.77E-02	-4.00E-02	-0.5141603	0.00E+00	-9.54E-07
df-1	-9.83E-02	-6.53E-02	0.00E+00	-3.54E-03	-9.76E-04	-2.60E-02	0.00E+00	7.30E-03	0.00E+00	-3.54E-02	-3.52E-02	-0.4794911	0.00E+00	0.00E+00
ce-vf-2	-4.87E-02	-4.39E-03	0.00E+00	-2.56E-03	-6.10E-04	-3.83E-02	-1.22E-04	1.17E-02	0.00E+00	-3.09E-02	-2.64E-02	-0.4291991	-1.22E-04	-2.44E-04
ce-vf-1	-4.54E-02	-9.76E-04	0.00E+00	-2.56E-03	-6.10E-04	-3.88E-02	-1.22E-04	1.22E-02	4.80E-04	-3.05E-02	-2.54E-02	-0.4267581	-1.22E-04	-1.22E-04

TETRA TECH

The value of the specific yield of the CAU affects the drawdown over a large area (Muddy River Springs area, Coyote Spring Valley, and California Wash). Increasing this value decreases the drawdown in all of the wells evaluated. The greatest effects are in the Muddy River Springs area, but the effects are only slightly less in Coyote Spring Valley. The sensitivity of the calculated drawdown to this parameter are about two orders of magnitude higher than the sensitivity of the model to the specific yield of the PC4 HGU. This is likely because of the limited area where the PC4 is present at the water table compared to the CAU.

Drawdowns are less sensitive to the value of the hydraulic conductivity of zone 3 of the CAU (kx_cau_3) than to the parameters discussed above. The drawdown in the Coburn well (near the Arrow Canyon wells and completed only in Layer 1) decreases when kx_cau_3 is increased. This is likely because the drawdown caused by changes in seasonal ET rates and shallow pumping is less when the hydraulic conductivity is higher. In contrast, the simulated drawdown in wells completed in the underlying carbonate increases, as the drawdown caused by the seasonal stresses are transmitted downward more.

Examination of the drawdown figures reveals that, with the exception of the parameters discussed above, there is little noticeable of changing the model parameters evaluated on the simulated drawdown. Thus, the Order 1169 pumping provides information for the estimation of the PC4 near the pumped well and in the Muddy River Springs area and of the specific yield of the CAU, but limited information on other parameters.

7.0 SUMMARY AND CONCLUSIONS

A new three-dimensional model has been completed of all or parts of 13 hydrographic areas within the Colorado Regional Groundwater Flow System in SE Nevada. This model simulates the movement of groundwater in an area ranging from the Clover and Delaware Mountains on the north to the Las Vegas Valley Shear Zone and Lake Mead on the south, and from the Sheep Range on the west to the Virgin and Beaver Dam Mountains on the east.

Development of this new model was based, in part, on studies funded by federal bureaus: (1) geophysical studies, geologic mapping, and new geologic cross-sections; (2) synoptic discharge-measurement runs on the Muddy and Virgin rivers; (3) an ET study over the whole model area; (4) boundary flux estimates developed by Jim Harrill (retired USGS hydrologist);; and (5) preliminary hydrogeochemical investigations. Other information, such as lithologic information from new drillholes and recent water-level and water-use data, has been provided by other (non-federal) parties and organizations with interest in the groundwater resources of the study area. All of this new information has been quite useful in development of this simulation tool.

Initial development of this model was funded by the National Park Service and the U.S. Fish & Wildlife Service intermittently from 2000 – 2005. The model was completed with funding through the Southern Nevada Public Lands Management Act (SNPLMA) Conservation Initiatives Program, as part of a project on behalf of the National Park Service, the U.S. Fish & Wildlife Service, and the Bureau of Land Management (collectively, the DOI bureaus).

The impetus for the DOI bureaus to develop this model is to have a tool with which to make quantitative estimates of the future impacts on springs and streams throughout the model area as a result of ongoing pumping of existing groundwater rights and additional groundwater applications currently pending before the Nevada State Engineer. The DOI bureaus are interested in the potential adverse effects to springs and streams on federal lands for which they have responsibility.

The model is based on a new geologic framework model which was developed as part of this modeling effort. It incorporates information from surface mapping, lithologic information from drillholes, geophysical investigations, and interpretative cross sections and structural contour maps. Twenty-seven Hydrogeologic Units (HGUs) were used to describe the different lithologic units and the complications caused by the tectonic history of the area.

MODFLOW-2000 was used for the groundwater model. The HUF package, which was developed to allow areas of complicated geology to be simulated by MODFLOW, was used in this model, allowing hydrologic properties to be assigned to each HGU. Other packages which

were instrumental in the development of the model include the MNW (which allowed pumping to be allocated to different model layers using information on the geology and hydrologic properties) and SFR2 packages. The SFR2 package allowed streamflow data to be used in the calibration process, and for the model to predict changes in streamflow that might occur as a result of pumping of the groundwater. Calibration was performed using a combination of regression (using PEST) and manual approaches.

The model has 18 layers, representing different depths below the water table. The uppermost layer is 100 feet thick, and the thickness of the layers increases with depth. The total model is 15,630 feet thick. The grid has 314 rows and 209 columns, and the model cells range in length from 1,500 meters (4921 feet) down to 250 meters (820 feet). The grid is oriented north-south, east-west. The grid spacing is finest (250 meters) in the Muddy River Springs Area, Coyote Spring Valley, and California Wash to take advantage of the greater number of drillholes, and better information on pumping rates, groundwater discharge, and water-level changes in these areas.

The model was calibrated based on many different types of information, including measurements of water levels and drawdown, discharge rates for springs, streamflow measurements, reported pumping rates that varied through time, seasonal estimates of ET based on field measurements and satellite mapping of plant communities, and estimates of model boundary fluxes based on regional information. A “pre-production” model was developed to match water levels and water-budget information. Simulated water levels agree well with observed water levels. The correlation between measured and simulated water levels was 0.96. The largest model residuals are in high gradient areas, where model errors can result in large differences, in the Clover Mountains where the volcanic stratigraphy is greatly simplified, and in the Tule Desert where some of the structural complexity may not be incorporated in the geologic model and the model grid is relatively coarse.

The model was also calibrated to the effects of time-varying pumping and seasonal ET during the period October 2008 through December 2011, primarily in the area of the Muddy River Springs, Coyote Spring Valley, and California Wash. The simulated drawdowns agree reasonably well with the observed drawdowns. In California Wash, the seasonal variation observed in the measurements is not present in the simulated water levels but the longer term trends are present.

The simulated discharge rates in the Muddy River Springs area and at Rogers and Blue Point springs agree very well with measured values. The simulated streamflow in the Muddy River near Moapa is less than measured, indicating that more water discharges directly into the stream above the gage than is being simulated, rather than downstream of the gage. In the lower part of Meadow Valley Wash, simulated water levels are higher than observed, causing simulated discharge into the stream over a larger area than it occurs. Similarly, simulated water

levels are higher than measured in the lower parts of Beaver Dam Wash, causing simulated flow in the stream over a larger reach than observed. In these areas, the model is likely to underestimate the drawdown that occurs because of the larger area in which buffering of drawdown is simulated to occur. The effects of the drawdown on the Muddy River Springs and discharge into the Muddy River may occur sooner than would be predicted by the model because of the simulated capture in lower reaches of the Muddy River and in the lowermost reaches of Meadow Valley Wash.

Pertinent observations and comments about the model are provided so that the user of the model is aware of limitations that may affect decisions made related to modeling predictions:

1. The responses of the groundwater system to pumping are determined primarily by the local geology and the hydrologic properties of the aquifers being pumped. Pumping in the carbonate aquifer in the western part of the model produces widespread drawdown because of the high transmissivity and low storativity of the carbonate aquifer. The model predicts that pumping in the Virgin River basin causes more local (less widespread) drawdown of greater magnitude. Elsewhere, current groundwater development is more limited. In the volcanic rocks in the Clover and Delaware Mountains, the complex stratigraphy of the volcanic rocks will likely limit the extent of drawdown, and the productivity of the rocks will likely be highly variable. The complex stratigraphy is not incorporated in the model. The drawdown is reduced by proximity to large-volume springs, and to perennial reaches of streams. This local effect is caused by the buffering of drawdown caused by capture of water at these locations by pumping.
2. Groundwater production from the Virgin Valley is primarily from the Muddy Creek (CAU HGU). This HGU is treated as homogeneous and isotropic both laterally and vertically in this area. Water levels in the Virgin River Valley are primarily determined in the model by the elevation of the Virgin River, and not by the geology or by the hydraulic conductivities used in the model. In addition, detailed pumping information and responses to pumping were not available. Therefore, a transient model calibration has not been completed in this area, and predictions of the effects of pumping should be used with caution.
3. Cross sections developed in the Tule Desert by consultants for Vidler Water Company were not used in the construction of the geologic model. There are differences between the interpretations presented in these cross sections and other cross sections developed by Page and others (2011). Given the scale of the modeling and the use of the sections by Page and others in the remainder of the model, some of the information contained in the sections developed by Vidler Water Company was not incorporated. In future work, evaluation and incorporation of some of the more detailed information might improve the model in the Tule Desert.
4. The use of the Well Package to simulate ET (so that seasonal changes in ET rates could be used as a driving function during model calibration) may cause head changes to be exaggerated during the long-term predictions of pumping in areas where ET rates are high

and where drawdown from pumping occurs. In nature, as the water table declines, the ET decreases and the decrease in ET decreases the drawdown. However, in the simulation the rate of ET will remain constant and produce a greater drawdown. This effect has only been observed in a small reach of Meadow Valley Wash, where it appears that drawdown could be oversimulated by tens of feet over a small area. Effects in other areas do not appear to be significant, but are unknown.

Prediction of the effects of groundwater pumping will be more reliable in areas where data are available on the responses to pumping and time-varying ET. The best dataset is from the vicinity of the Muddy River Springs and nearby areas (Coyote Spring Valley and California Wash). Thus, predictions for these areas will be most reliable. An evaluation of the uncertainty in model predictions would be a significant effort, and certainly was outside the scope of this current evaluation. An estimate (based on experience with this model and the sensitivity testing that was performed) of the prediction uncertainty for drawdown in these areas would be in the range of 20 to 30 percent over a period of 20 to 30 years. With increasing distance from the area of the Muddy River Springs, the uncertainty increases. In other areas where pumping is occurring (Garnet Valley and the Virgin River Valley), the simulated drawdowns are reasonable, but cannot be compared with measured drawdowns. Thus, the there is more uncertainty of the model results to pumping in these areas. There are aquifer-testing data available in the Tule Desert, but no long-term pumping has yet occurred, and thus there is no information on long-term productivity or on response to pumping in areas distant from wells. Thus, there is substantial uncertainty on the magnitude and timing of drawdown in the Tule Desert. The most uncertainty is in the Clover and Delaware Mountains. The drawdown that will occur will be very dependent on local conditions and rock properties because of the complex volcanic stratigraphy, which has been generalized.

In summary, this model is a great improvement over previous models of the area, because of the advances in information on the geology and hydrology of the study area, and improvements in modeling codes available. This is also the first model to include the Virgin River Valley and Tule Desert, the lower White River Flow System, and the area of Lower Meadow Valley Wash. It can be used to evaluate cumulative effects of pumping in different areas within the model, and to estimate the magnitude and timing of changes that will occur as a result of use of the groundwater. Predictions made using the model will be approximate, but can be used to guide decisions about management of the groundwater resource and to determine whether there will be impacts on sensitive environments and on other users of the water. The uncertainty in the predictions will primarily affect the timing of when impacts become significant, not whether there will be impacts.

8.0 REFERENCES

Anderman, E.R., and Hill, M.C., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model – Documentation of the Hydrogeologic-Unit Flow (HUF) Package: U.S. Geological Survey Open-File Report 00-342, 89 p.

Anderman, E.R., and Hill, M.C., 2003, MODFLOW-2000, the U.S. Geological Survey modular ground-water model – Three additions to the Hydrogeologic-Unit Flow (HUF) Package: Alternative storage for the uppermost active cells, Flows in hydrogeologic units, and the Hydraulic-conductivity depth-dependence (KDEP) capability: U.S. Geological Survey Open-File Report 03-347, 36 p.

Belcher W.R., Elliott, P.E., and A.L. Geldon, 2001, Hydraulic-Property Estimates for use with Transient Ground-Water Flow Model of the Death Valley Regional Ground-Water Flow System, Nevada and California, U.S. Geological Survey, Water Resources Investigation 01-4120, 28p.

Belcher, W.R., ed., 2004, Death Valley regional ground-water flow system, Nevada and California—Hydrogeologic framework and transient ground-water flow model: U.S. Geological Survey Scientific Investigations Report 2004-5205, 408 p.

Berger, D.L., Kilroy, K.C., Schaefer, D.H., 1988, Geophysical logs and hydrologic data for eight wells in the Coyote Spring Valley area, Clark and Lincoln Counties, Nevada, U.S. Geological Survey, Open-File Report 87-679, 59 p.

Beck, D.A., Wilson, J.W., 2005, "Discharge and Physical-Property Measurements from Virgin River Narrows, Arizona, to Lake Mead, Nevada, February 12, 2003" U.S. Geological Survey, Scientific Investigations Report 2005-5286

Beck, D.A., Wilson, J.W., 2006, "Synoptic Discharge, Water-Property and pH Measurements for Muddy River Springs Area and Muddy River, Nevada, February 7, 2001" U.S. Geological Survey, Scientific Investigations Report 2006-5237

Black, K.R. and S.J. Rascona, 1991, Maps Showing Groundwater Conditions in the Virgin River Basin, Mohave County, Arizona, Lincoln and Clark Counties, Nevada – 1991, Department of Water Resources, Hydrologic Map Series Report Number 22.

Burbey, T.J., Warner, S.M., Blewitt, Geoff, Bell, J.W., and Hill, Emma, 2005, Three-dimensional Deformation and Strain Induced by Municipal Pumping, Part 1: Analysis of Field Data: Journal of Hydrology, v. 319, p. 123-142

Bureau of Land Management (BLM), 2009, Final Environmental Impact Statement, Lincoln County Land Act Groundwater Development and Utility Right of Way Project, FES 09-05, May 2009.

Brothers, K., Katzer, T., Mojib, R.M., Grinnell, G., Bernholtz, A., and M. Johnson, 1993, Addendum to Hydrology and Interactive Computer Modeling of Ground and Surface Water in the Lower Virgin River Valley, Primarily in Clark County, Nevada, Las Vegas Valley Water District, 35pp.

Bunch and Harrill, 1984, Compilation of Selected Hydrologic Data from the MX Missile-Siting Investigation, East-Central Nevada and Western Utah, U.S. Geological Survey, Open-File Report 84-702, 123 pp.

Buqo, T.S., Drici, Q., and Goings, D.B., 1992, Hydrology and steady-state ground-water model of Coyote Spring Valley, Clark and Lincoln Counties, Nevada: Las Vegas Valley Water District,

Cooperative Water Project, Report No. 3, 84 p.

Buqo, T.S., 2000, Preliminary Hydrogeologic and Water Supply Assessment, Lewis Farm Area, Lower Meadow Valley Wash Hydrographic Basin (Basin 205), Prepared for Moapa Valley Water District, 20 p.

Buqo, T.S., 2002, Preliminary Results of Testing of the Arrow Canyon #2 Well, Prepared for Moapa Valley Water District, July 2002.

Buqo, T.S., 1994, Results of Long-Term Testing of the Arrow Canyon Well, Prepared for Moapa Valley Water District, June 1994.

Converse Consultants, 2000, Groundwater level monitoring program 1999 annual report Moapa, Nevada, Prepared for Nevada Power Company, 14 p.

Converse Consultants, 2001, Groundwater level monitoring program 2000 annual report Moapa, Nevada, Prepared for Nevada Power Company, 24 p.

Converse Consultants, 2002, Production Well Construction and Testing, RW-2 Well, Coyote Spring Valley, Clark County, Nevada, Prepared for Nevada Power Company, June 2002.

Converse Consultants, 2004, Groundwater level monitoring program 2003 annual report Moapa, Nevada, Prepared for Nevada Power Company, 26 p.

Converse Consultants, 2005, Groundwater level monitoring program 2004 annual report Moapa, Nevada, Prepared for Nevada Power Company, 27 p.

DeMeo, G.A., Smith, J.L., Damar, N.A., and J. Darnell, 2008, Quantifying Ground-Water and Surface-Water Discharge from Evapotranspiration Processes in 12 Hydrographic Areas of the Colorado Regional Ground-Water Flow System, Nevada, Utah, and Arizona, U.S. Geologic Survey, Scientific Investigations Report 2008-5116, 23 p.

Dettinger, M.D., Harrill, J.R., Schmidt, D.L., and Hess, J.W., 1995, Distribution of carbonate-rock aquifers and the potential for their development, southern Nevada and adjacent parts of California, Arizona, and Utah: U.S. Geological Survey Water-Resources Investigations Report 91-4146, 100 p. and 2 plates.

Dixon, G.L, and Katzer, Terry, 2002, Geology and Hydrology of the Lower Virgin River Valley in Nevada, Arizona, and Utah: Report VVWD-01, 113 p. + appendices and plates.

Doherty, J., 2003, Ground Water Model Calibration Using Pilot Pints and Regularization: Ground Water, v. 41, no. 2, p. 170-177.

Doherty, J. 2010, PEST: Model-Independent Parameter Estimation, version 12, Watermark Numerical Computing.

Eakin, T.E., 1964, Ground-water appraisal of Coyote Spring and Kane Spring Valleys and Muddy River Springs area, Lincoln and Clark Counties, Nevada: Nevada Department of Conservation and Natural Resources, Ground-Water Resources Reconnaissance Series, Report 25, 40 p.

Enright, M., Selected Hydrologic Data for the Beaver Dam Wash Area, Washington County, Utah, Lincoln County, Nevada, and Mohave County, Arizona, 1991-1995, U.S. Geological Survey, Open-File Report 96-493, 36p., 1 pl.

ESRI 2011, ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Harrill, J.R., 2007, Evaluation of boundary fluxes for the ground-water flow model being prepared as part of the SNPLMA-5 project: unpublished consultant report, December 2007, 17 p.

Hess, J.W., 1986, Summary of Deep Drilling Activities at NPC Reid Gardner Facility, Clark County, Nevada, October, 1985 – May, 1986, 26 p.

Hydrosystems, 2002, Tule Desert Field Activity and Data Report, Prepared for Lincoln County, Nevada and Vidler Water Company, April 26, 2002.

IT Corporation, 1996, Underground test area subproject, Phase I data analysis task – Volume IV, hydrologic parameter data documentation package: IT Corporation, Las Vegas, Nevada, Report ITLV/10972-181, 78 p.

IT Corporation, 1997, Underground test area subproject, Phase I data analysis task – Volume VI, groundwater flow model documentation package: IT Corporation, Las Vegas, Nevada, Report ITLV/10972-181, 222 p.

Johnson, C., Mifflin, M.D., Johnson, R.J., and Haitjema, H., 2001, Hydrogeologic and groundwater modeling analyses for the Moapa Paiute Energy Center – A Calpine Company project in cooperation with the Moapa Band of Paiute Indians, Moapa Indian Reservation, Clark County, Nevada: Prepared by Mifflin and Associates, Inc., Las Vegas, NV, February 2001, 78 p. and 6 appendices.

Johnson, M.E., 2005a, Drilling and Development of CSI Well No. 1 for Coyote Springs Investment, LLC, August 2005.

Johnson, M.E., 2005b, Drilling and Development of CSI Well No. 2 for Coyote Springs Investment, LLC, December 2005.

Johnson, M.E., 2007, Drilling and Development of CSI Well No. 3 for Coyote Springs Investment, LLC, January 2007.

Johnson, M.E., 2008, Drilling and Development of CSI Well No. 4 for Coyote Springs Investment, LLC, Coyote Spring Valley, Clark County, Nevada.

Kleinfelder, 2000, 1999 Hydrologic Impacts from Groundwater Withdrawals in the Upper Muddy River Valley, Nevada, February 2000, 22 p.

Las Vegas Valley Water District, 2001, Water resources and ground-water modeling in the White River and Meadow Valley flow systems, Clark, Lincoln, Nye and White Pine Counties, Nevada.

Lincoln County Water District (LCWD) and Vidler Water Company (VWC), 2005, A Status Report of Tule Desert Valley Water Monitoring Operations, Prepared for the Nevada State Engineer and the National Park Service, September 2005.

LCWD and VWC, 2007, A Status Report of Tule Desert Valley Water Monitoring Operations, Prepared for the Nevada State Engineer and the National Park Service, March 2007.

Maurer, D.K., Lopes, T.J., Medina, R.L., and J.L. Smith, 2004, Hydrogeology and hydrologic landscape regions of Nevada, U.S. Geological Survey, Scientific Investigations Report 2004-5131, 35 p.

Maxey, G.B., and Eakin, T.E., 1949, Ground water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada: Nevada State Engineer, Water Resources Bulletin 8, 59 p.

Mifflin, M.D., Johnson, C.L., and R.J. Johnson, 1989, Hydrogeologic Assessment, Upper Muddy River Valley, Nevada: Mifflin & Associates, 47 p.

Mifflin, M.D., and Zimmerman, D.E., 1984, Ground-water availability in the Lower Meadow Valley Wash near Glendale, Nevada: Desert Research Institute, Water Resources Center, 51 p.

Moapa Valley Water District, 1997, Muddy Springs Interim Monitoring Report, February 1997, 9 p.

Moapa Valley Water District, 1998, Muddy Springs Area Monitoring Report, April 1998, 10 p.

Moapa Valley Water District, 1999, Muddy Springs Area Monitoring Report, April 1999, 10 p.

Moapa Valley Water District, 2000, Muddy Springs Area Monitoring Report, May 2000, 10 p.

Nevada Division of Water Resources, 2011, Accessed multiple times during 2011, http://water.nv.gov/mapping/order1169/

National Information Water System, 2012, Accessed multiple times between 2001 and 2012, http://waterdata.usgs.gov/nwis

Page, W.R., Scheirer, D.S., Langenheim, V.E., and Berger, M.A., 2011, Revised Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona: U.S. Geological Survey Open-File Report 2006-1040, 1 sheet, 25 p. pamphlet.

Page, W.R., Dixon, G.L., Rowley, P.D., and Brickey, D.W., 2005, Geologic Map of Parts of the Colorado, White River, and Death Valley Groundwater Flow Systems, Nevada, Utah, and Arizona: Nevada Bureau of Mines and Geology Map 150, Plate plus text.

Pohlmann, K.F., Morris, T.M., and Patterson, P.A., 1988, Nevada Power Company Reid-Gardner Groundwater Level Monitoring Program 1987 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 15 p.

Pohlmann, K.F., Wert, B.L., 1989, Nevada Power Company Reid-Gardner Groundwater Level Monitoring Program 1988 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 11 p.

Pohlmann, K.F., Wert, B.L., 1990, Nevada Power Company Reid Gardner Groundwater Level Monitoring Program 1989 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 26 p.

Pohlmann, K.F., Wert, B.L., 1991, Moapa Valley Ground-water Level Monitoring Program 1990 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 56 p.

Pohlmann, K.F., Wert, B.L., 1992, Moapa Valley Ground-water Level Monitoring Program 1991 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 72 p.

Pohlmann, K.F., Wert, B.L., 1993, Moapa Valley Ground-water Level Monitoring Program 1992 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 72 p.

Pohlmann, K.F., 1994, Moapa Valley Ground-water Level Monitoring Program 1993 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 38 p.

Pohlmann, K.F., 1995, Moapa Valley Ground-water Level Monitoring Program 1994 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 42 p.

Pohlmann, K.F., 1996, Moapa Valley Ground-water Level Monitoring Program 1995 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 48 p.

Pohlmann, K.F., Russell, C.E., 1997, Moapa Valley Ground-water Level Monitoring Program 1996 Annual Report: Desert Research Institute, Water Resources Center, Prepared for the Nevada Power Company, 55 p.

Rush, E.F., 1964, Ground-water appraisal of the Meadow Valley area, Lincoln and Clark Counties, Nevada: Nevada Department of Conservation and Natural Resources, Ground-water resources - Reconnaissance Report 27, 43 p.

SAHRA, 2008, Wells Database, Accessed multiple times between 2007-2008, http://www.sahra.arizona.edu/wells/

Southern Nevada Water Authority and Las Vegas Valley Water District, 2003, Survey of Wells and Stream Gages in the Black Mountains Area, California Wash Basin, Coyote Spring Valley, Garnet valley, Hidden Valley, and Muddy River Springs Area, March 2005, 13 p.

Southern Nevada Water Authority and Las Vegas Valley Water District, 2005, Addendum #1 to Survey of Wells and Stream Gages in the Black Mountains Area, California Wash Basin, Coyote Spring Valley, Garnet valley, Hidden Valley, and Muddy River Springs Area, March 2005, 9 p.

Southern Nevada Water Authority, 2012, Portal, Accessed multiple times between 2003 and 2012, http://www.snwawatershed.org/portal.

SRK Consulting, 2001, Installation Report, Harvey Well Replacement, RW-1, Prepared for Nevada Power Company, September 2008.

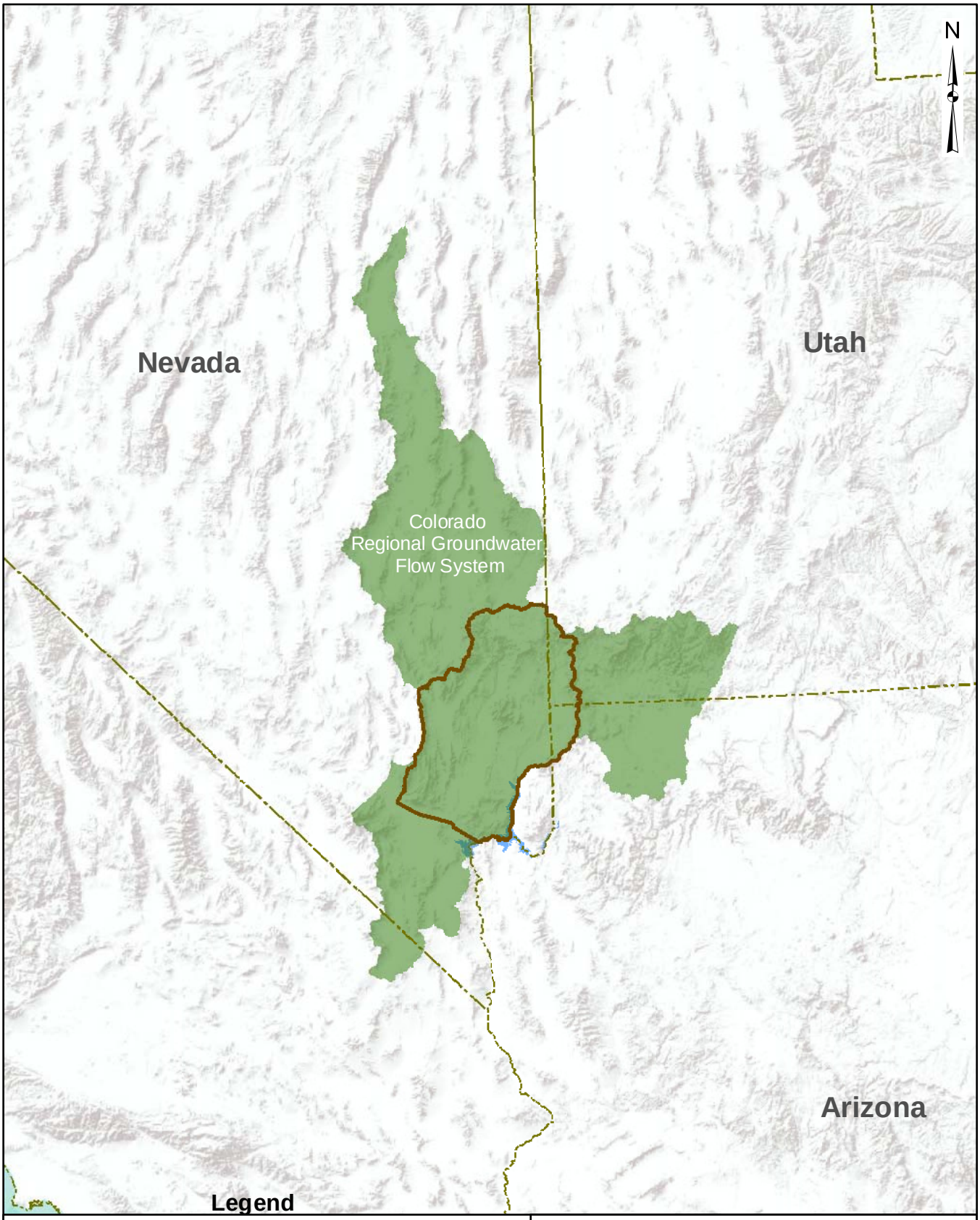
Twichell, D.C., Cross, V.A., and S.D. Belew, Mapping the floor of Lake Mead (Nevada and Arizona): Preliminary discussion and GIS data release, U.S. Geologic Survey, Open-File Report 03-320, http://pubs.usgs.gov/of/2003/of03-320/index.htm.

URS, 2001, Report of Groundwater Assessment – Lower Meadow Valley Wash, Meadow Valley Generating Project, Clark and Lincoln Counties, Nevada, Prepared for PG&E National Energy Group, November 1, 2001.

URS, 2006, Final Well Completion Report, Kane Springs Valley, Lincoln County, Nevada, Prepared for Lincoln County Water District and Vidler Water Company, March 2006.

Virgin Valley Water District (VVWD) and Entrix, 2006, Hydrological Monitoring and Mitigation Plan, Virgin River Basin, Nevada, Prepared for the City of Mesquite, September 2006, 36 p.

FIGURES

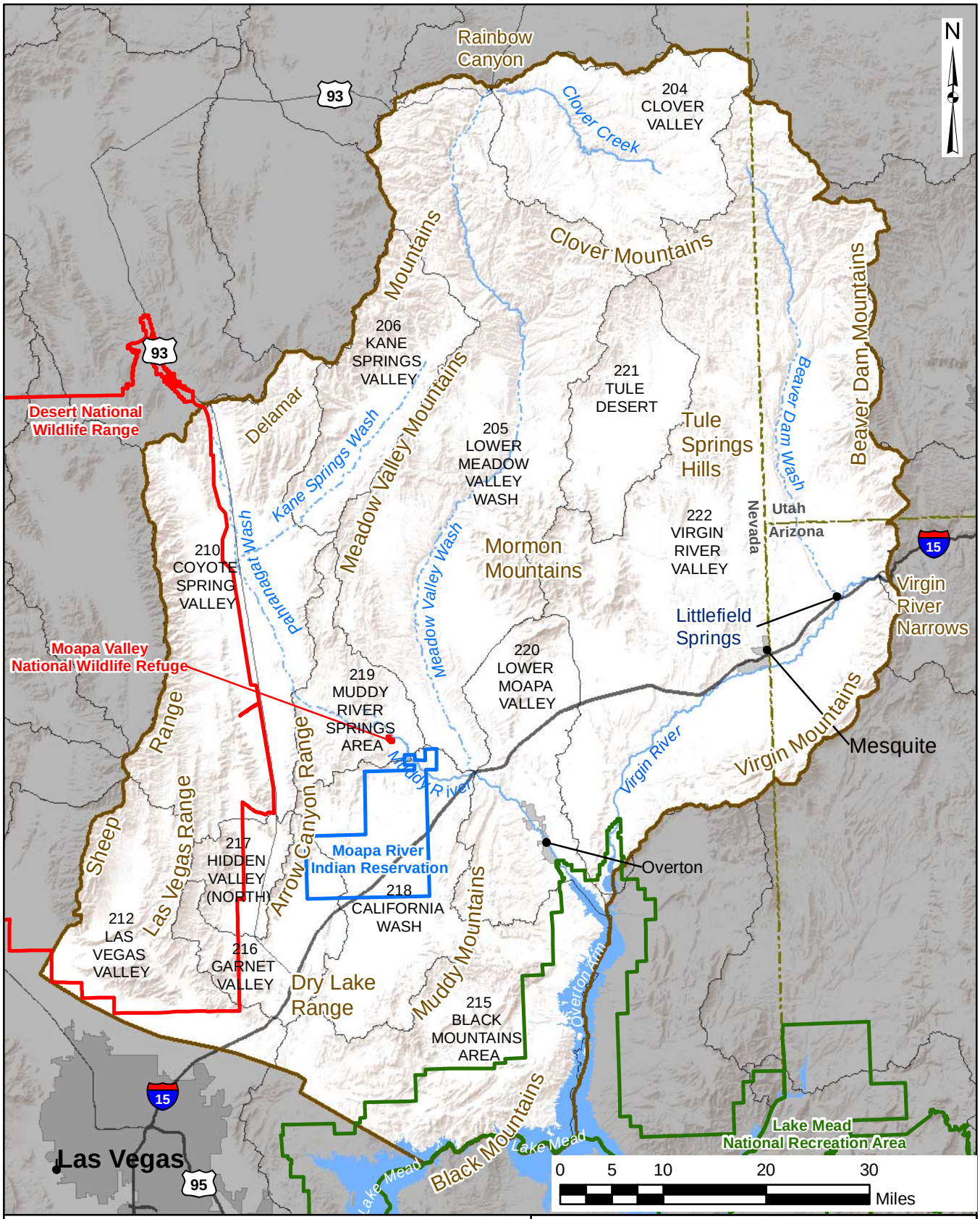


TITLE: **Location of Study Area**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada, Utah, and Arizona**

TETRA TECH

FIGURE **1.1-1**



Legend

219 Active Model Domain

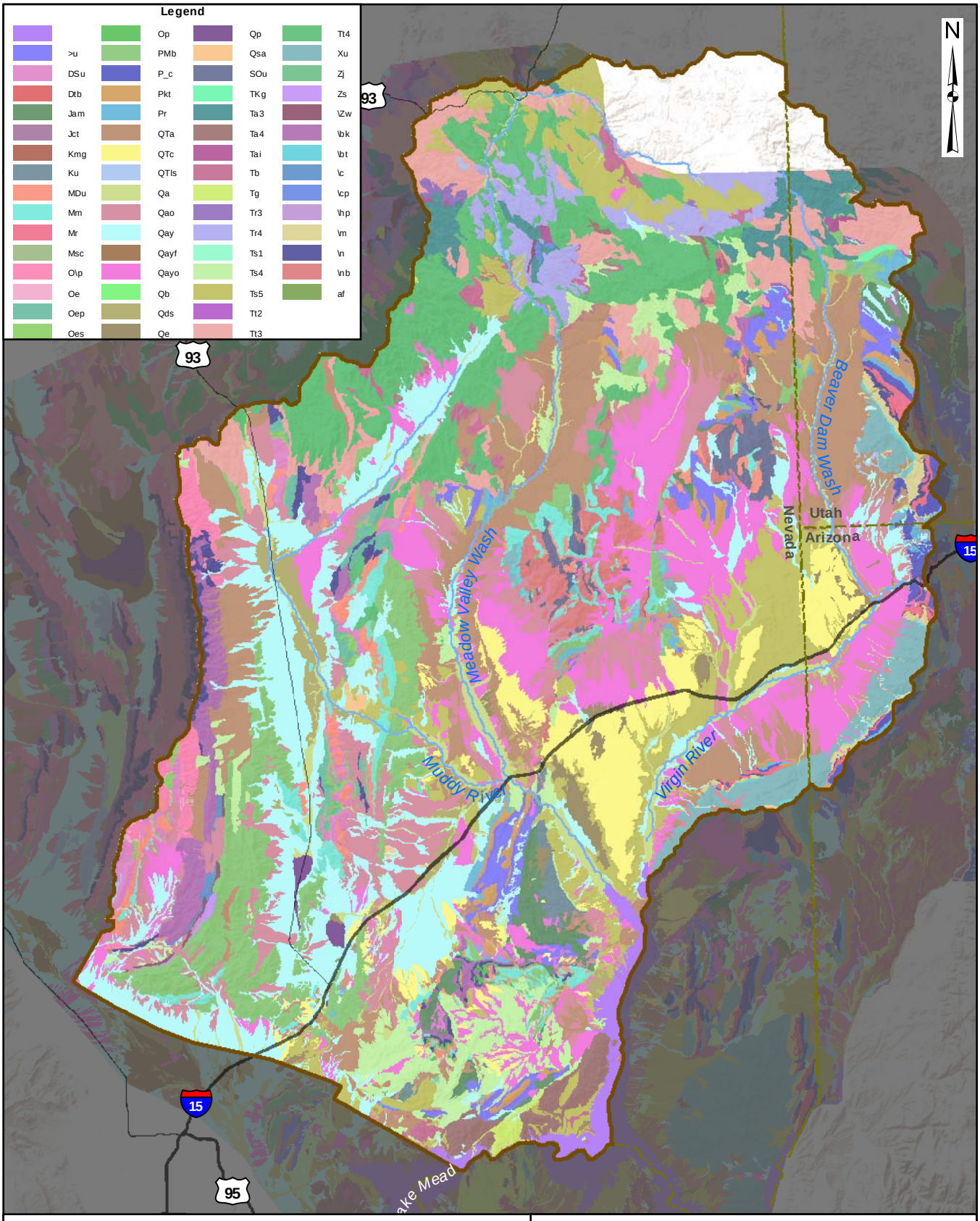
Hydrographic Area

TITLE: **Physiographic Features of Study Area**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **1.1-2**



0 5 10 20 30 Miles

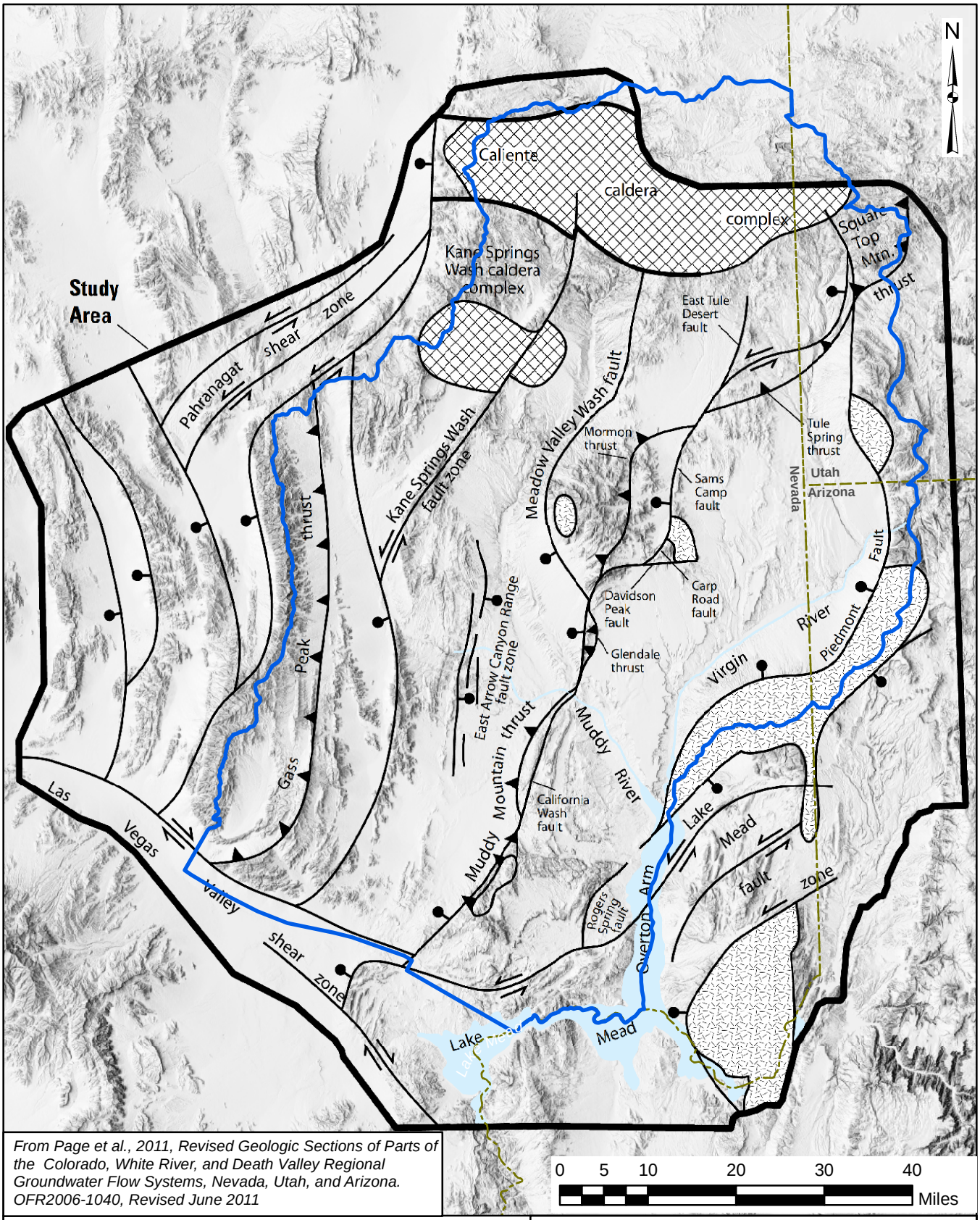
From Page et al., 2011, Revised Geologic Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona. OFR2006-1040, Revised June 2011

TITLE: **Geologic Map**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.1-1**



From Page et al., 2011, Revised Geologic Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona. OFR2006-1040, Revised June 2011

Legend

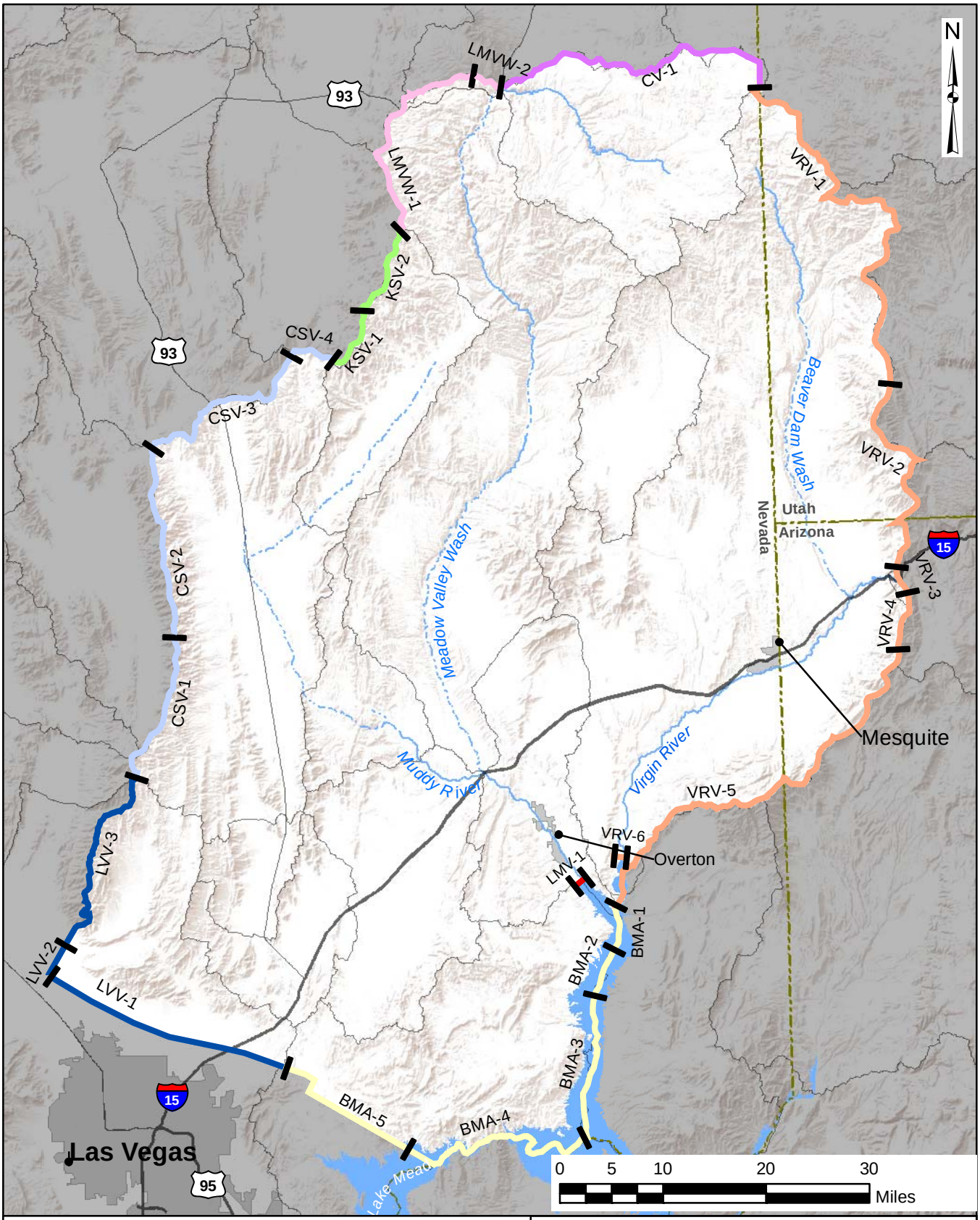
- Active Model Domain
- Tertiary caldera complex
- Early Proterozoic crystalline rocks
- Thrust fault
- Normal fault
- Strike-slip fault

TITLE: **Major Faults**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.1-2**



Legend

Hydrographic Area

CV-1 Boundary Segment

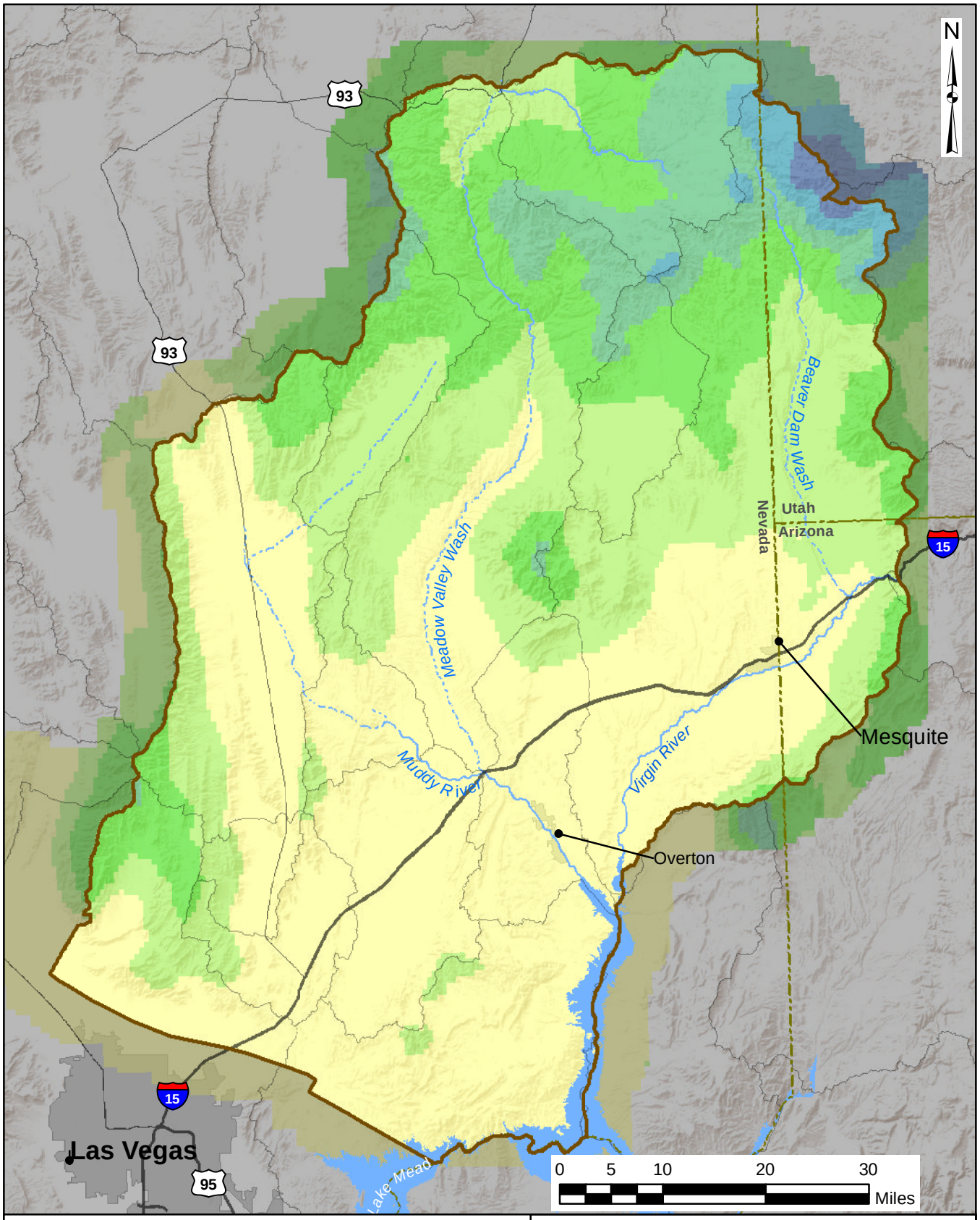
Source: Harrill, 2007

TITLE: **Location of Harrill's Boundary Segments**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.3-1**



Legend

- Active Model Domain
- Hydrographic Region
- 10 - 20 cm
- 21 - 30 cm
- 31 - 40 cm
- 41 - 50 cm
- 51 - 60 cm
- 61 - 70 cm
- 71 - 80 cm

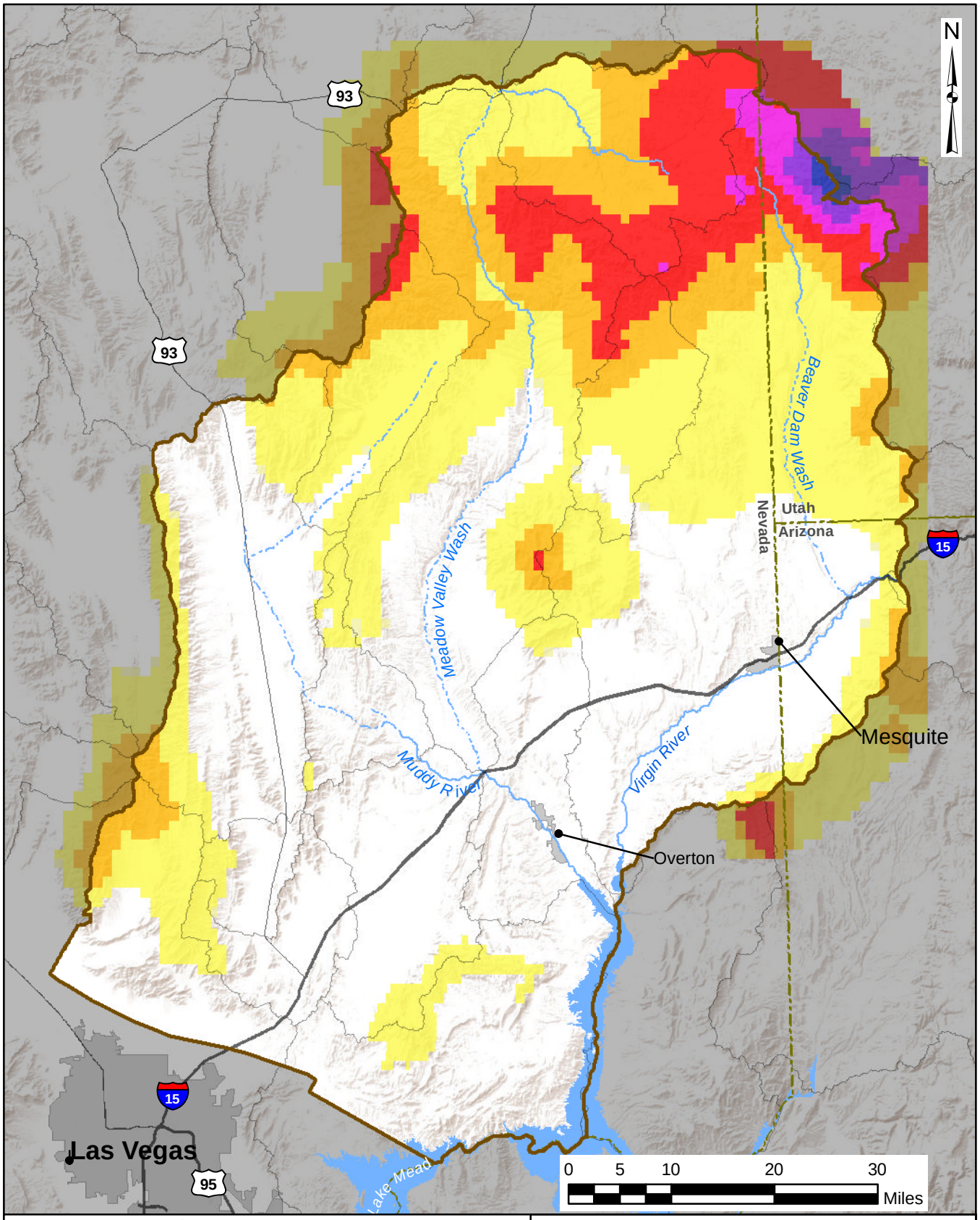
Source: PRISM 2006

TITLE: **Estimated Annual Precipitation**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.4-1**



Legend

- Active Model Domain
- Hydrographic Region

Recharge (in/yr)

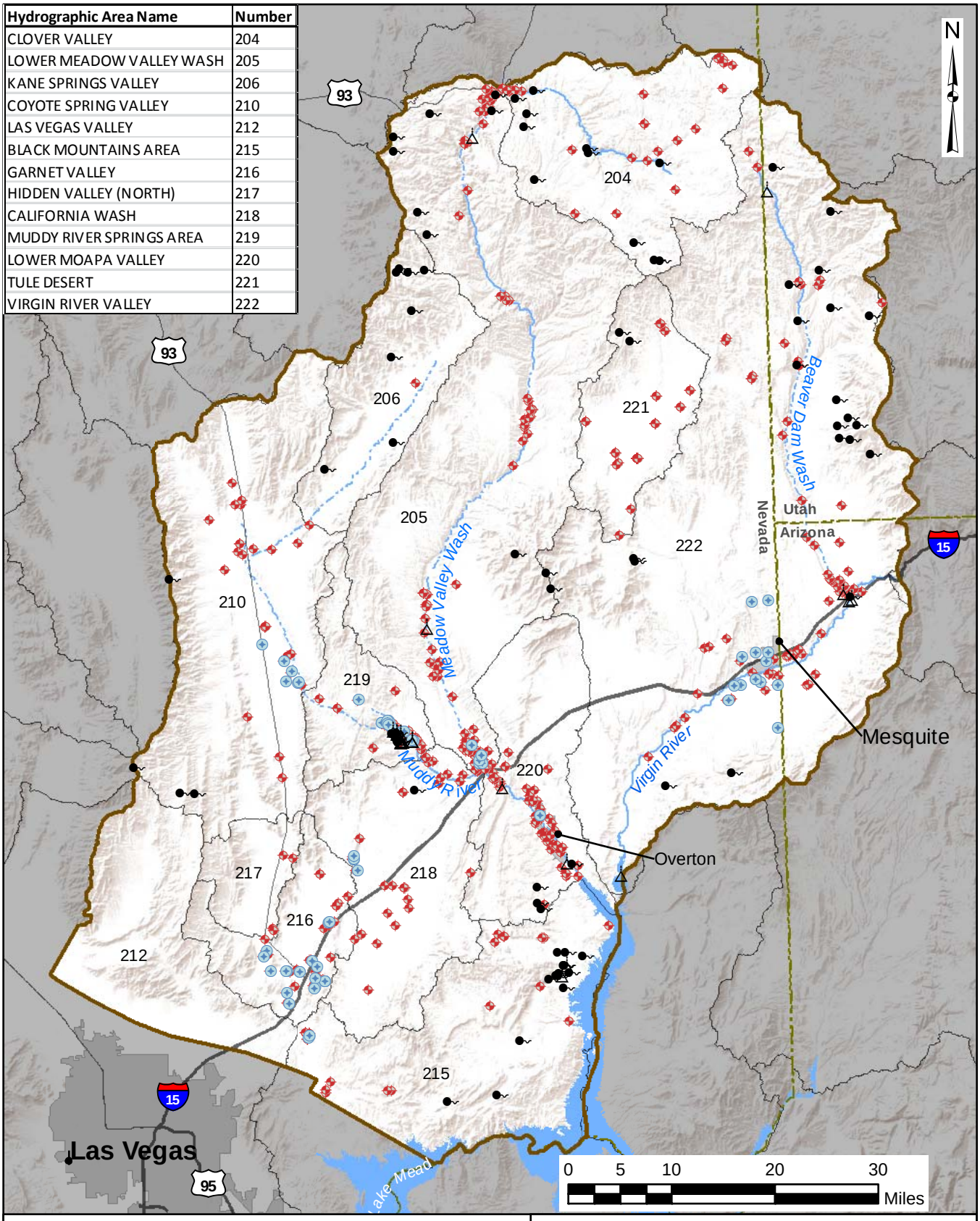
- 0.1 - 1.0
- 1.1 - 2.0
- 2.1 - 4.0
- 4.1 - 6.0
- 6.1 - 8.0
- 8.0 - 10.0

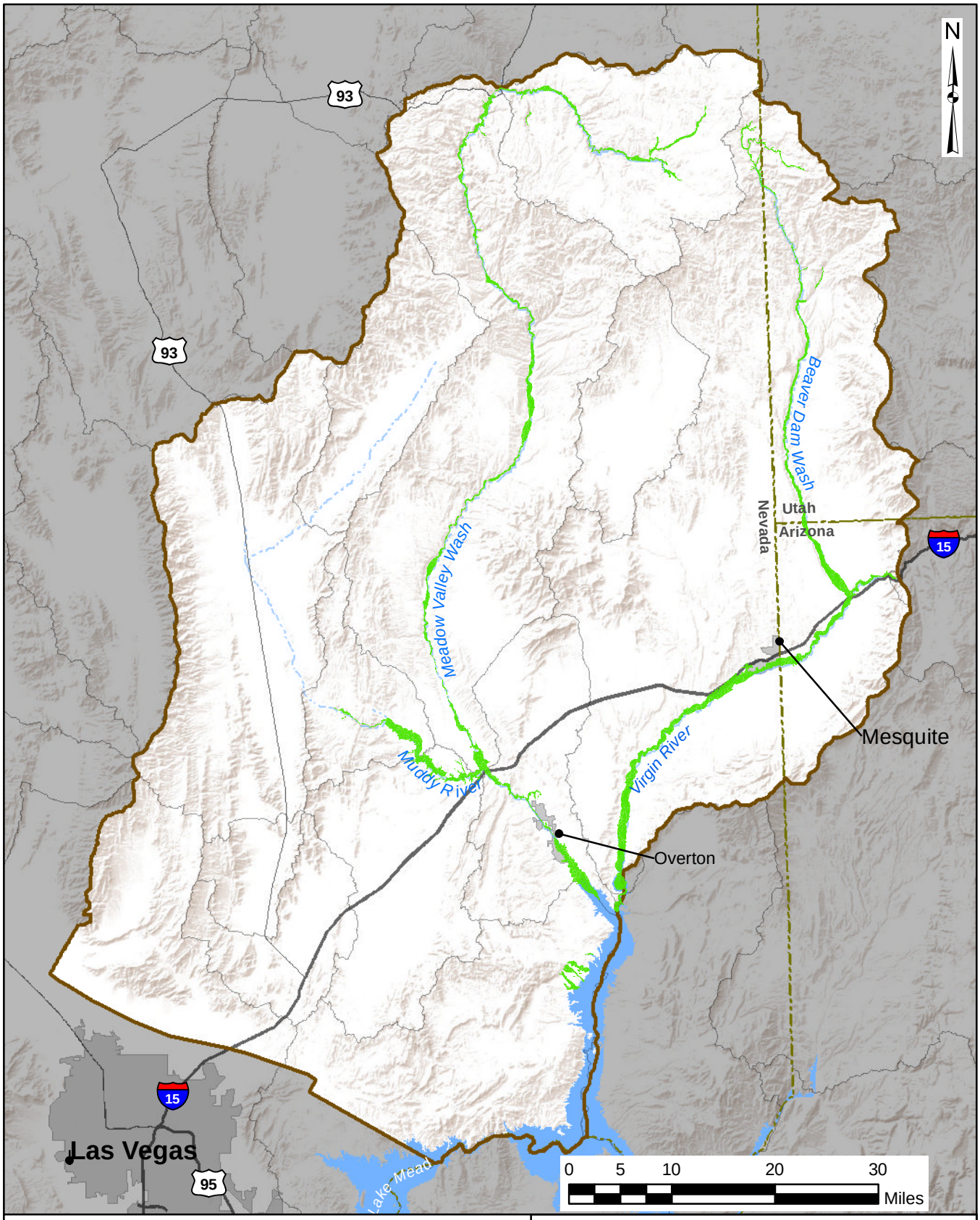
TITLE: **Estimated Annual Recharge Rate**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.4-2**


Hydrographic Area Name | Number
CLOVER VALLEY | 204
LOWER MEADOW VALLEY WASH | 205
KANE SPRINGS VALLEY | 206
COYOTE SPRING VALLEY | 210
LAS VEGAS VALLEY | 212
BLACK MOUNTAINS AREA | 215
GARNET VALLEY | 216
HIDDEN VALLEY (NORTH) | 217
CALIFORNIA WASH | 218
MUDDY RIVER SPRINGS AREA | 219
LOWER MOAPA VALLEY | 220
TULE DESERT | 221
VIRGIN RIVER VALLEY | 222
N
93
93
204
206
221
205
222
210
219
220
217
218
216
212
215
Beaver Dam Wash
Meadow Valley Wash
Muddy River
Virgin River
Nevada
Utah
Arizona
15
15
Mesquite
Overton
Las Vegas
95
Lake Mead
0 5 10 20 30
Miles
Legend
Spring
Water Level Observation Well
Gauging Station
Active Model Domain
Production Well
219
Hydrographic Area
TITLE:
Locations of Wells, Springs, Stream Reaches, and Gauging Stations
LOCATION:
Colorado Regional Groundwater Flow System Southeastern Nevada
TETRA TECH
FIGURE
3.5-1



Legend

- Evapotranspiration Area
- Active Model Domain
- Hydrographic Region

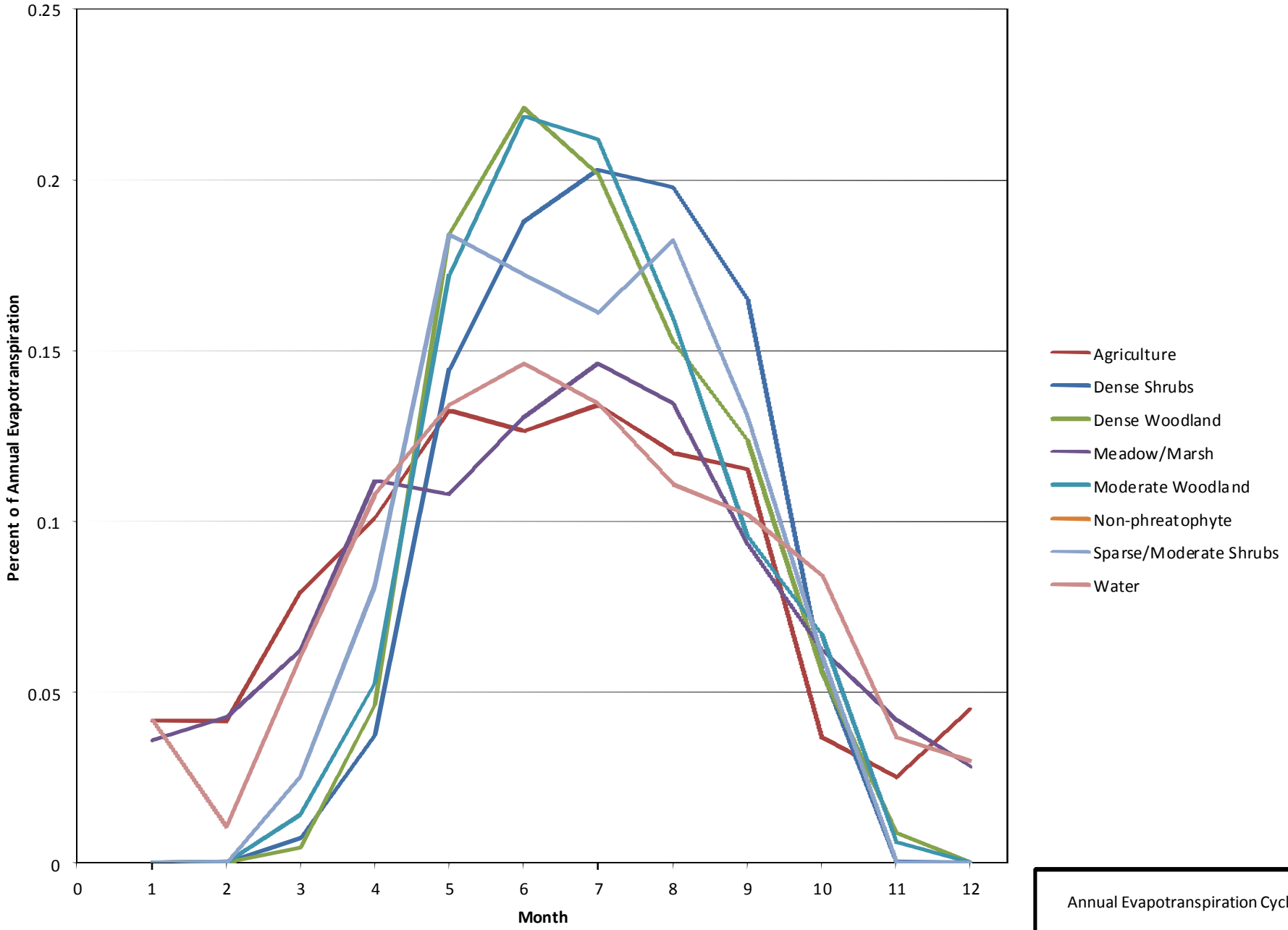
Source: DeMeo et al., 2008

TITLE: **Designated Areas of Evapotranspiration**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.5-2**



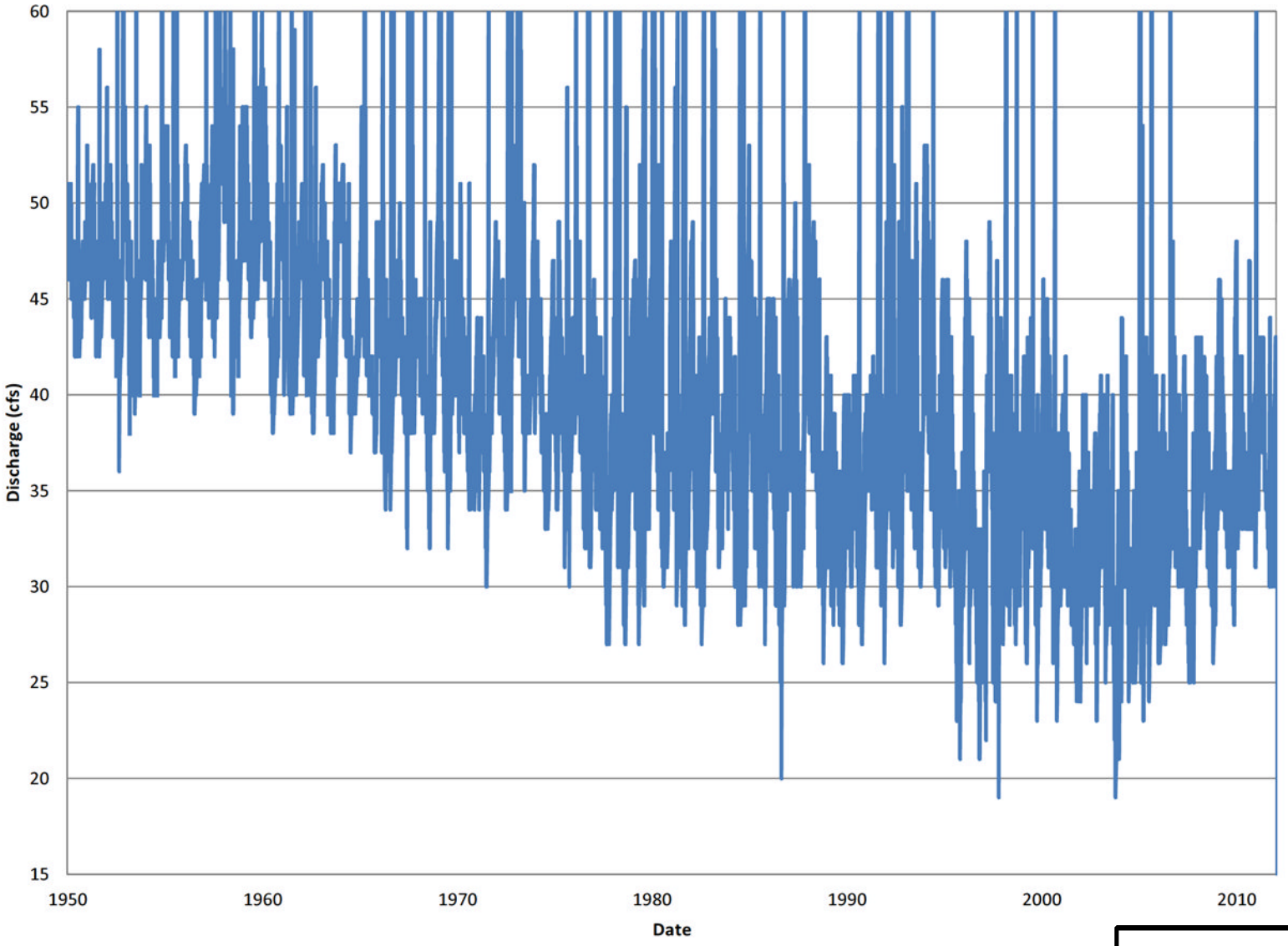
Source: DeMeo et al., 2008; Bureau of Reclamation, 2004

Annual Evapotranspiration Cycle

Lower Colorado River Flow System

TETRA TECH GEO

Figure 3.5-3



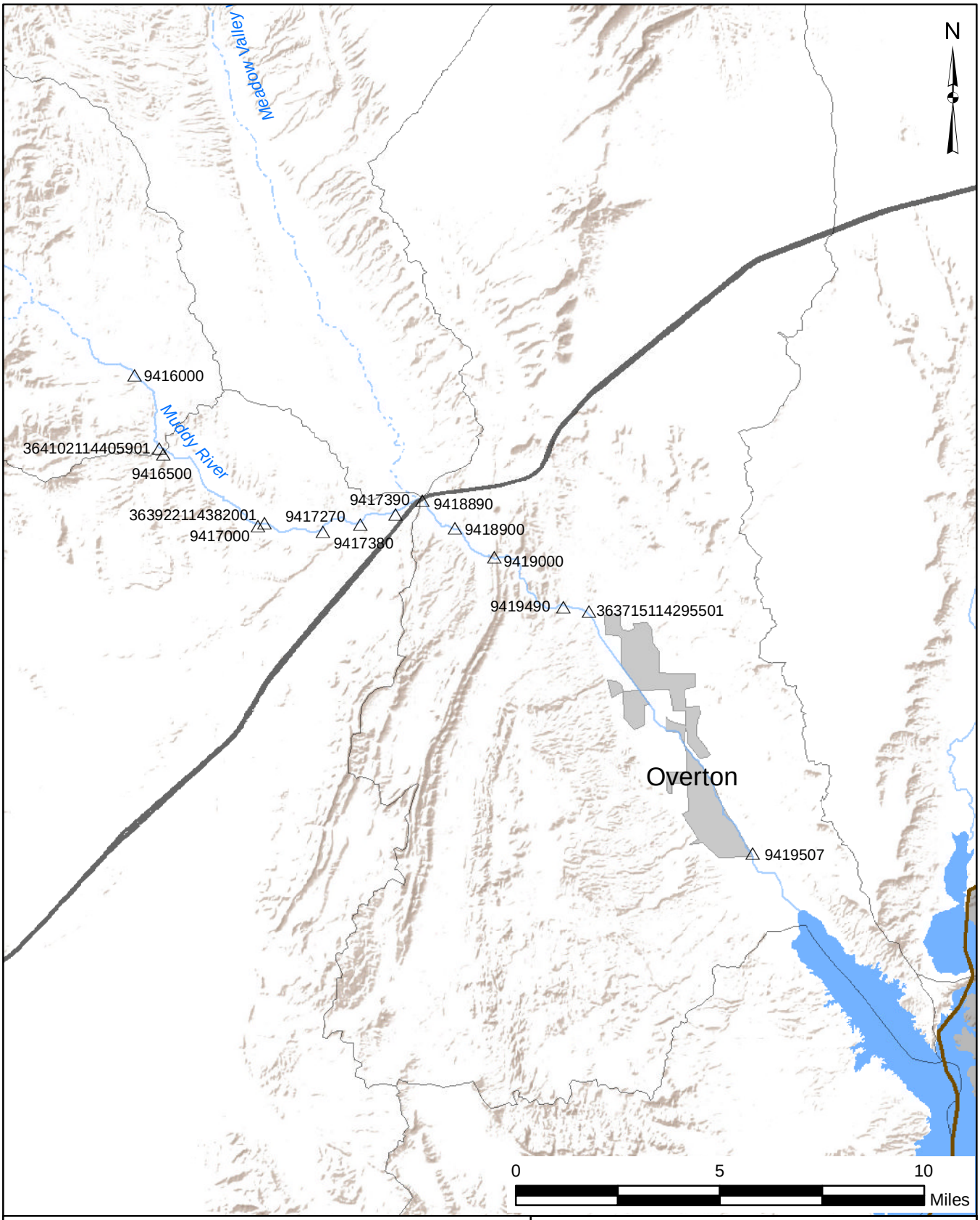
Discharge at Muddy River near Moapa

Lower Colorado River Flow System

TETRA TECH GEO

Figure 3.5-4

Note: Magnitude of storm peaks are not shown.



Legend

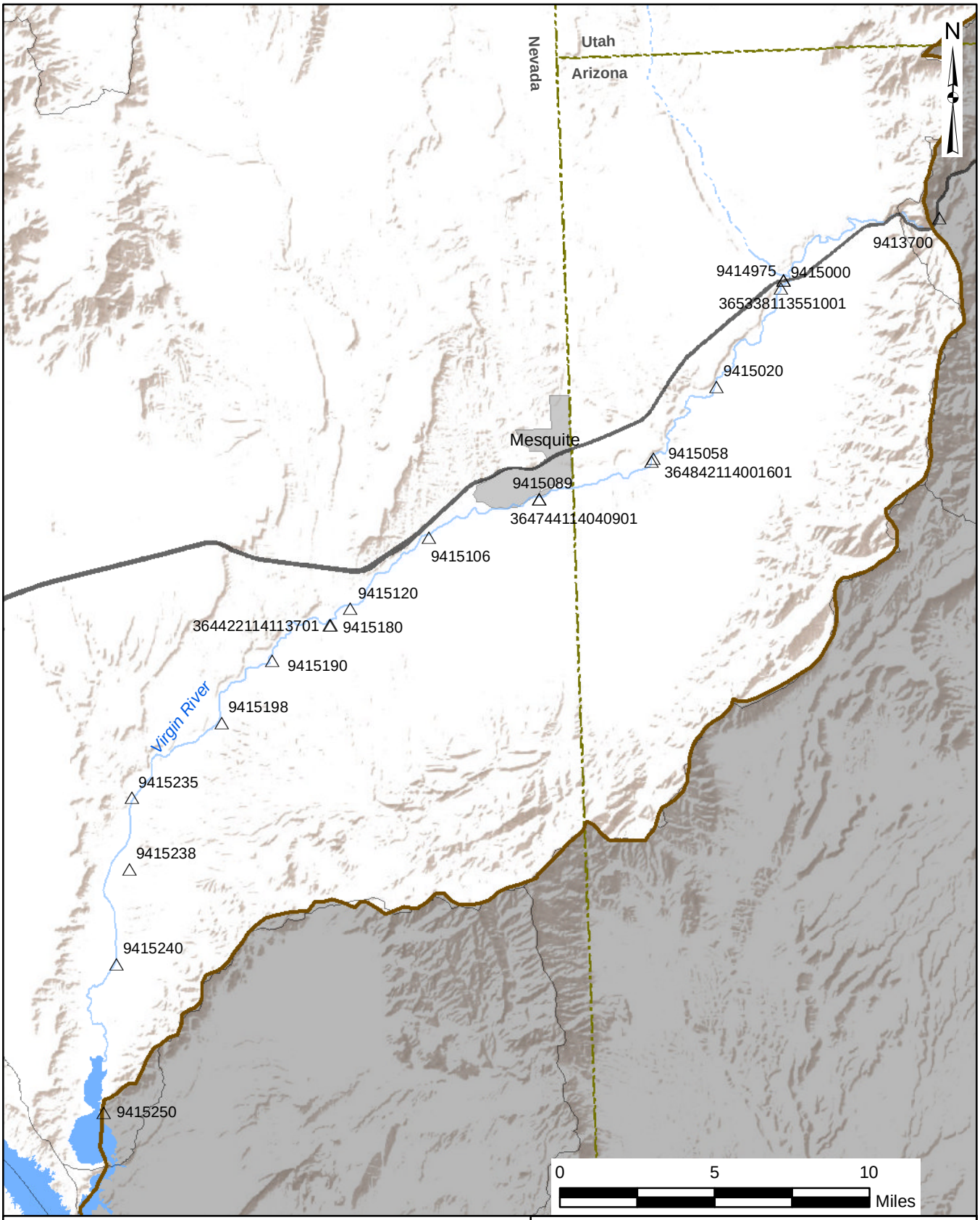
- △ Discharge Measurement Site
- Active Model Domain
- Hydrographic Area

TITLE: **Streamflow-Measurement Locations, Muddy River Synoptic Study**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.5-5**



Legend

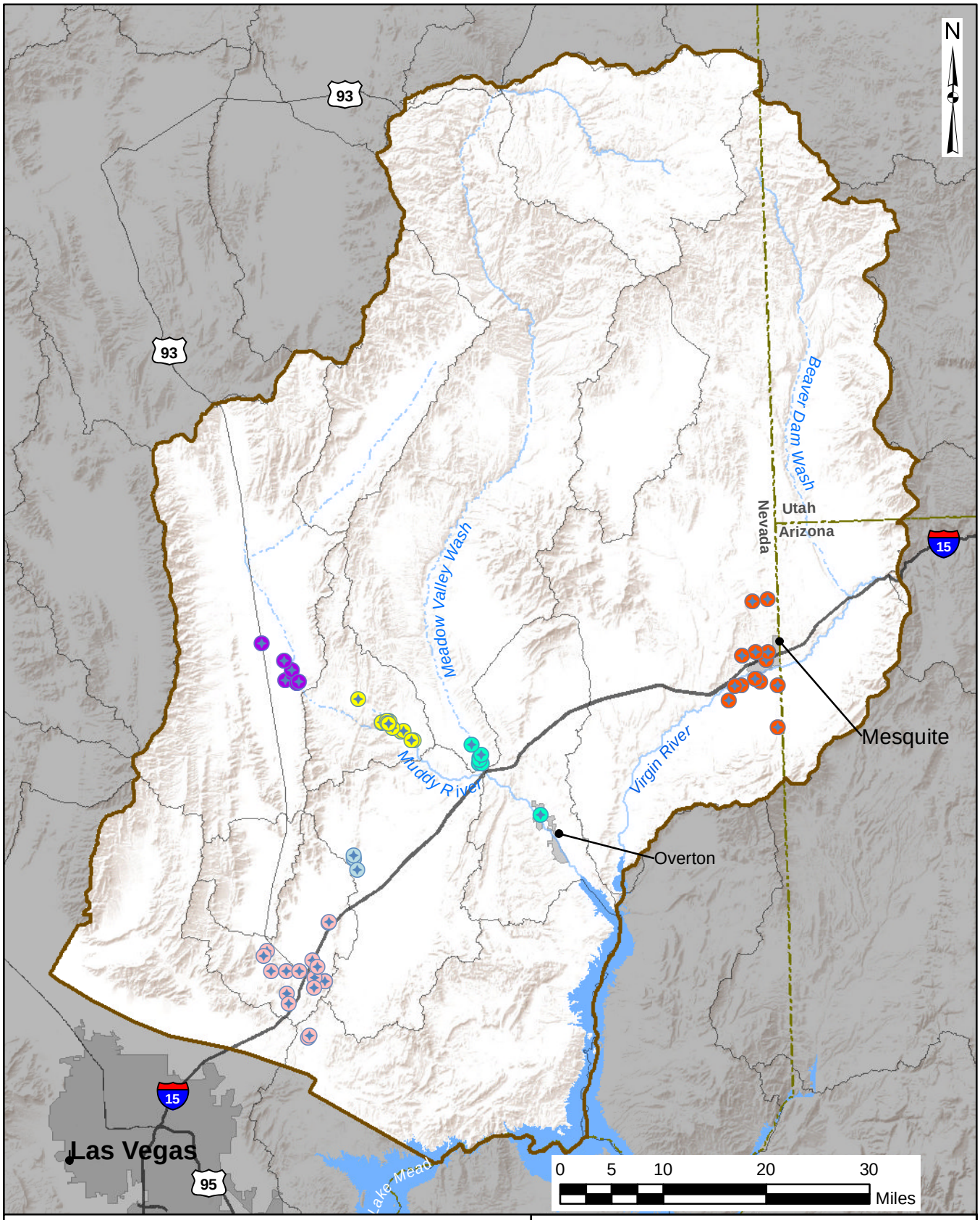
- △ Discharge Measurement Site
- Active Model Domain
- Hydrographic Area

TITLE: **Streamflow-Measurement Locations, Virgin River Synoptic Study**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.5-6**



Legend

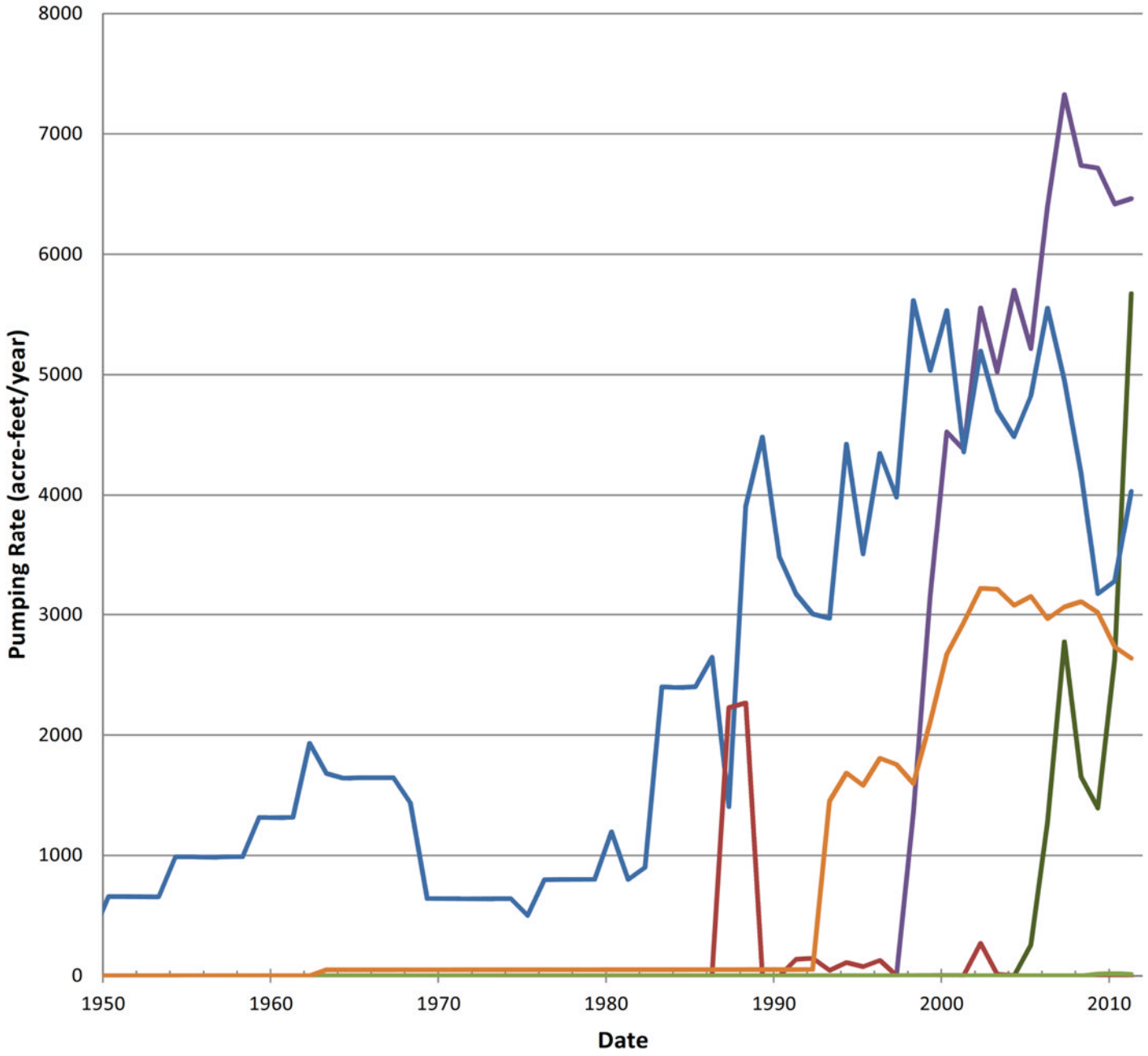
- Hydrographic Area
- Active Model Domain
- California Wash Wells
- Coyote Spring Valley Wells
- Garnet Valley Wells
- Lower Meadow Valley Wash Wells
- Muddy River Springs Area Wells
- Virgin Valley Wells

TITLE: **Locations of Production Well Groups Used in Figure 3.5-3**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.6-1**

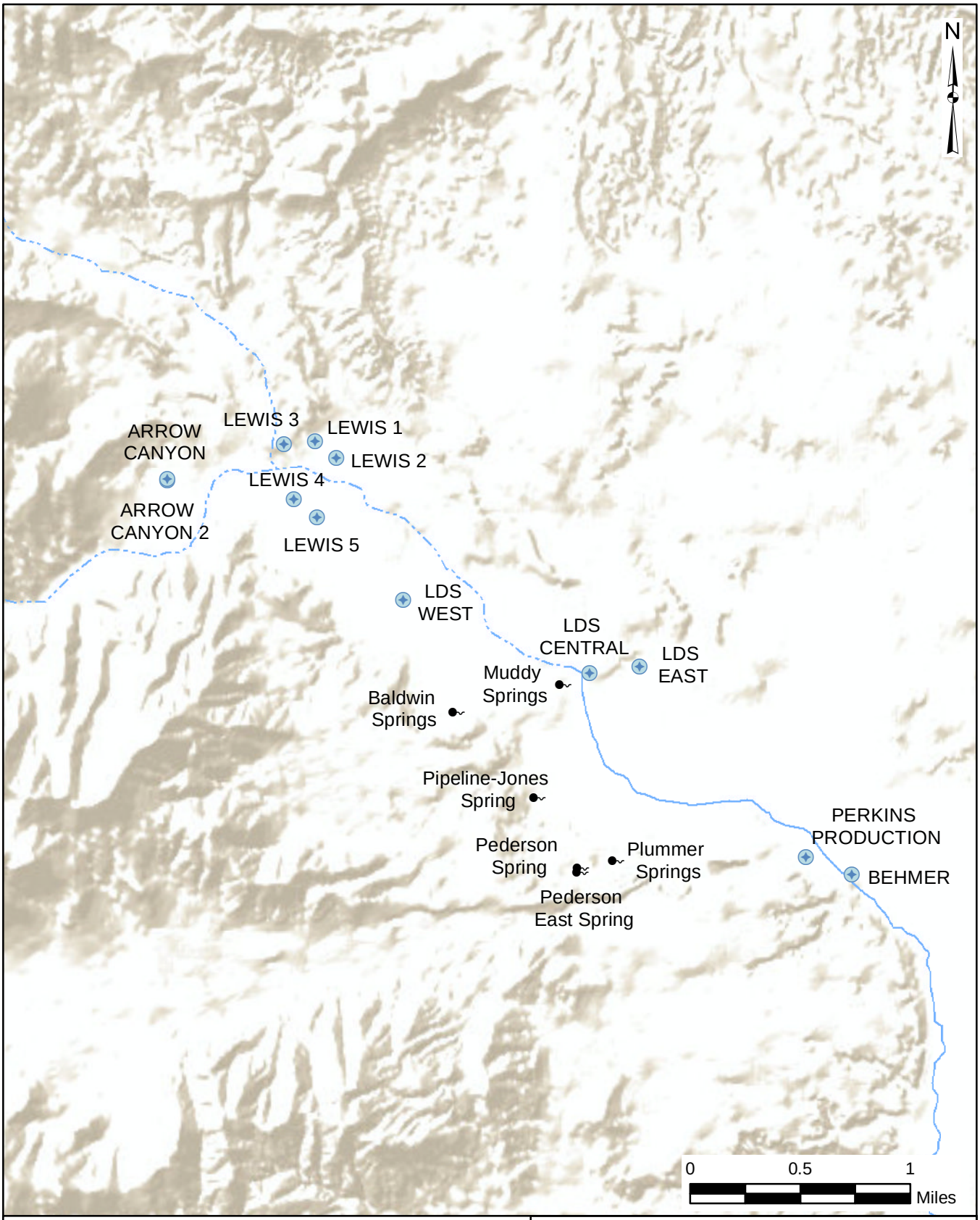


Annual Groundwater Pumping in Different Areas

Lower Colorado River Flow System

TETRA TECH GEO

Figure 3.6-2



Legend

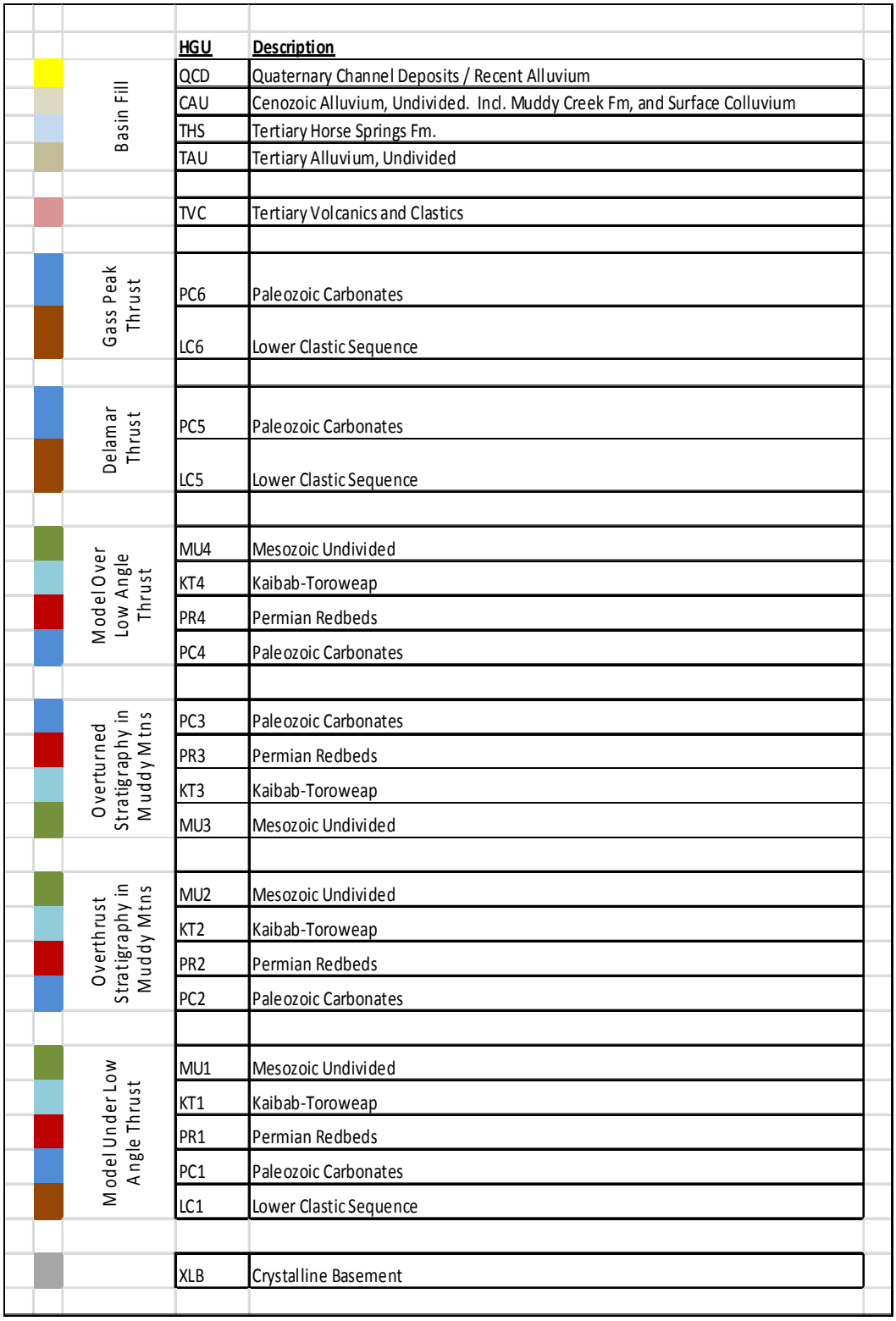
- Springs
- Production Wells
- Active Model Domain

TITLE: **Location of Production Wells and Springs in Muddy River Springs Area**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **3.6-3**

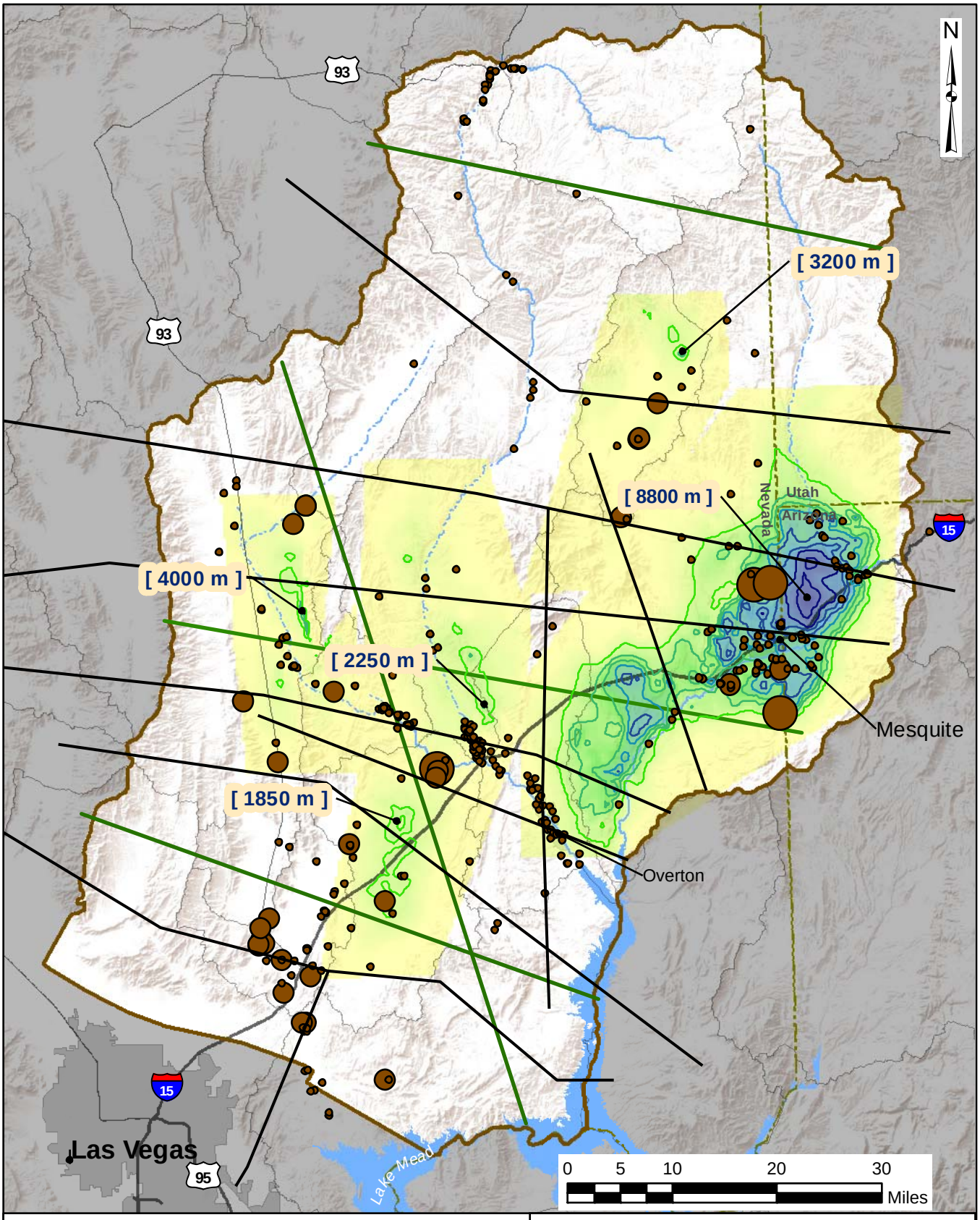


Stacking of
Hydrostratigraphic Units

Lower Colorado River Flow System

TETRA TECH GEO

Figure
4.1-1



Legend

- Sections Derived from Geologic Model
- USGS Section Lines
- Active Model Domain
- State Boundary

Borehole Depth

- 0 - 1333
- 1334 - 2667
- 2668 - 4000

Sediment Thickness (m)

High : 8830

Low : 0

TITLE:

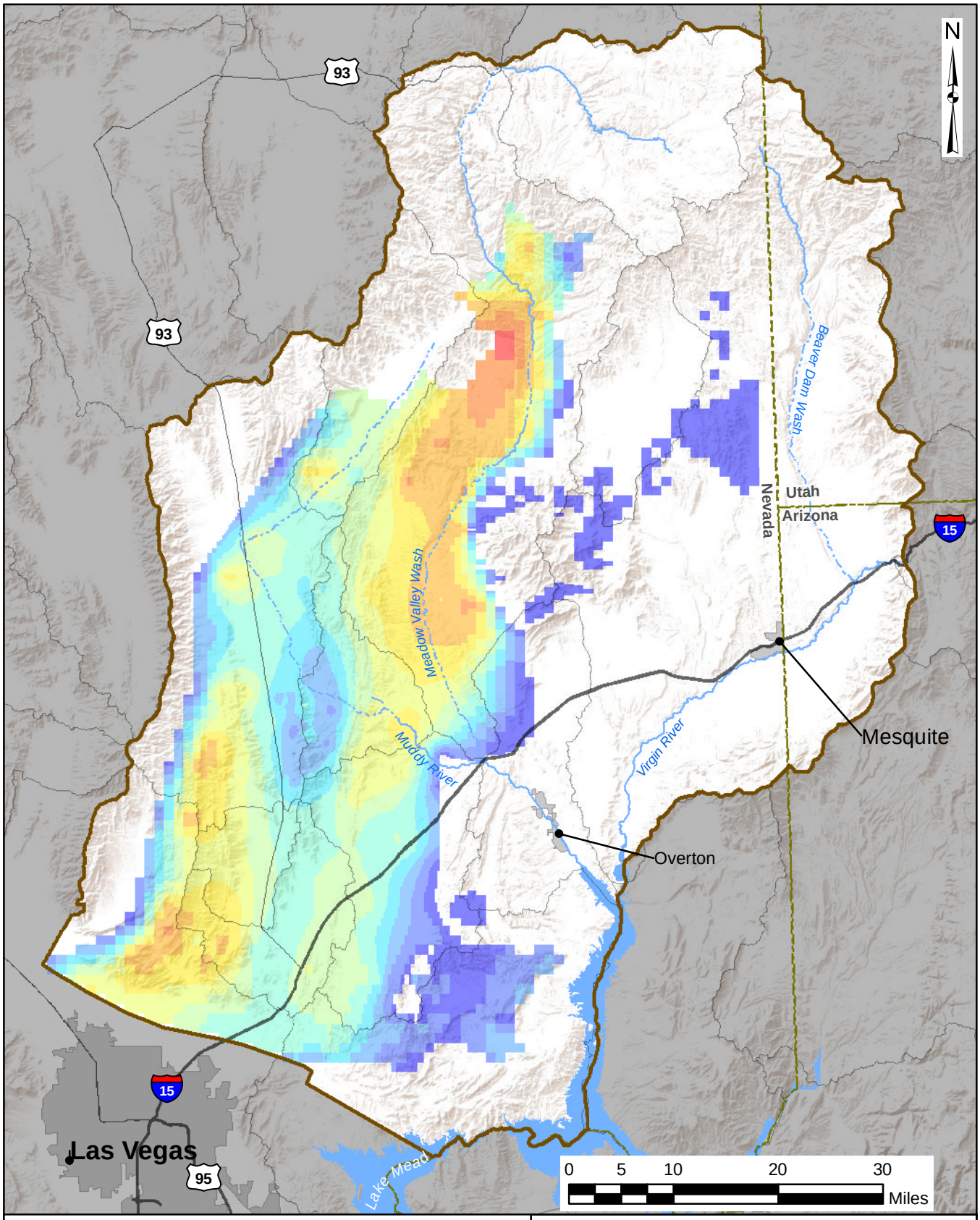
Locations of Geologic Sections, Drill-Hole Control, and Gravity Interpretation

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE

4.1-2



Legend

- Active Model Domain
- Hydrographic Region

Approximate Unit Thickness

- 22000 ft
- 12000 ft
- 6000 ft
- 2000 ft

TITLE: **Kriging-Interpolated Thickness, PC4**

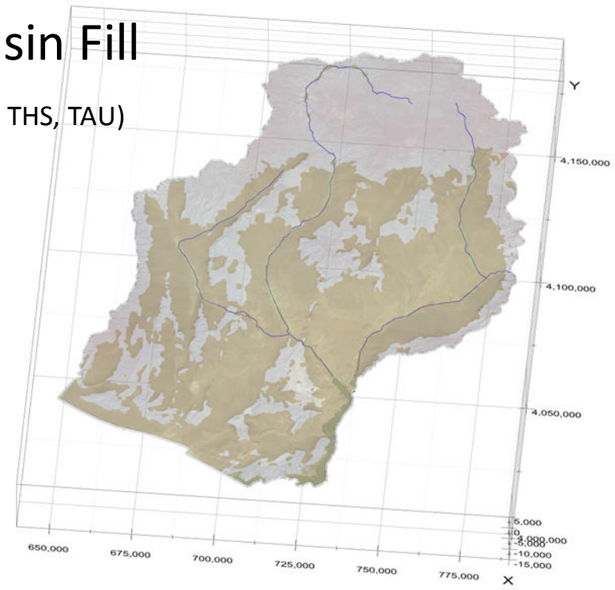
LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

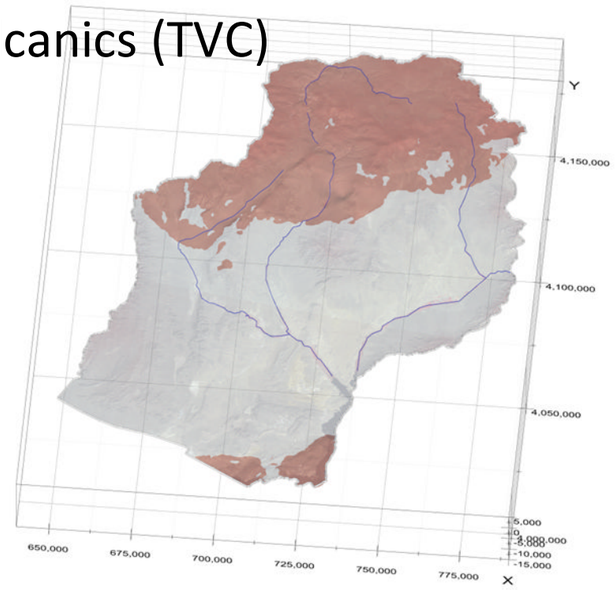
FIGURE **4.1-3**

Cenozoic Basin Fill

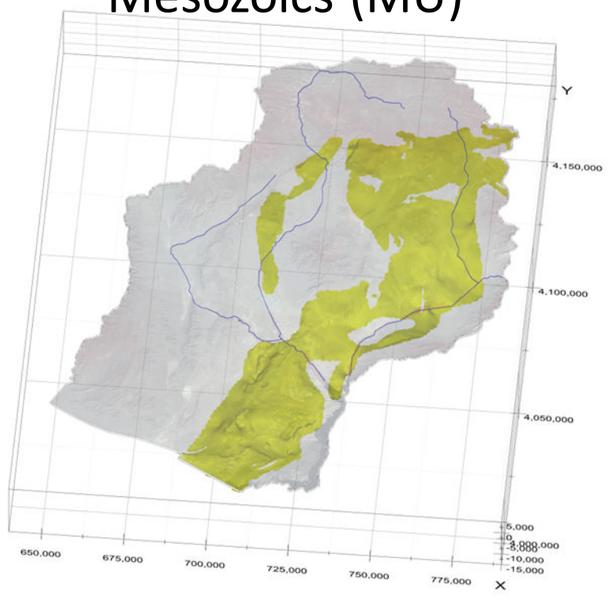
(includes QCD, CAU, THS, TAU)



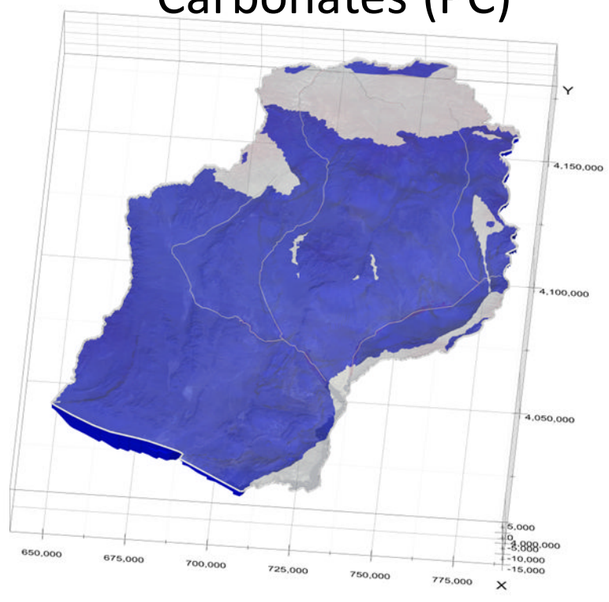
Tertiary Volcanics (TVC)



Mesozoics (MU)



Carbonates (PC)

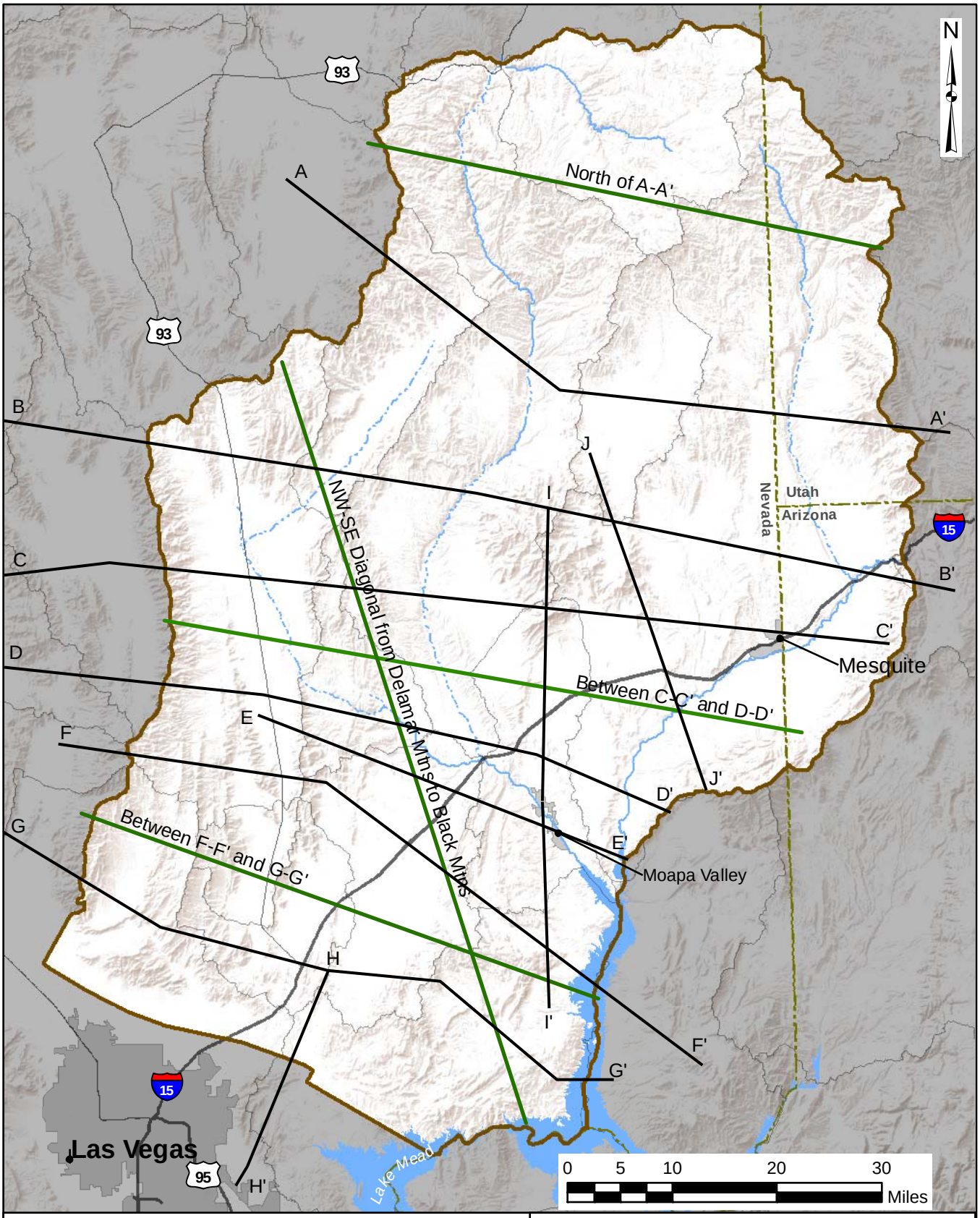


Estimated Unit Extents by Major Lithology

Lower Colorado River Flow System

TETRA TECH GEO

Figure 4.2-1



Legend

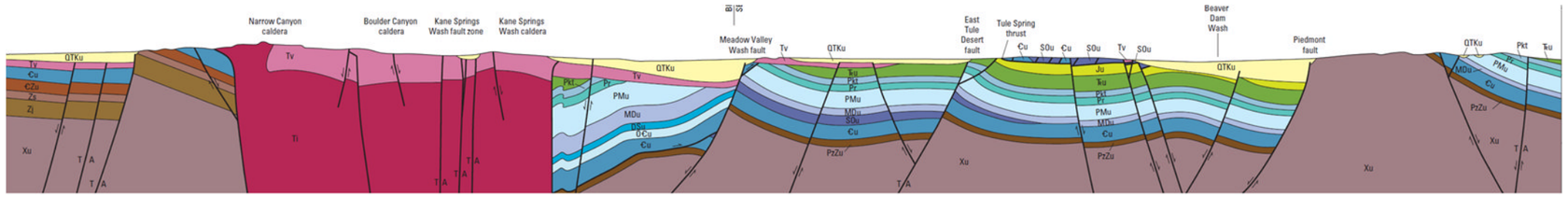
- Active Model Domain
- State Boundary
- Sections Derived from Geologic Model
- USGS Section Lines

TITLE: **Locations of Geologic Sections**

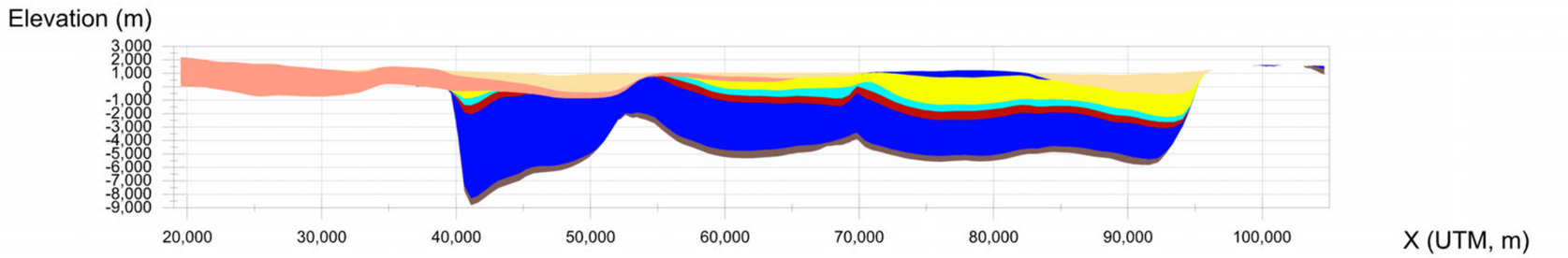
LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

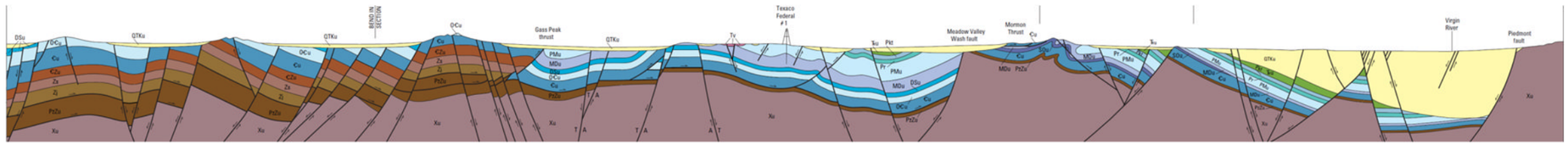
TETRA TECH

FIGURE **4.2-2**

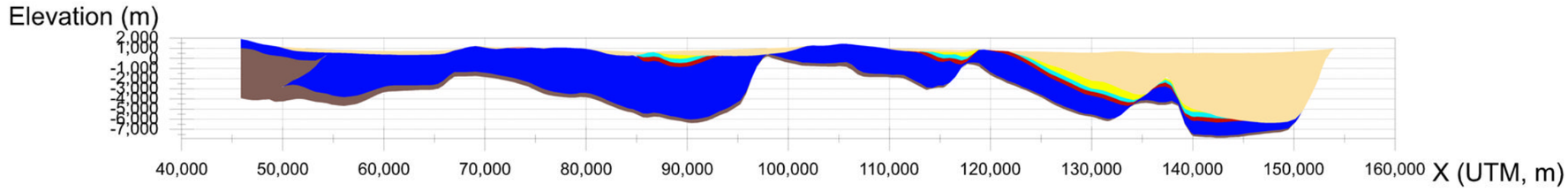


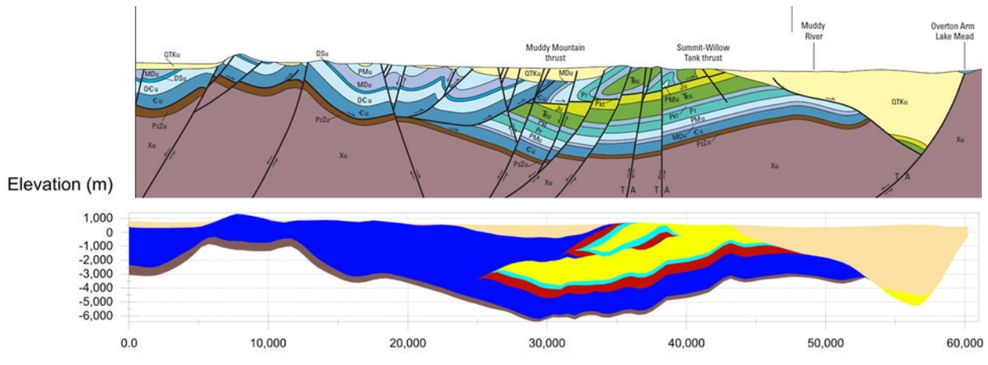
A – A’





C - C’





E - E’

XLB shown in white

Drafted sections from Page et al., 2011, Revised Geologic Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona. OFR2006-1040, Revised June 2011

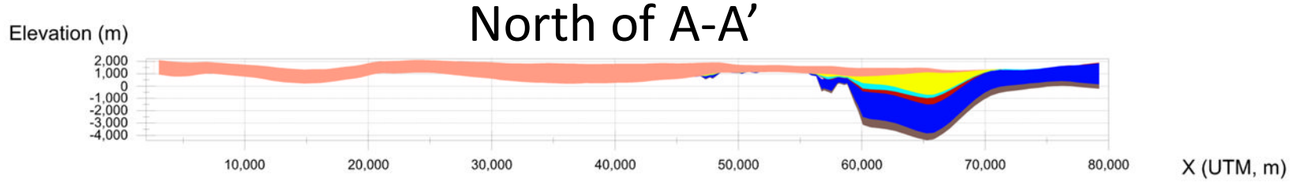
Comparison of Selected USGS and Geologic Model Sections

Lower Colorado River Flow System

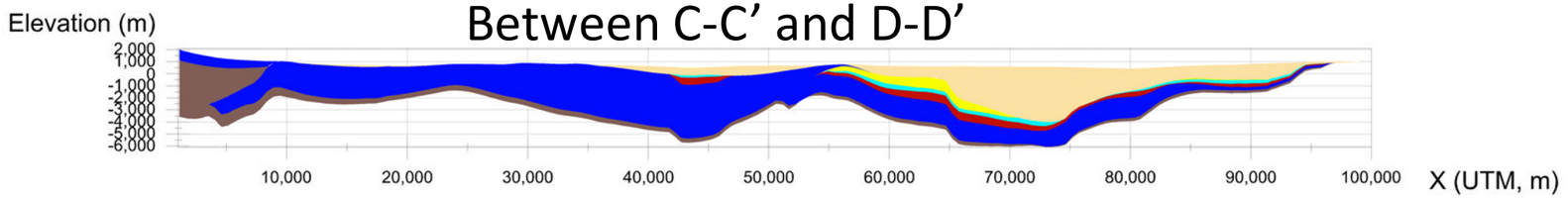
TETRA TECH GEO

Figure 4.2-3

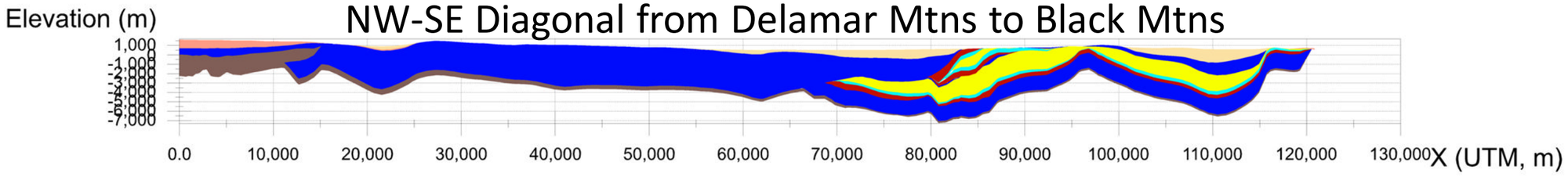
North of A-A’



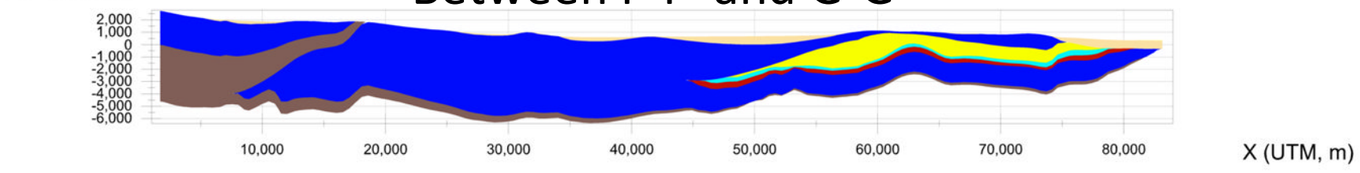
Between C-C’ and D-D’



NW-SE Diagonal from Delamar Mtns to Black Mtns



Between F-F’ and G-G’



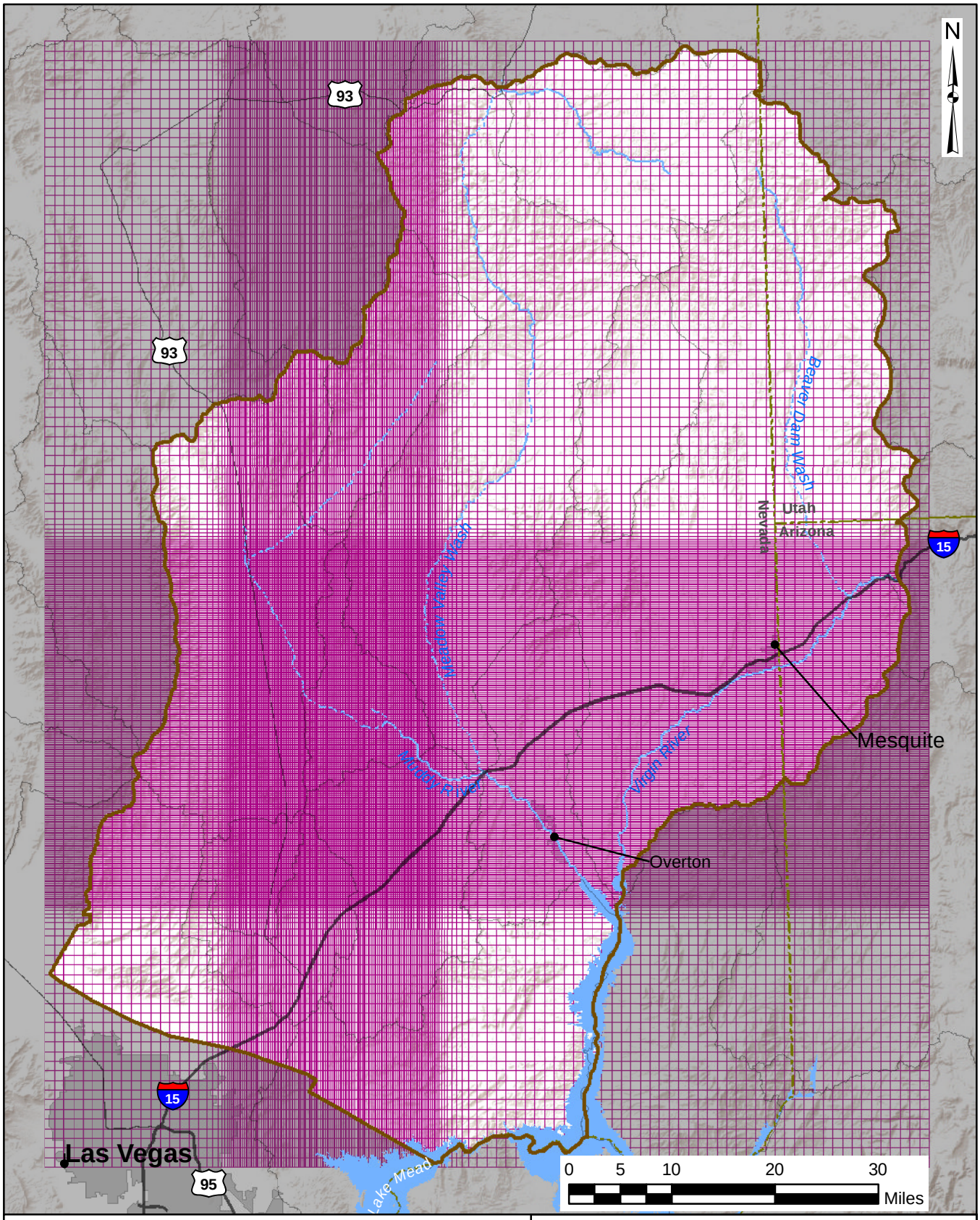
XLB shown in white

Examples of Geologic Model Sections between USGS Sections

Lower Colorado River Flow System

TETRA TECH GEO

Figure 4.2-4



Legend

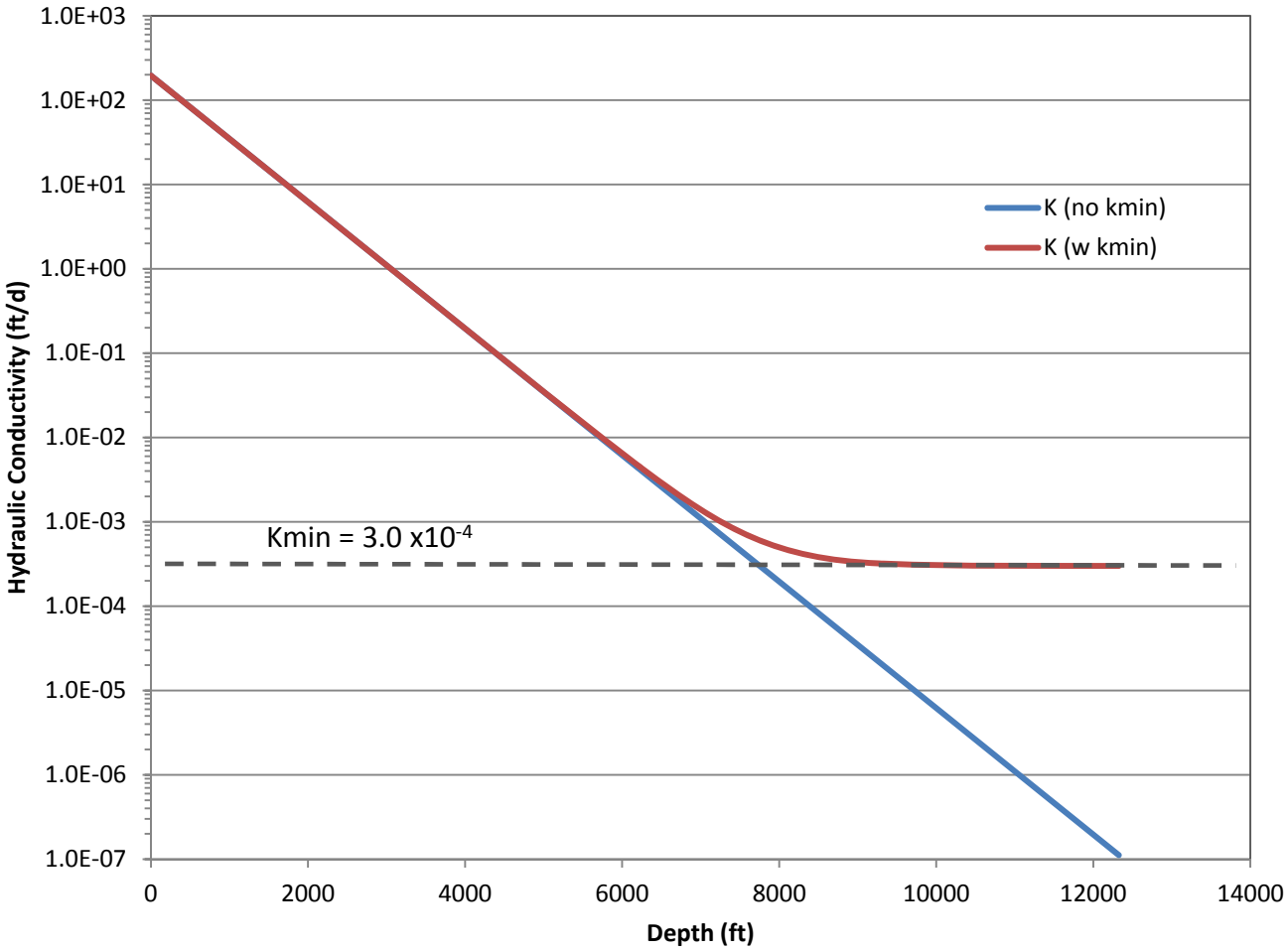
- Active Model Domain
- Hydrographic Region
- Flow-Model Grid

TITLE: **Flow-Model Grid**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **5.1-1**



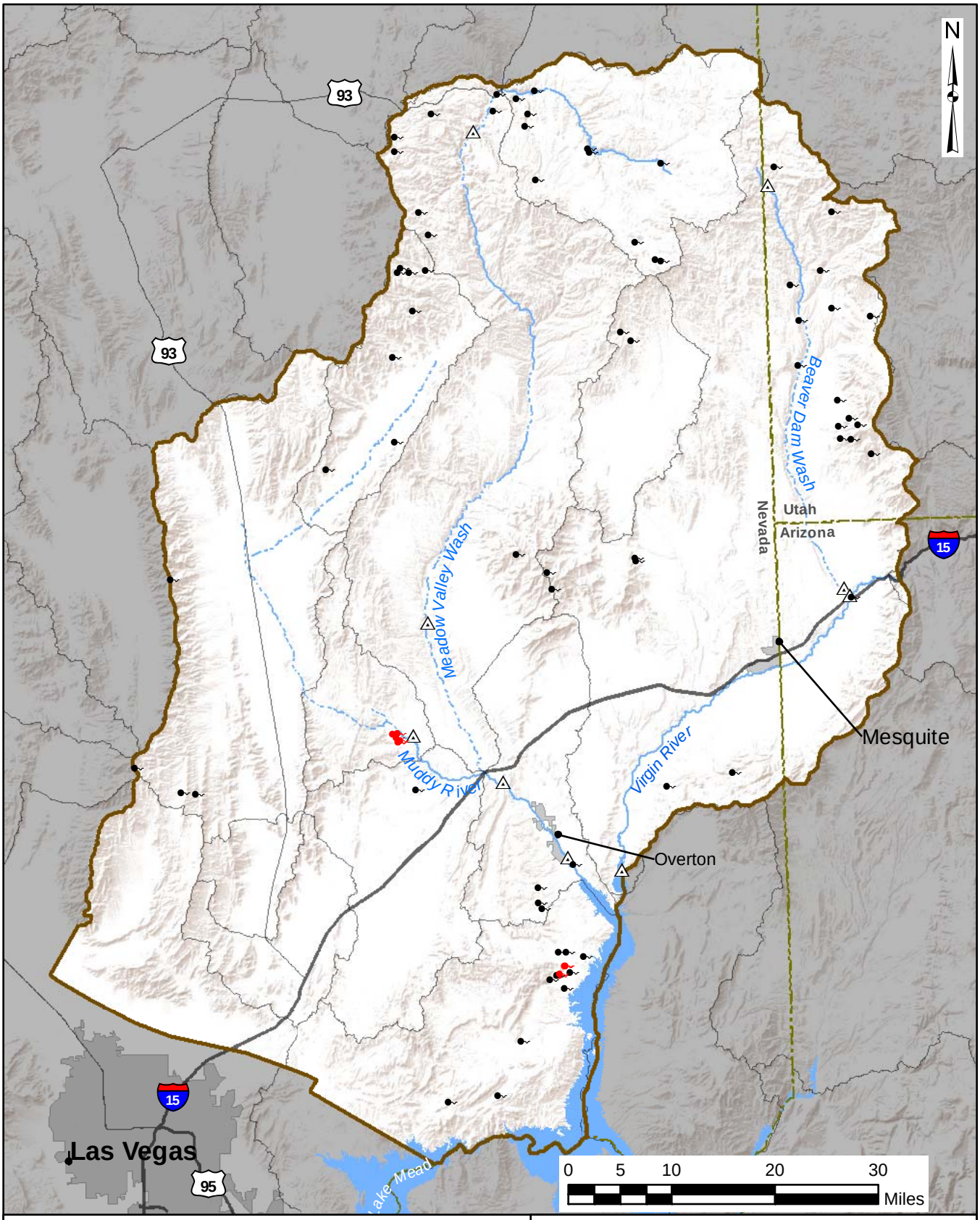
Lambda = 7.5E-04/ft

Example of Depth-Decay Relationship

Lower Colorado River Flow System

TETRA TECH GEO

Figure 5.1-2



Legend

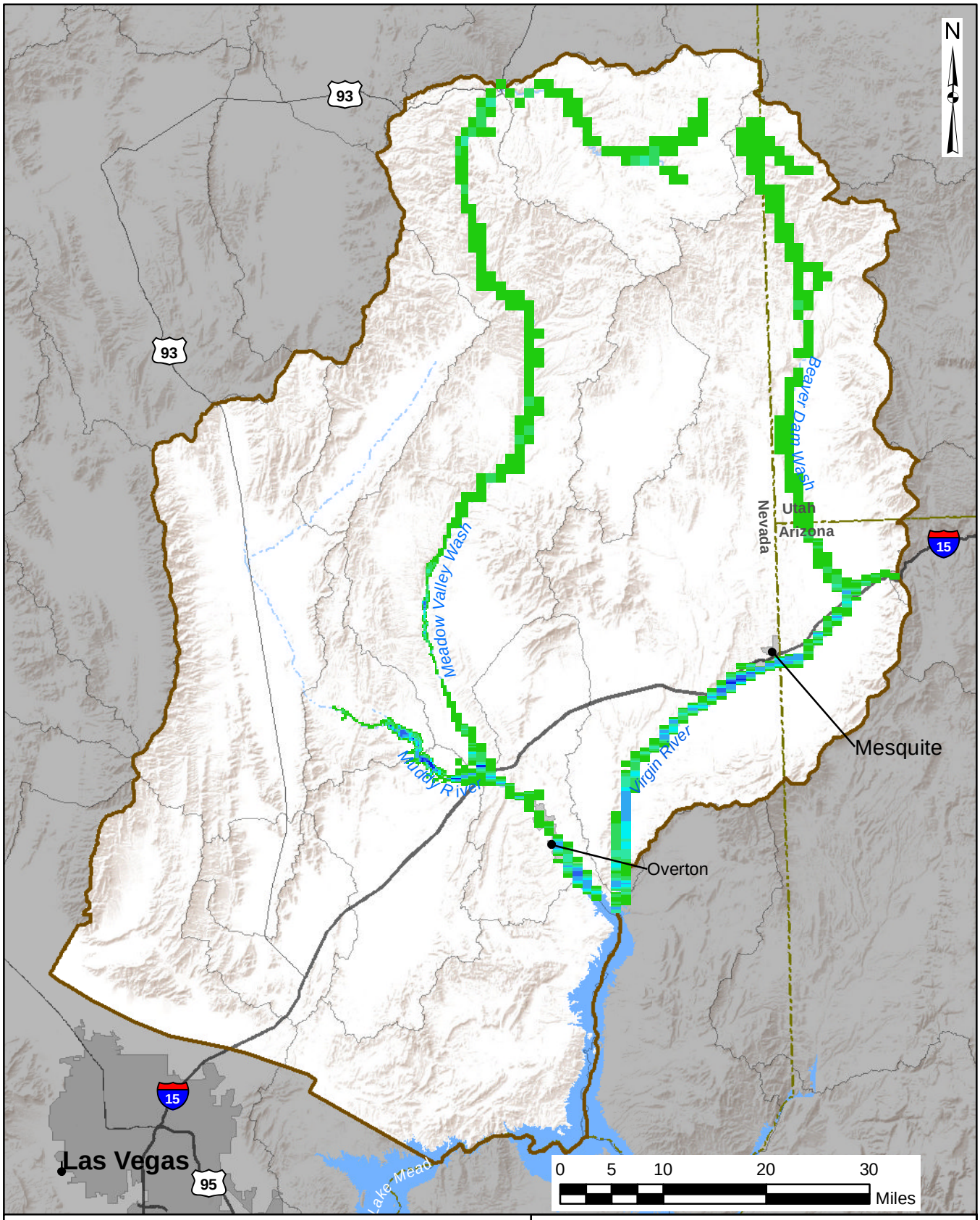
- Spring Simulated with DRN Package
- Spring Discharge Target
- Stream-flow Target
- Active Model Domain
- Hydrographic Area

TITLE: **Locations of Springs, Stream-Flow Targets, and Spring-Discharge Targets**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **5.2-1**



Legend

Evapotranspiration (in/yr)

- 0 - 0.5
- 0.5 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.3

Active Model Domain

Hydrographic Region

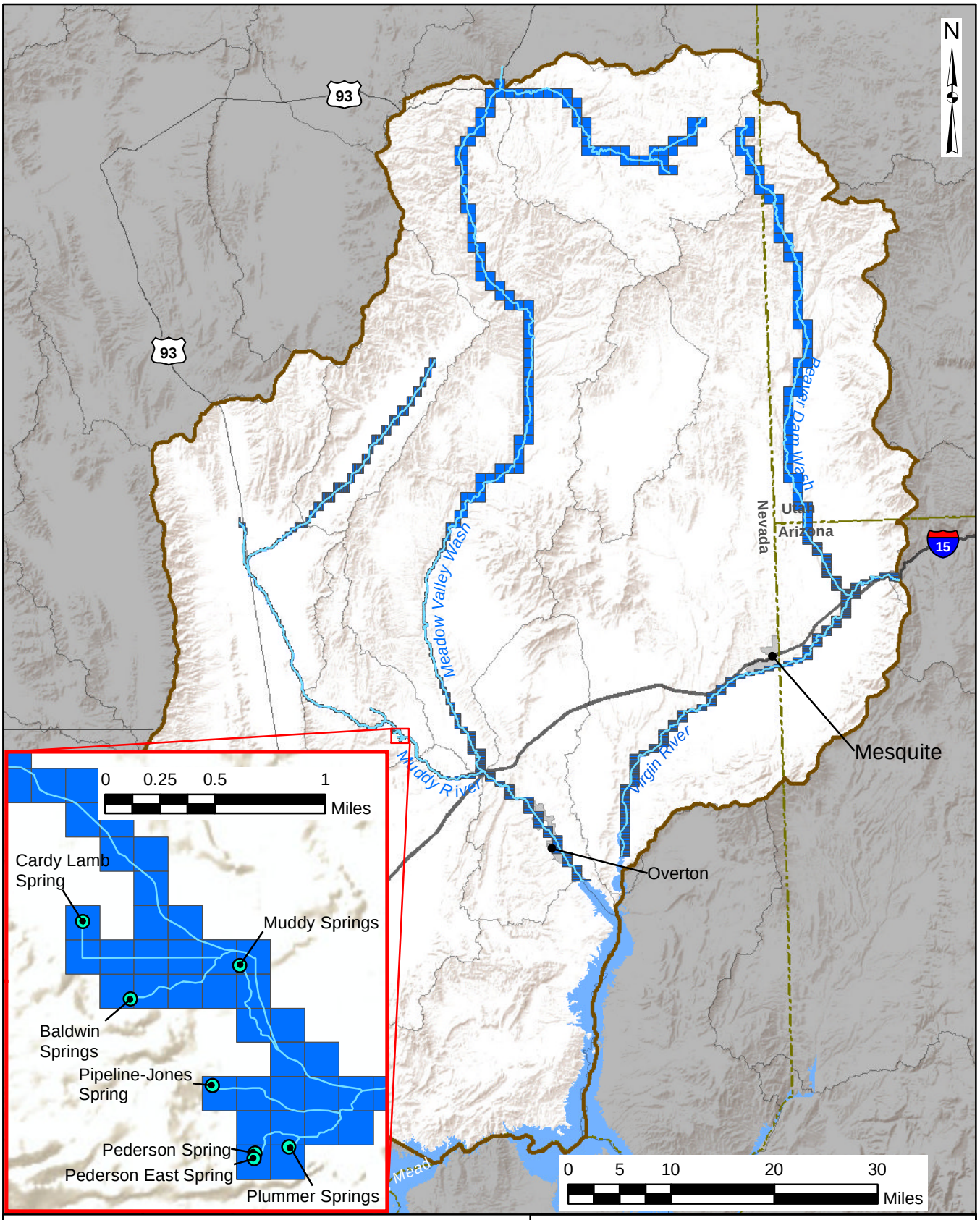
Based on: DeMeo et al., 2008

TITLE: **Designated Areas of Evapotranspiration**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **5.2-2**



Legend

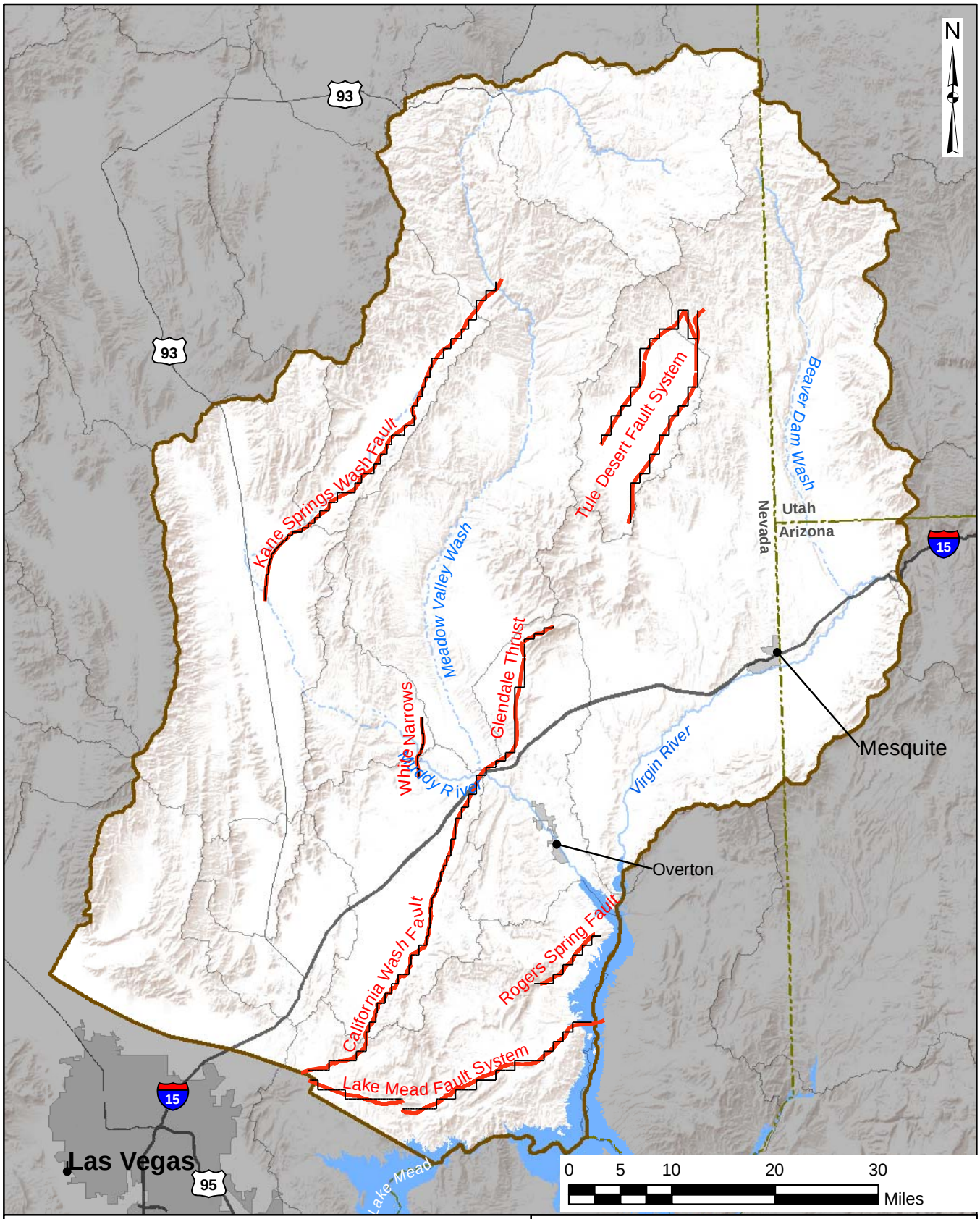
- Stream
- Streamflow-Routing Cell
- Active Model Domain
- Hydrographic Region

TITLE: **Streamflow-Routing Package Cells**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **5.2-3**



Legend

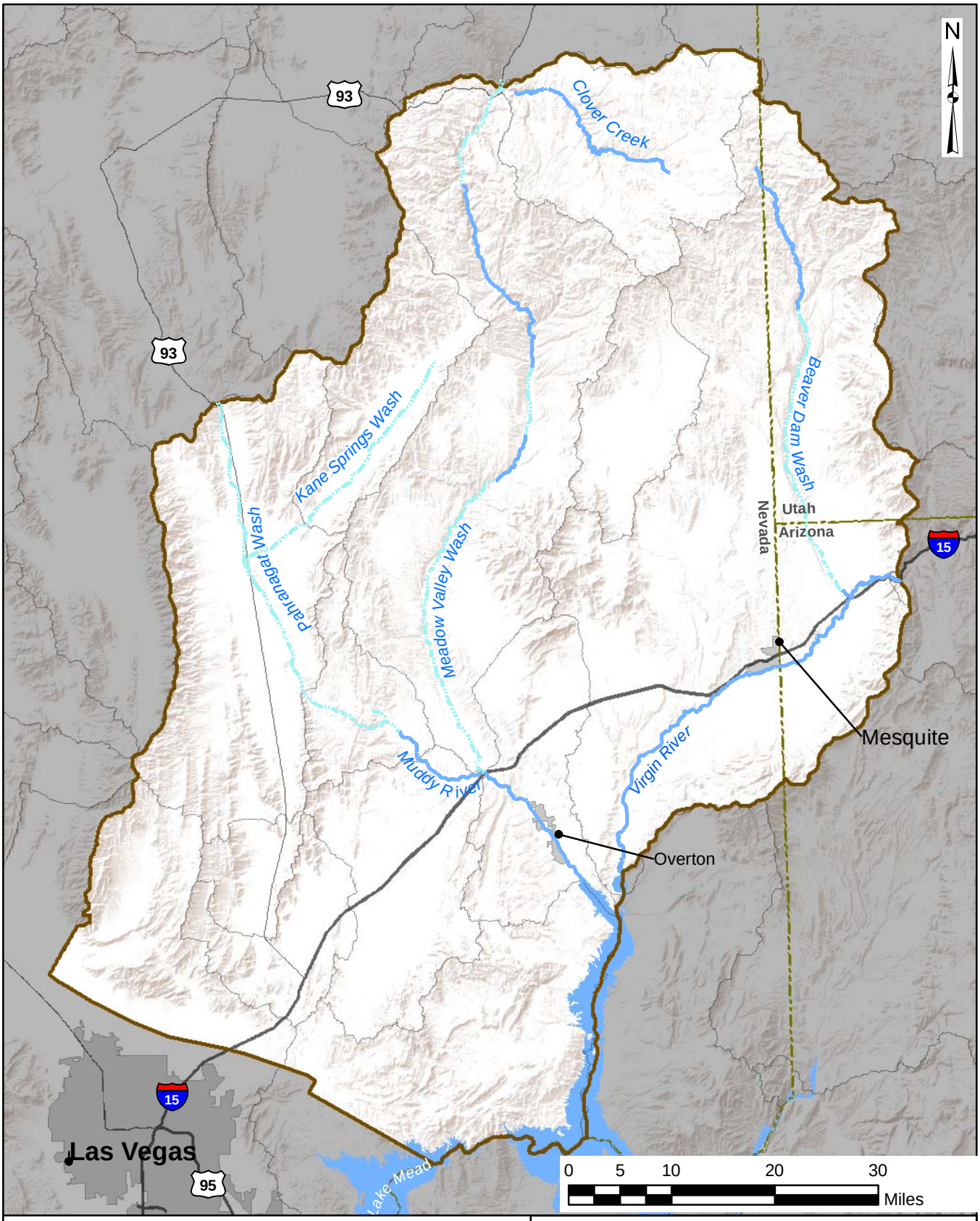
- Faults as HFB Boundaries
- Mapped Faults
- Active Model Domain
- Hydrographic Region

TITLE: **Faults Simulated Using HFB Package**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **5.2-4**



Legend

Ephemeral / Perennial Streams

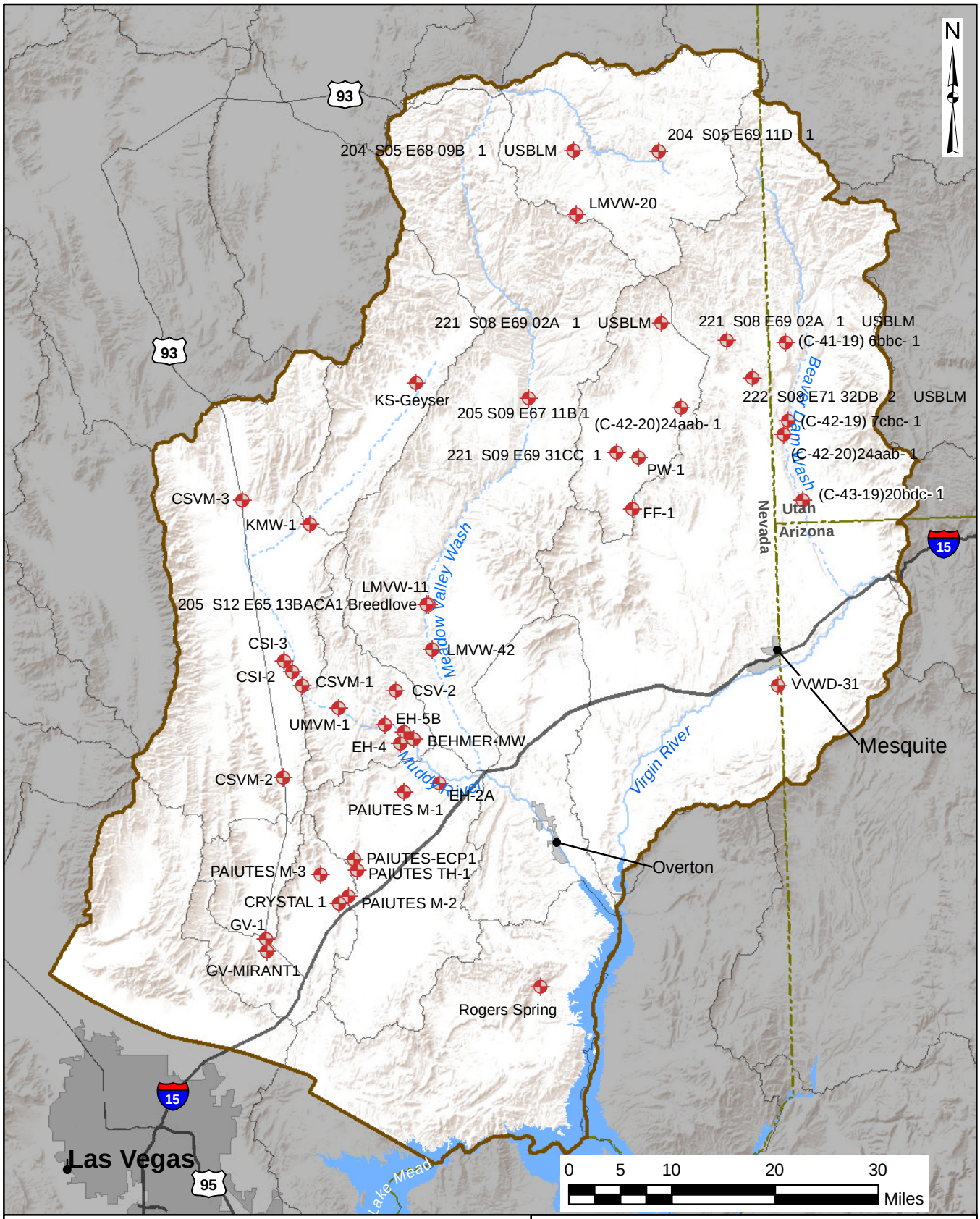
- Ephemeral
- Perennial
- Active Model Domain
- Hydrographic Region

TITLE: **Ephemeral and Perennial Stream Segments**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **5.3-1**



Legend

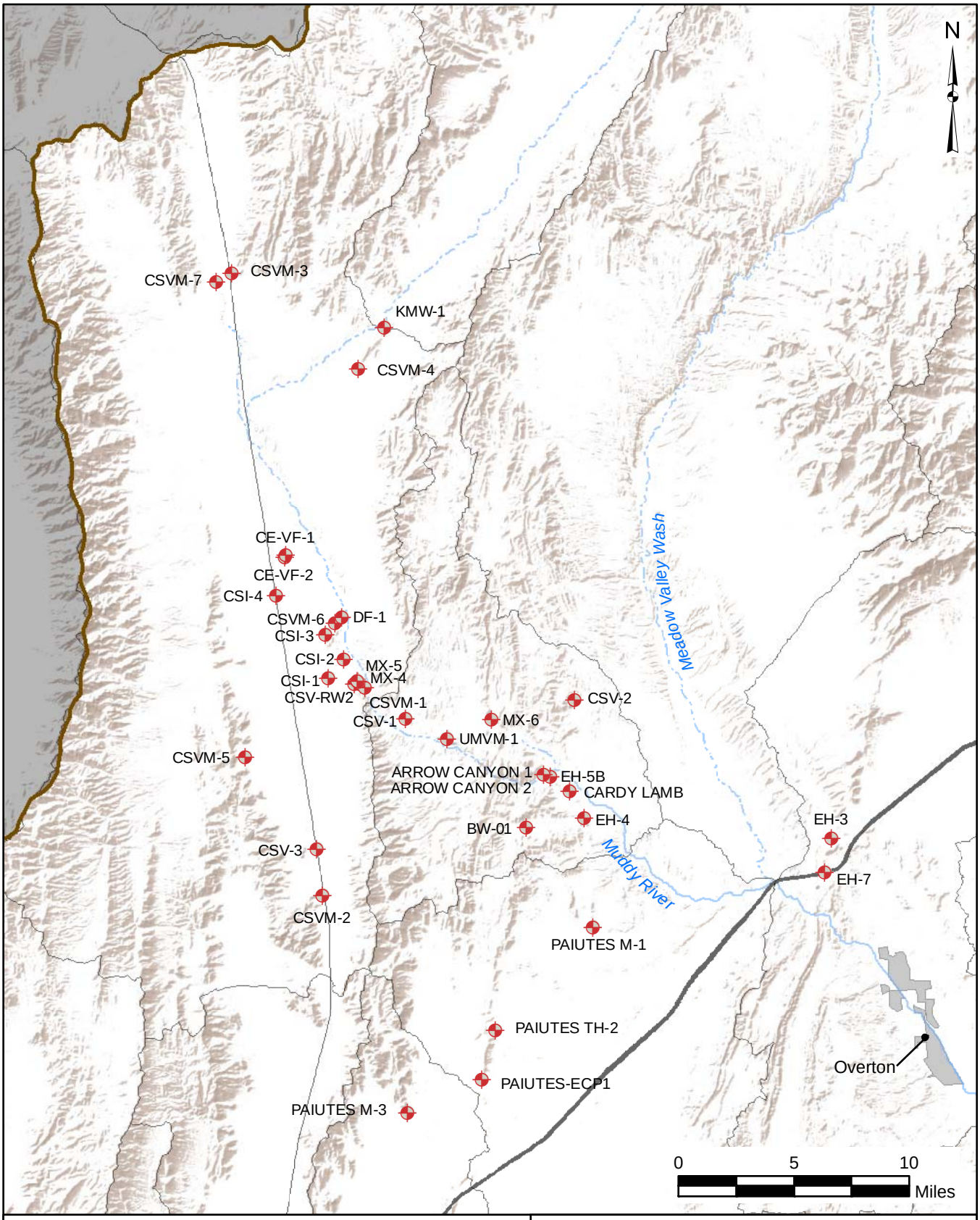
- Pre-Production Water-Level Target Well
- Active Model Domain
- Hydrographic Area

TITLE: **Pre-Production Water-Level Target Locations**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **5.3-2**



Legend

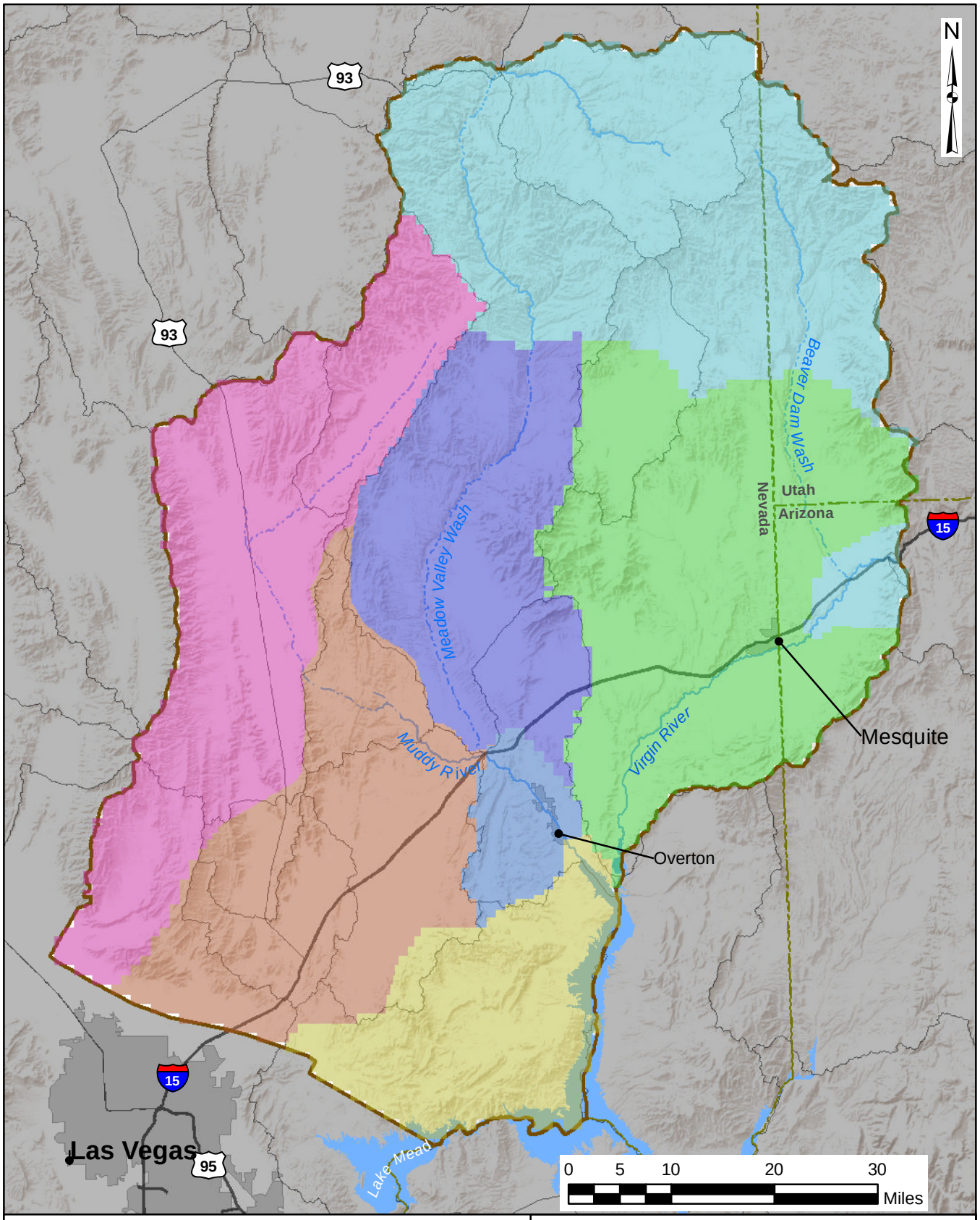
- Drawdown Target Wells
- Active Model Domain
- Hydrographic Area

TITLE: **Locations of Drawdown Target Wells**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **5.3-3**



Legend

- Active Model Domain
- Hydrographic Area

CAU Zone

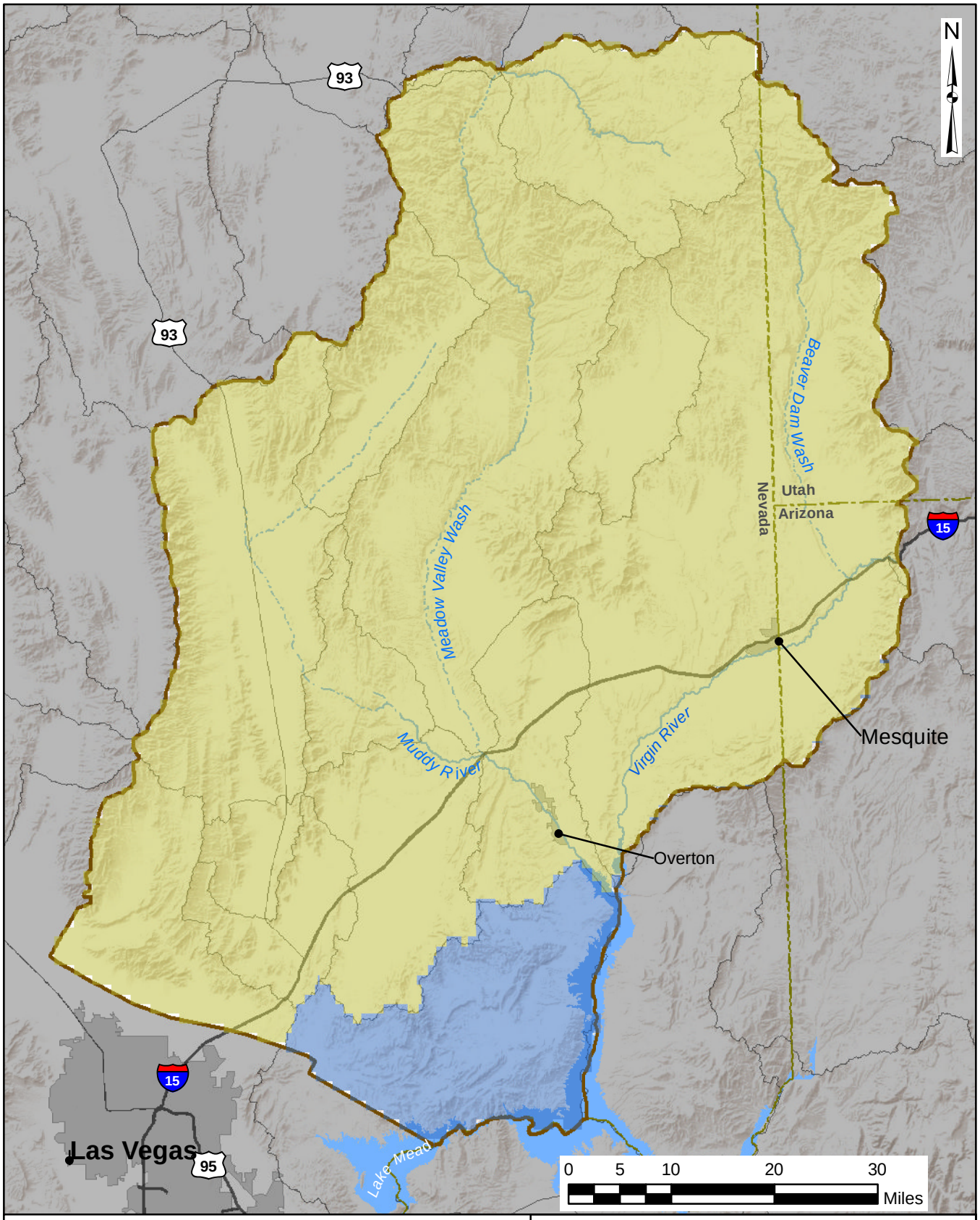
- 1
- 2
- 3
- 4
- 5
- 6
- 7

TITLE: **Zonation of CAU**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **6.1-1**



Legend

- Active Model Domain
- Hydrographic Area

Zones of TVC and XLB

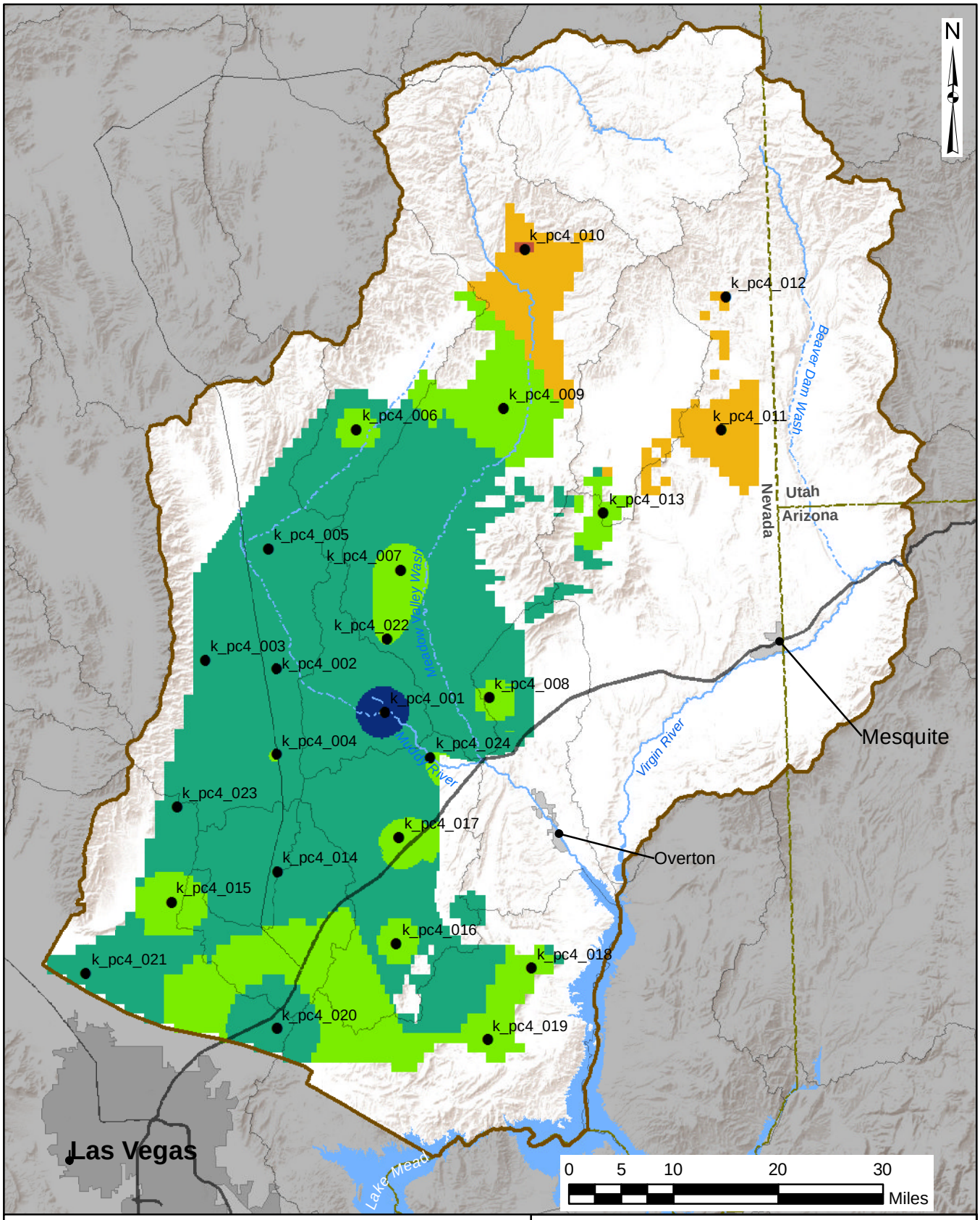
- 1
- 2

TITLE: **Zonation of TVC and XLB**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **6.1-2**



Legend

Log of Hydraulic Conductivity of PC4 (ft/d)

- 0.9997 - 1.0000
- 1.0001 - 2.0000
- 2.0001 - 3.0000
- 3.0001 - 4.0000
- 4.0001 - 5.0000

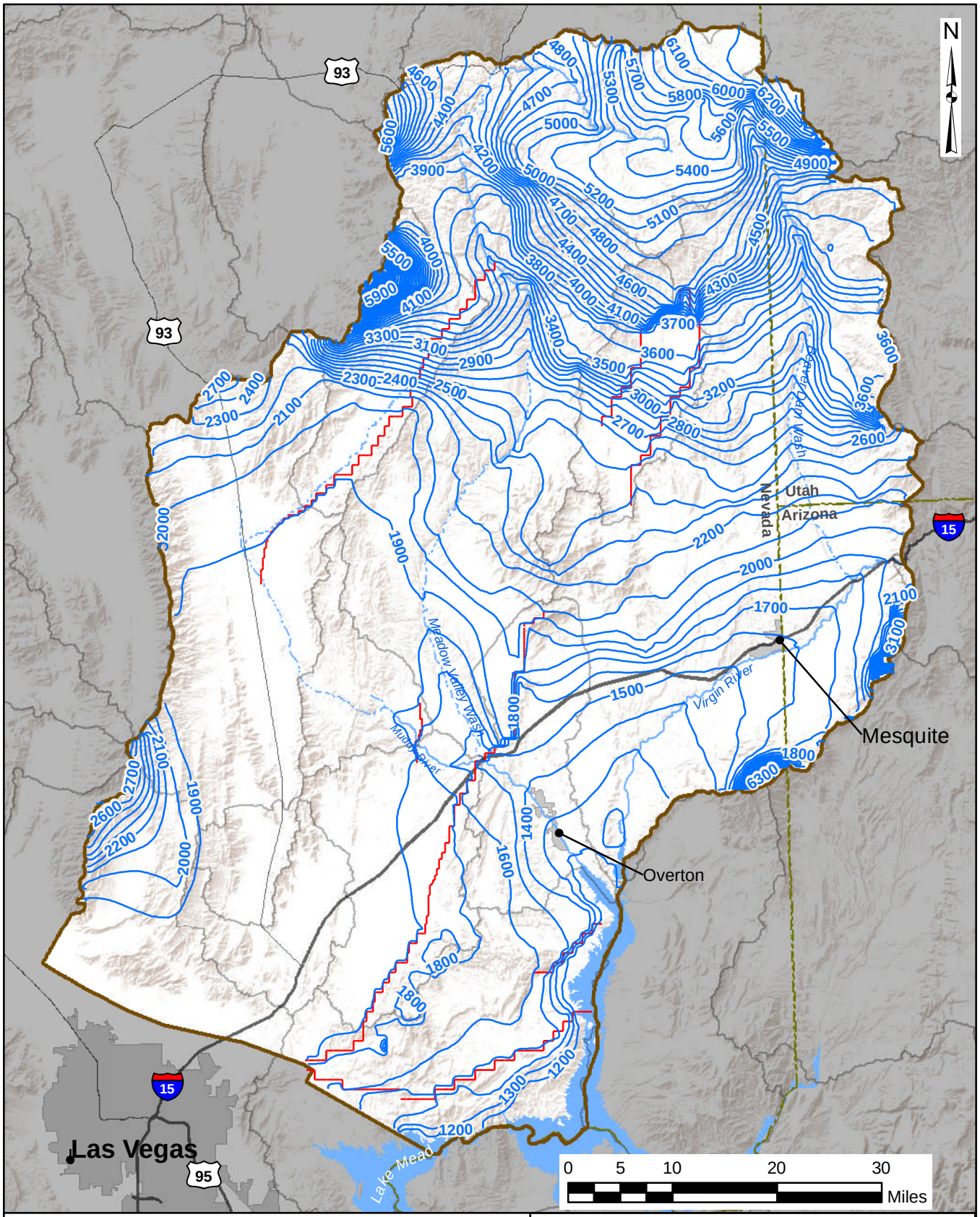
- PC4 Pilot Points
- Active Model Domain
- Hydrographic Region

TITLE: **Hydraulic Conductivity of PC4**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **6.1-3**



Legend

- Water Level Elevation Contour (ft amsl)
- Faults as HFB Boundaries
- Active Model Domain

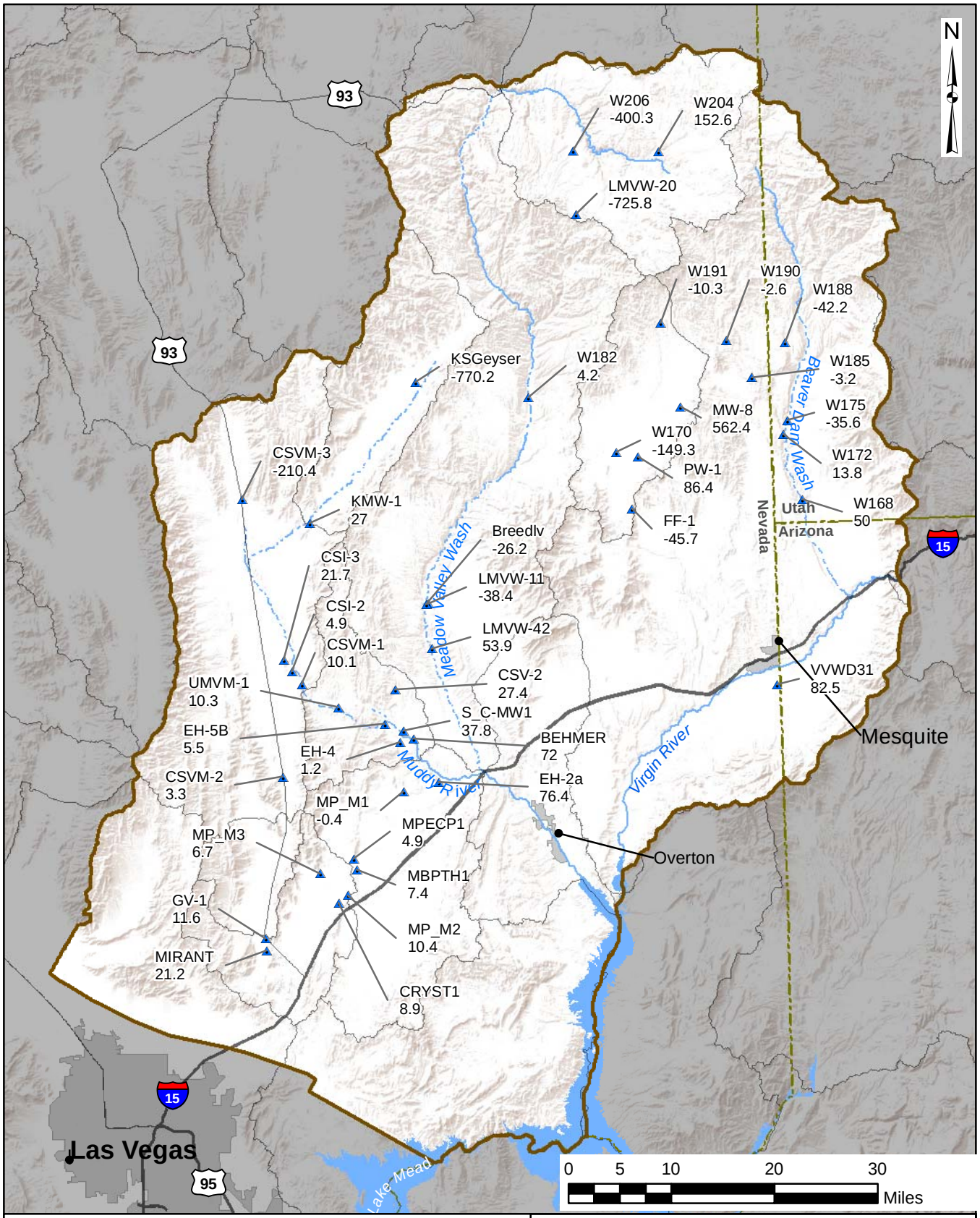
Contour Interval = 100 feet

TITLE:
Pre-Production Simulated Water Table

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE
6.2-1



Legend

- Pre-Production Target Locations
- Active Model Domain
- Hydrographic Area

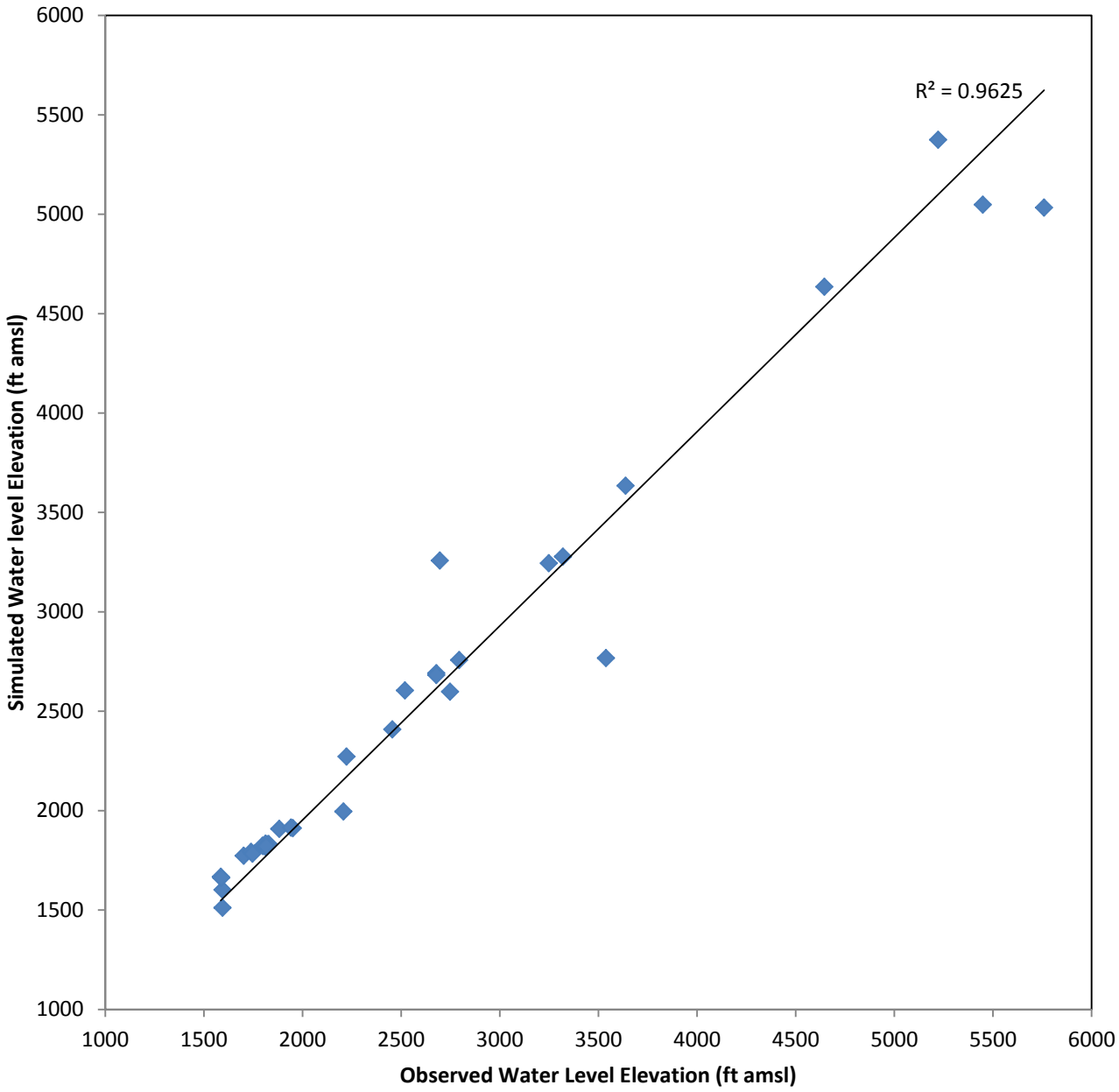
Residuals represent the difference between simulated water levels in 1949 and earliest appropriate measured water level at a location.

TITLE: **Pre-Production Water Level Residuals**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **6.2-2**

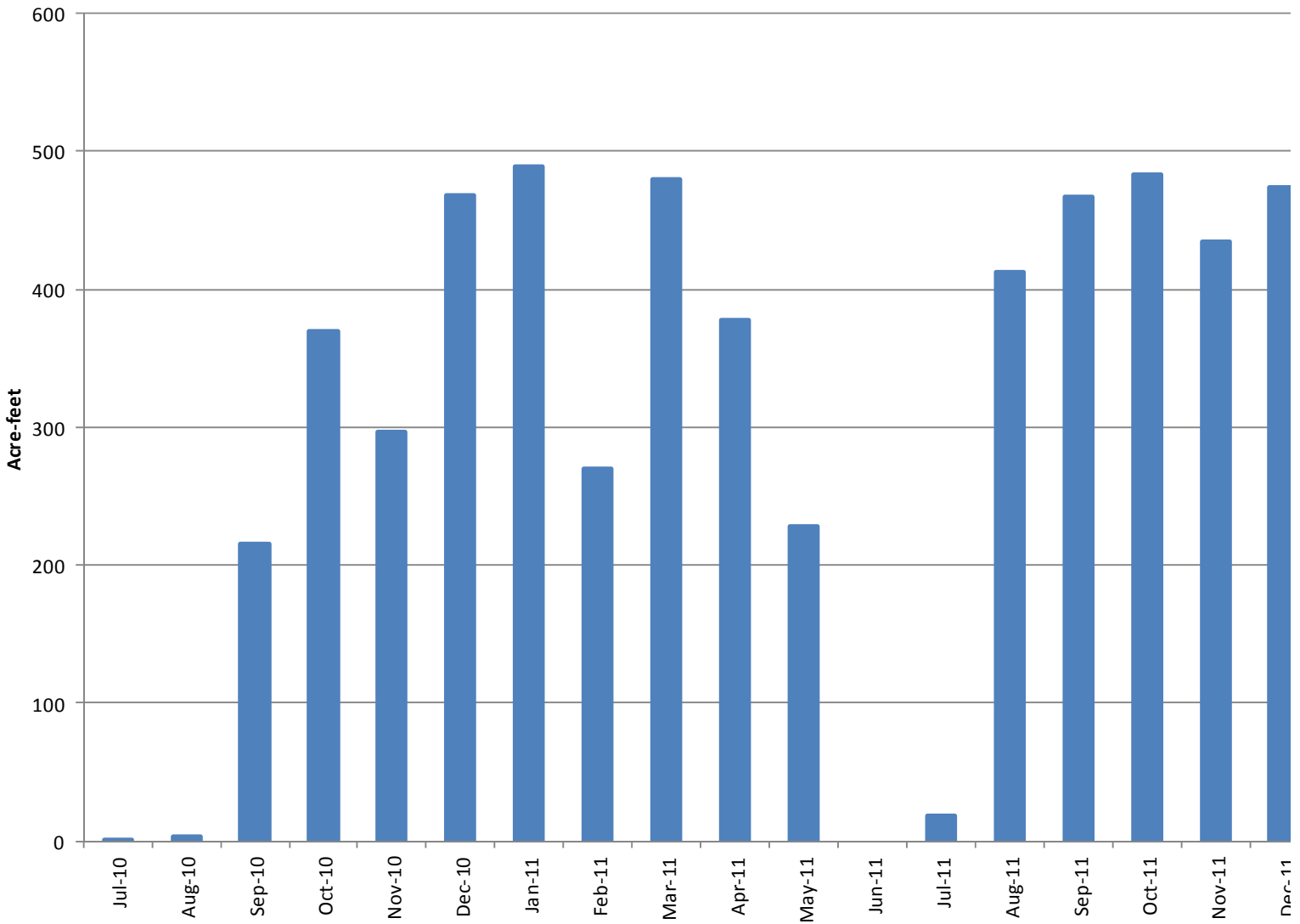


Correlation Between Measured and Simulated Water Levels, Pre-Production Model

Lower Colorado River Flow System

TETRA TECH GEO

Figure 6.2-3

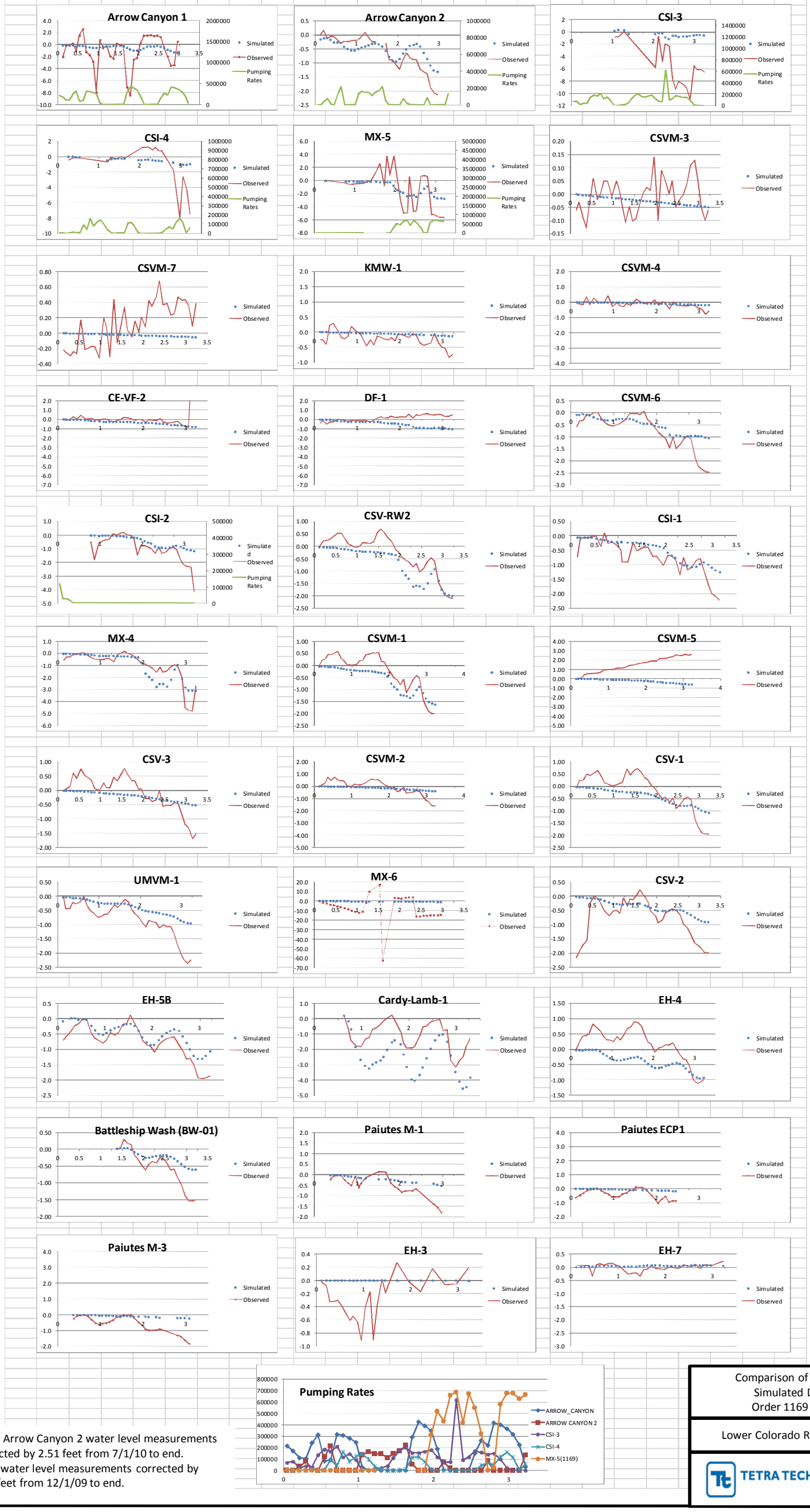


Order 1169 Pumping
July 2010 – December 2011 for MX-5

Lower Colorado River Flow System

TETRA TECH GEO

Figure
6.2-4



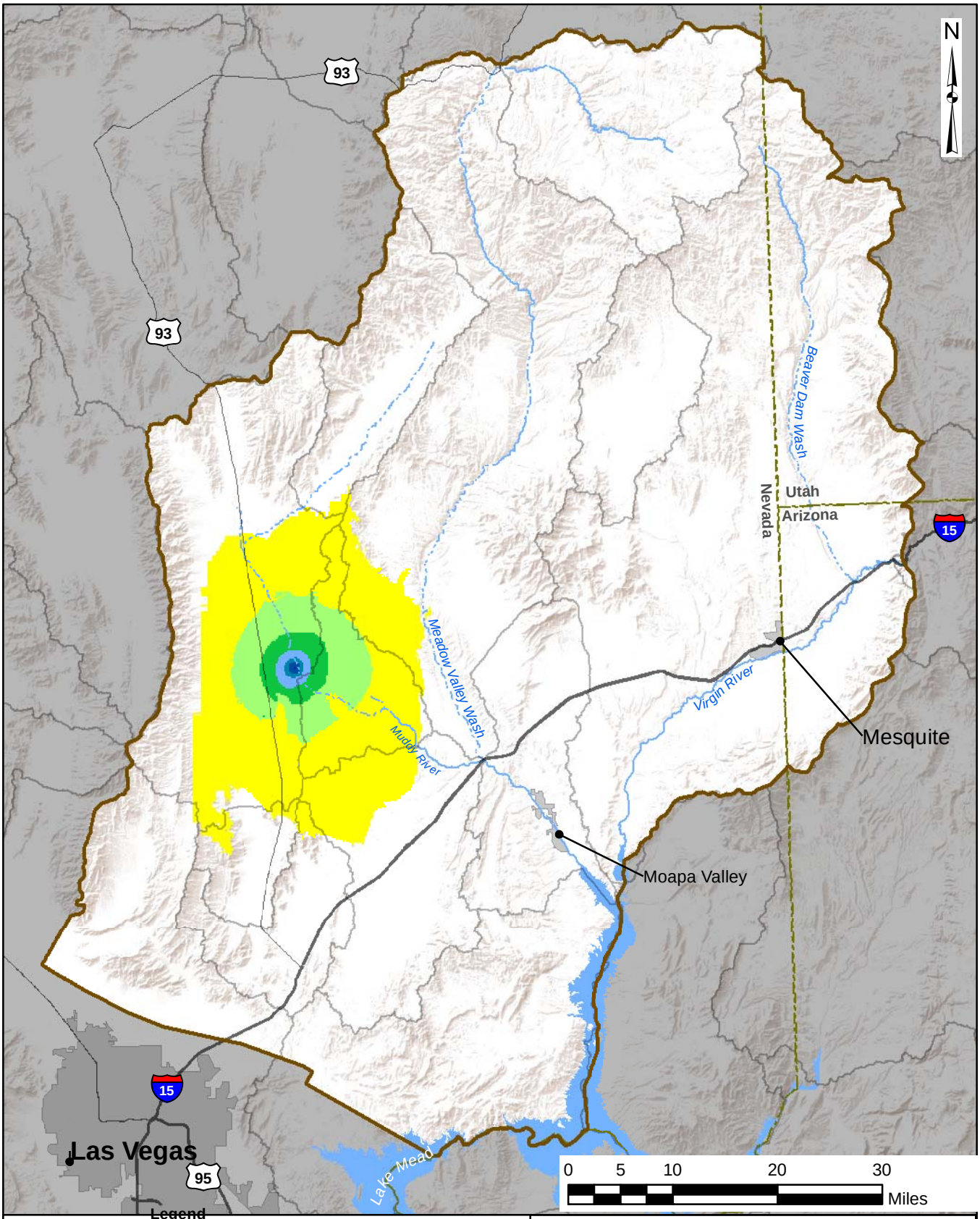
Note: Arrow Canyon 2 water level measurements corrected by 2.51 feet from 7/1/10 to end.
CSI-1 water level measurements corrected by 12.4 feet from 12/1/09 to end.

Comparison of Observed and Simulated Drawdown
Order 1169 Simulation

Lower Colorado River Flow System

TETRA TECH GEO

Figure 6.2-5

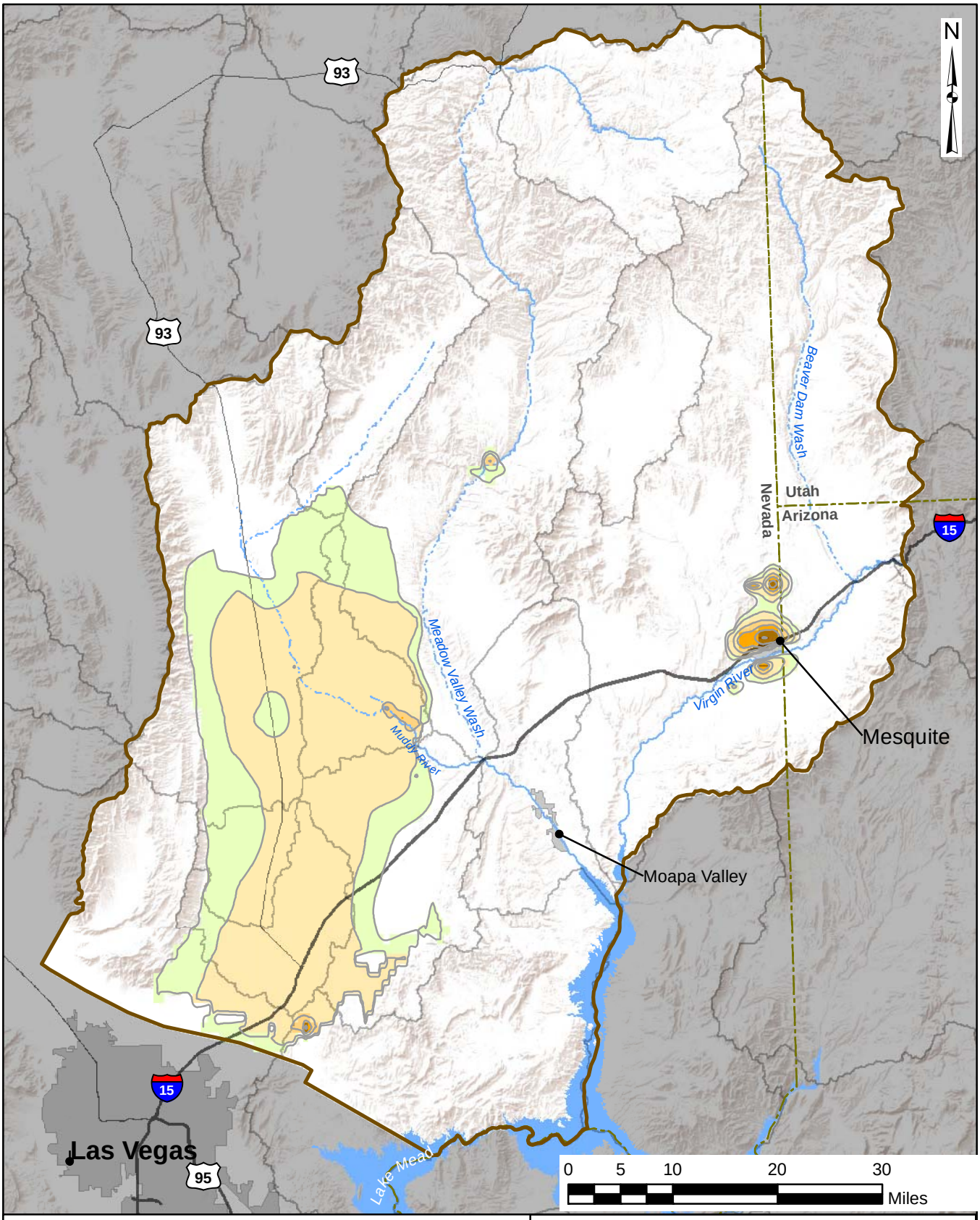


TITLE: **Drawdown from MX-5 Pumping, October 2009 - December 2011**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **6.2-6**



Legend

< 1	20 - 50	Active Model Domain
1 - 2	50 - 100	State Boundary
2 - 5	100 - 200	
5 - 10	200 - 500	
10 - 20	> 500	

Drawdown is in feet

Drawdown calculated as change in water level elevation between1949 and December 2011

TITLE:

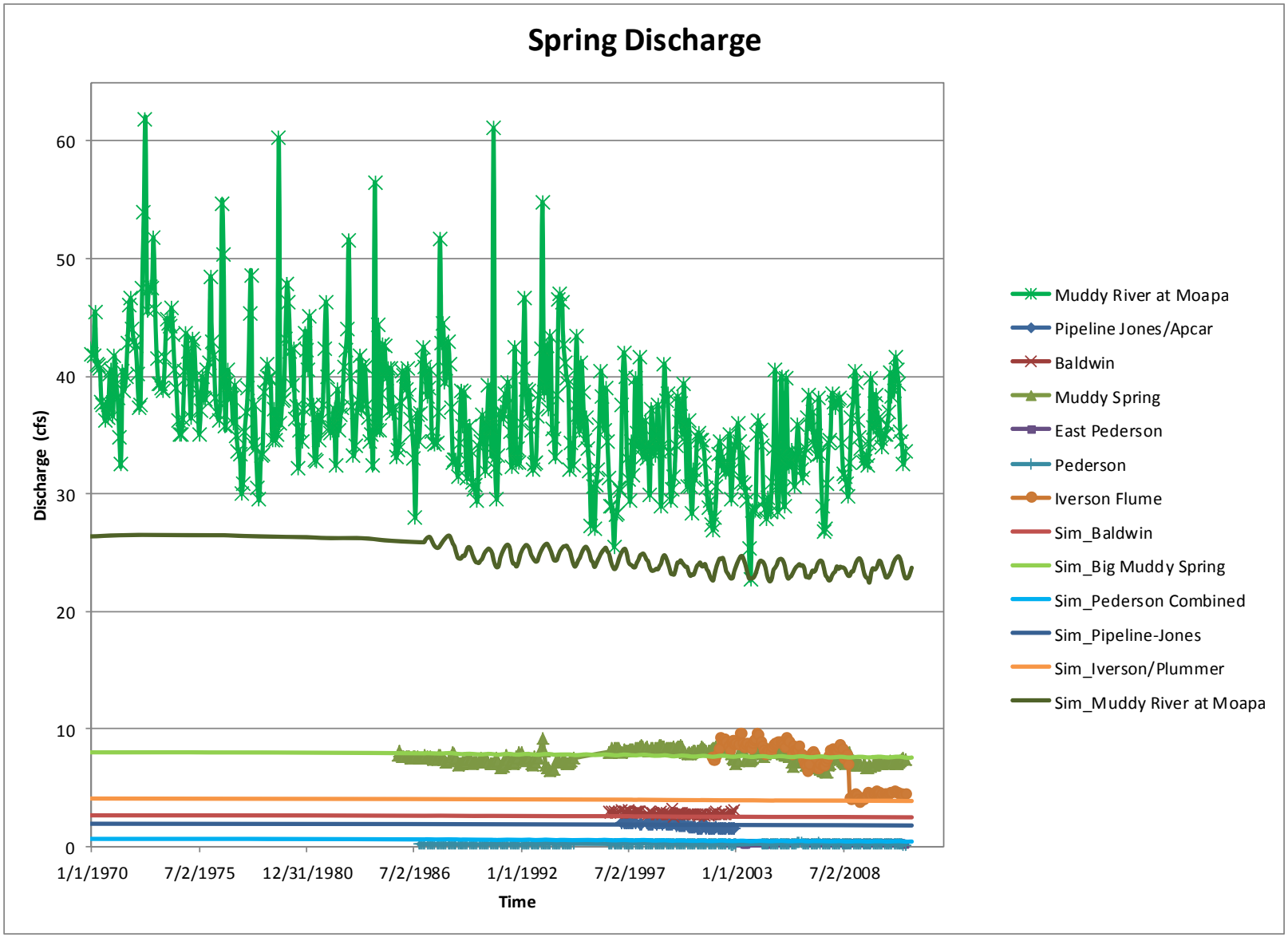
Simulated Drawdown, December 2011

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE

6.2-7

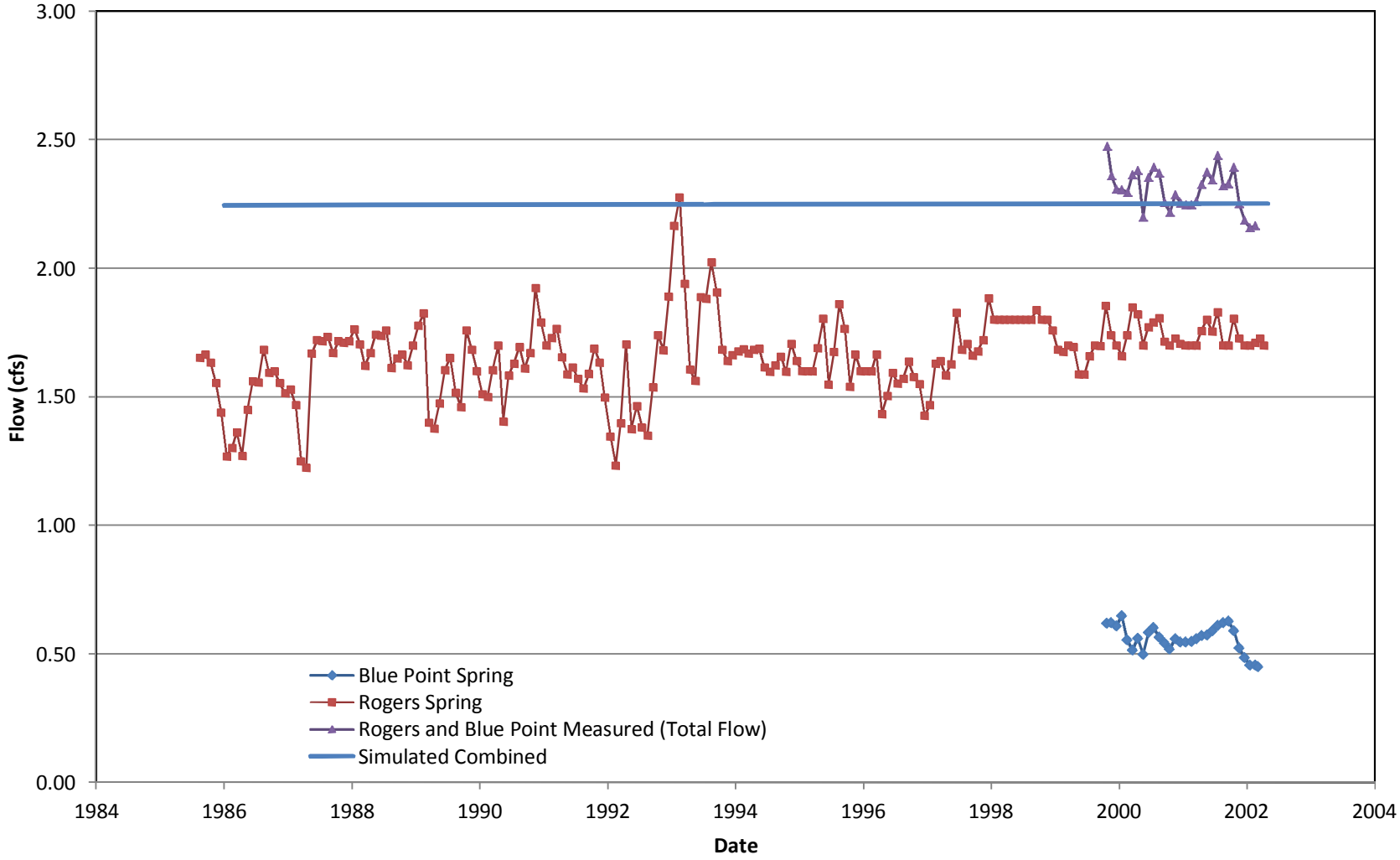


Observed and Simulated Spring Discharge

Lower Colorado River Flow System

TETRA TECH GEO

Figure 6.3-1

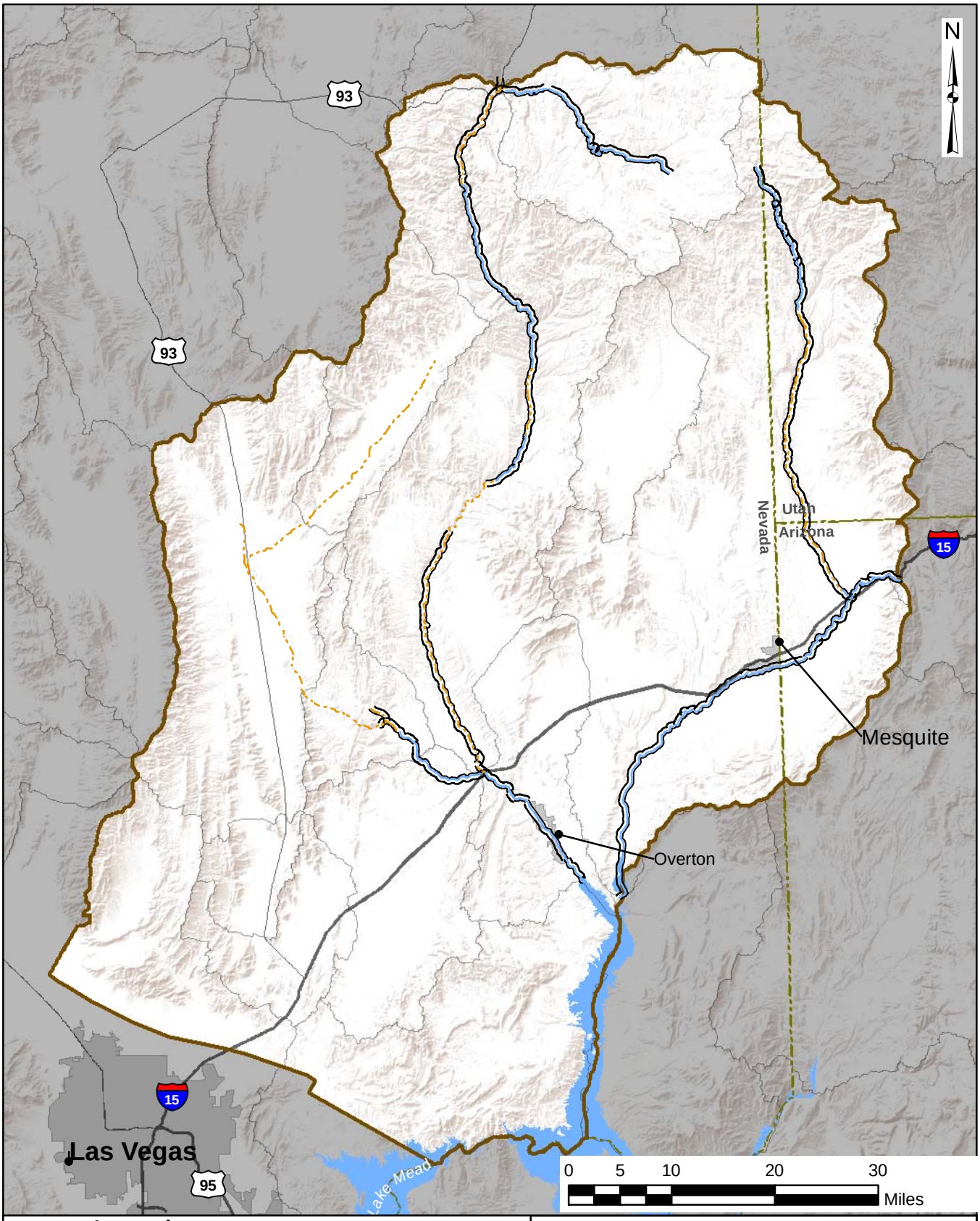


Observed and Simulated
Rogers and Blue Point Spring Discharge

Lower Colorado River Flow System

TETRA TECH GEO

Figure
6.3-2



Legend

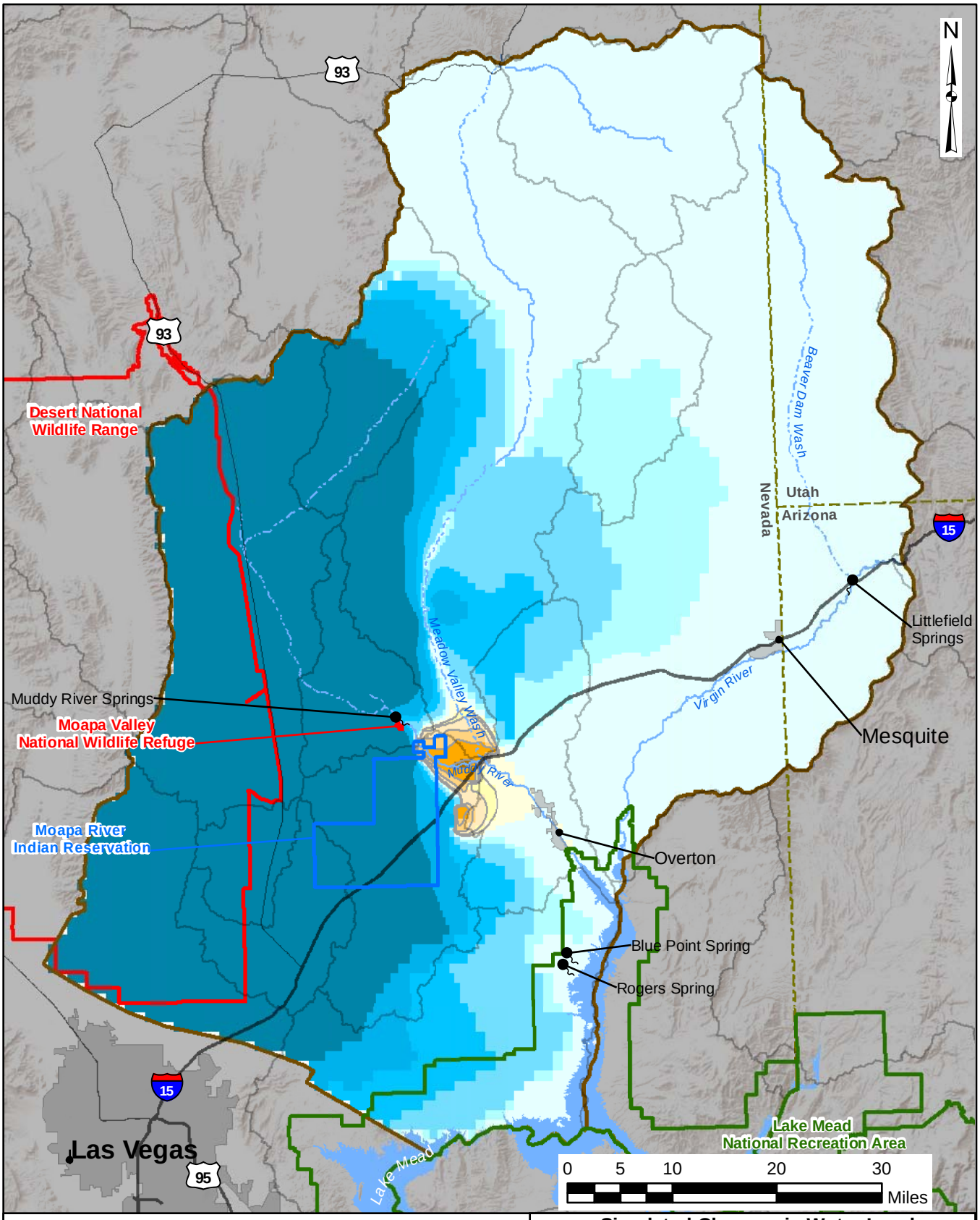
- Simulated Perennial Stream
- Ephemeral Stream
- Perennial Stream
- Active Model Domain
- Hydrographic Region

TITLE: **Observed and Simulated Ephemeral and Perennial Stream Segments**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **6.4-1**

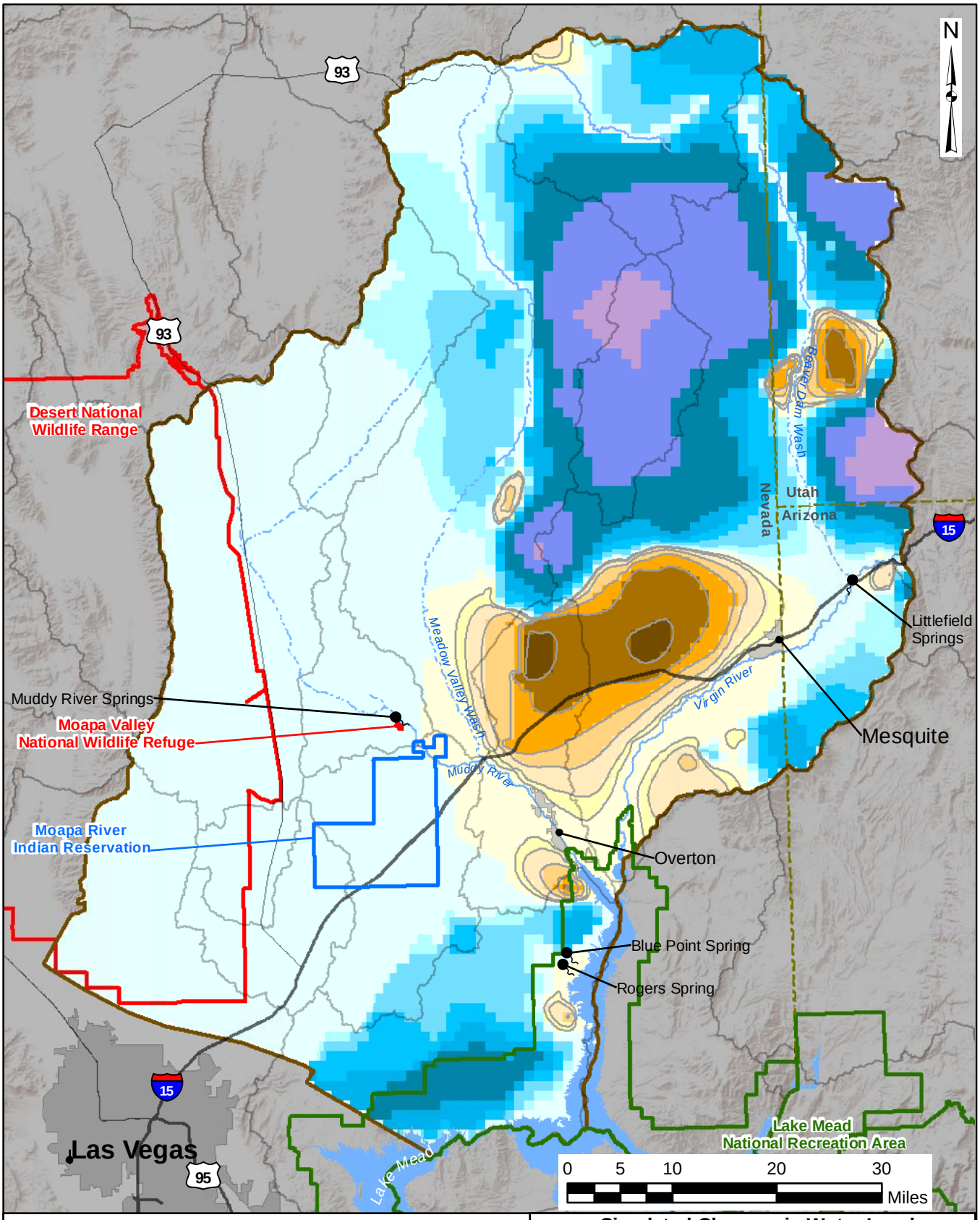


TITLE: **Simulated Changes in Water Level 100 Percent Increase in Horizontal Hydraulic Conductivity of CAU**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **6.6-1**

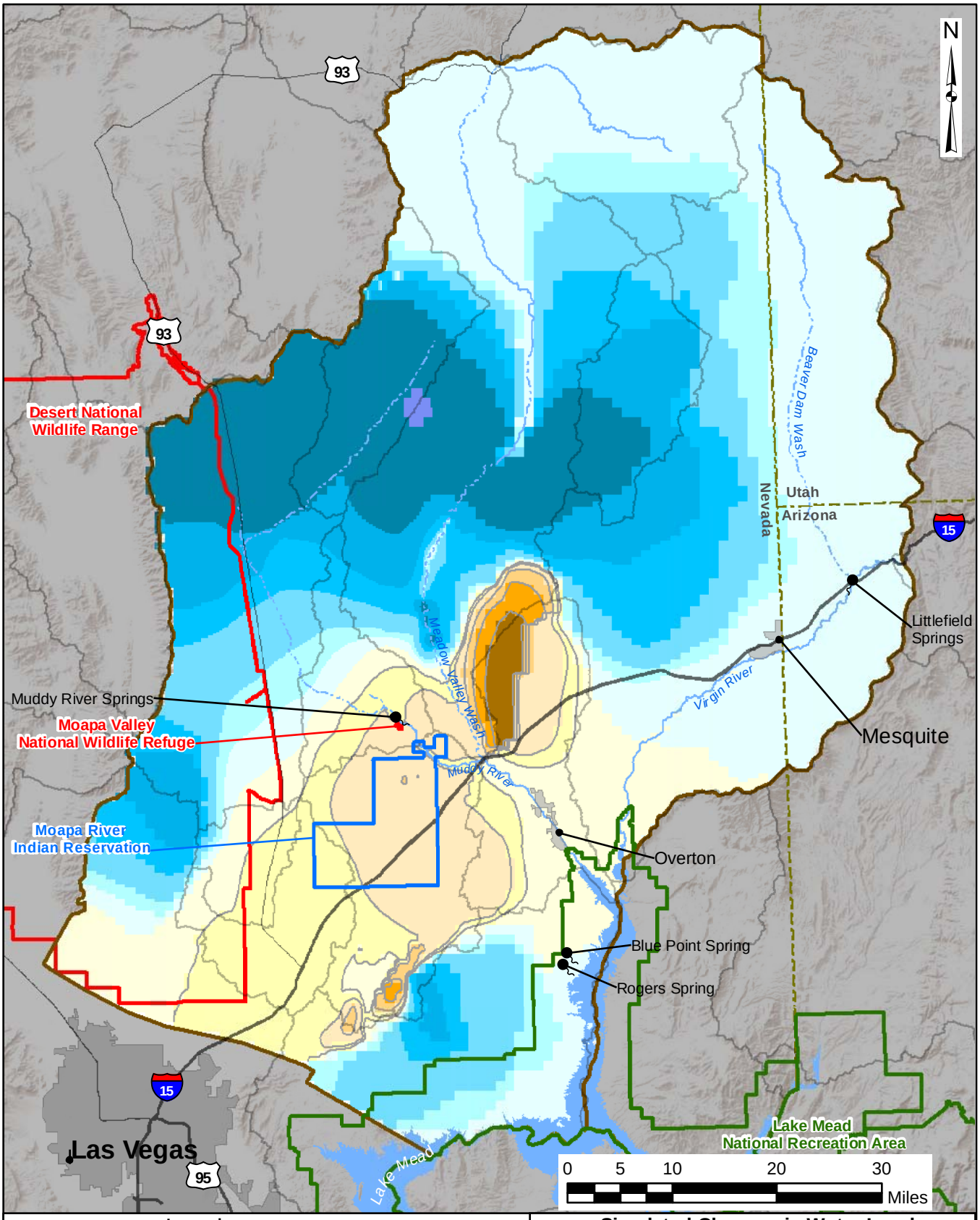


TITLE: **Simulated Changes in Water Level 100 Percent Increase in Horizontal Hydraulic Conductivity of PC1**

LOCATION: **Colorado Regional Groundwater Flow System Southeastern Nevada**

TETRA TECH

FIGURE **6.6-2**



Legend

-200 to -100	1 to 2	Active Model Domain
-100 to -50	2 to 5	State Boundary
-50 to -20	5 to 10	
-20 to -10	10 to 20	
-10 to -5	20 to 50	
-5 to -2	50 to 100	
-2 to -1	100 to 200	
-1 to 0	> 200	
0 to 1		

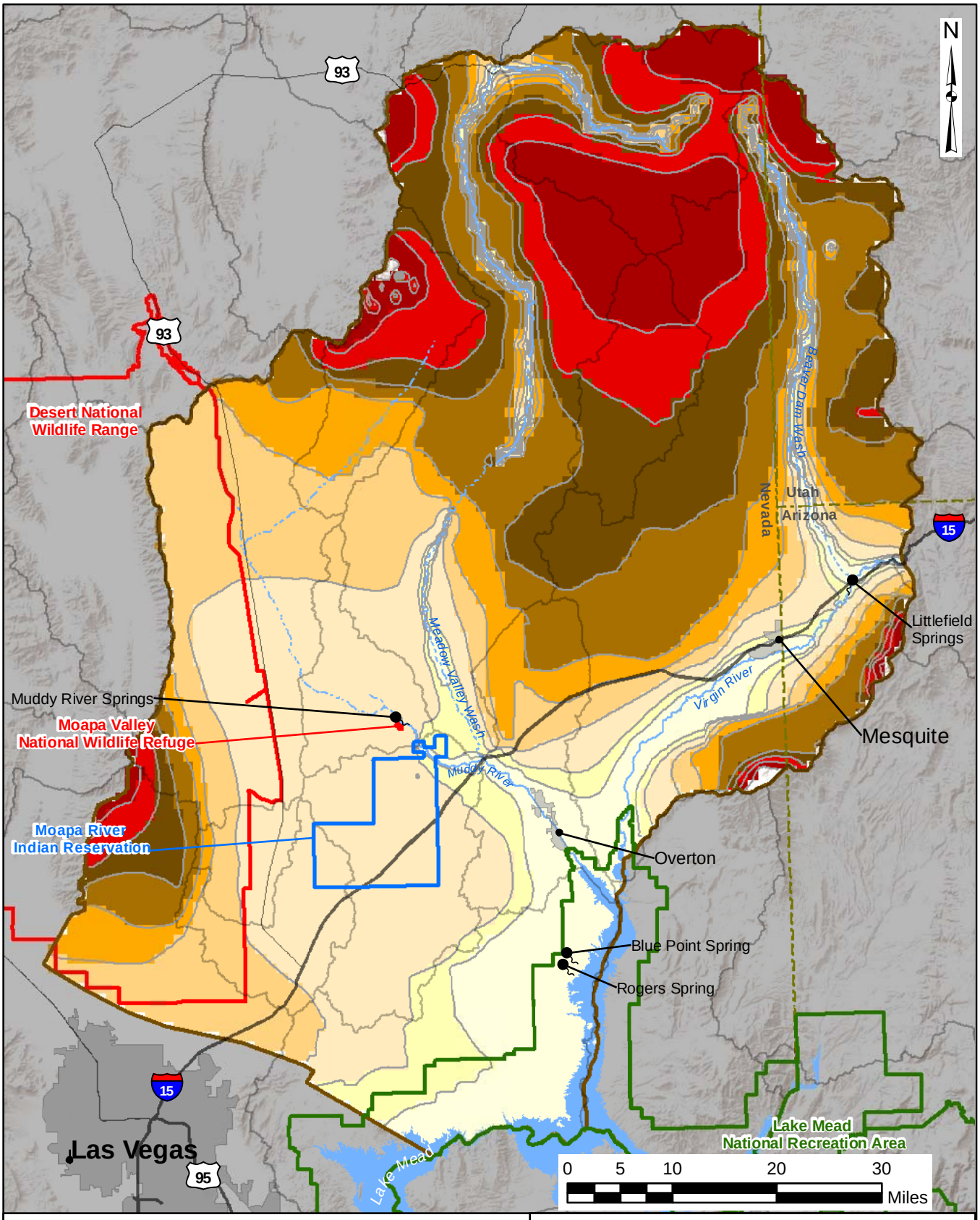
Simulated change is in feet.

TITLE: **Simulated Changes in Water Level**
100 Percent Increase in
Hydraulic Conductivity of PC4_1

LOCATION: **Colorado Regional Groundwater Flow System**
Southeastern Nevada

TETRA TECH

FIGURE
6.6-3



Legend

-200 to -100	1 to 2	Active Model Domain
-100 to -50	2 to 5	State Boundary
-50 to -20	5 to 10	
-20 to -10	10 to 20	
-10 to -5	20 to 50	
-5 to -2	50 to 100	
-2 to -1	100 to 200	
-1 to 0	> 200	
0 to 1		

Simulated change is in feet.

TITLE:

Simulated Changes in Water Level
25 Percent Increase in Regional Recharge

LOCATION: **Colorado Regional Groundwater Flow System**
Southeastern Nevada

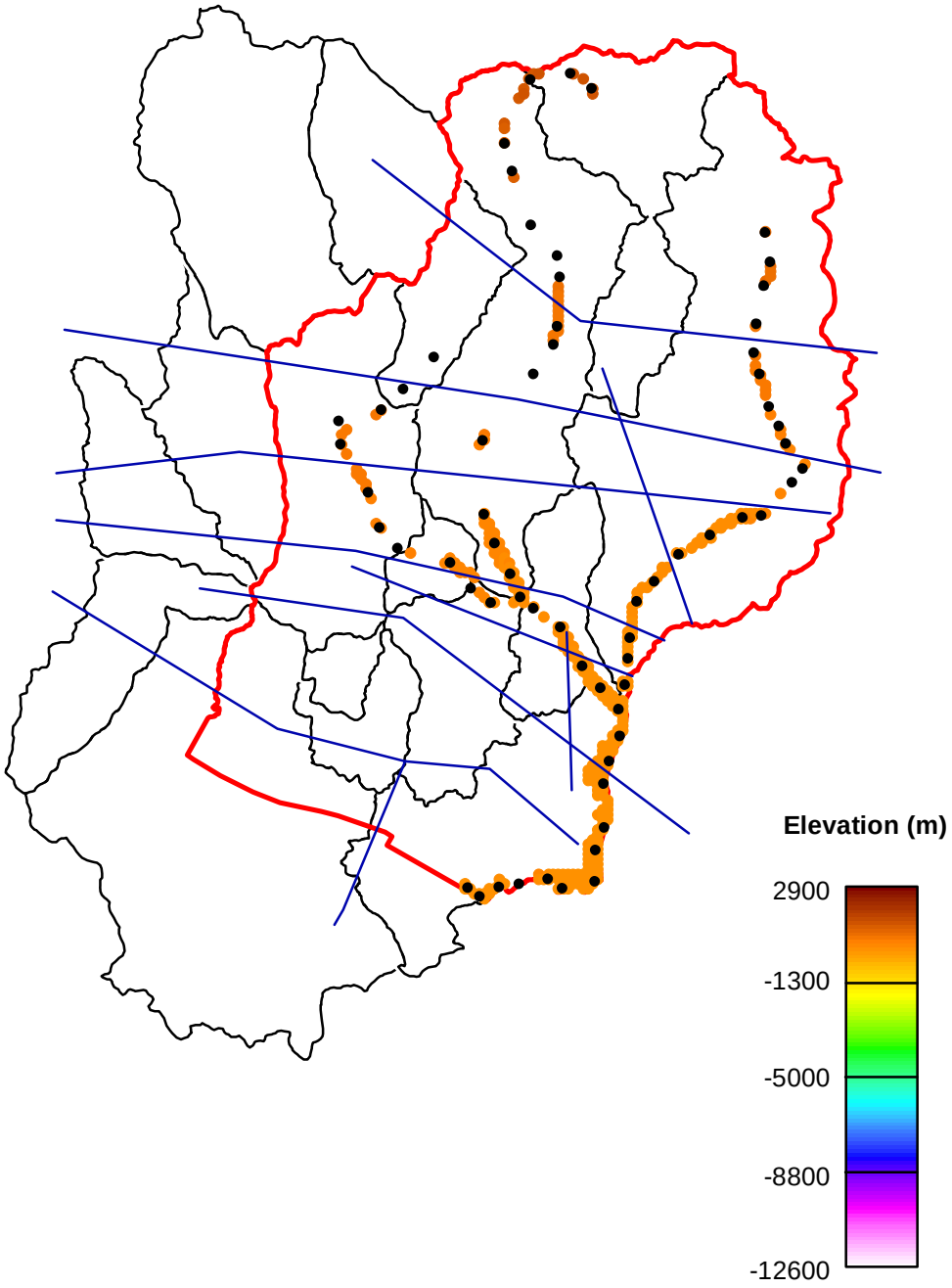
TETRA TECH

FIGURE
6.6-4

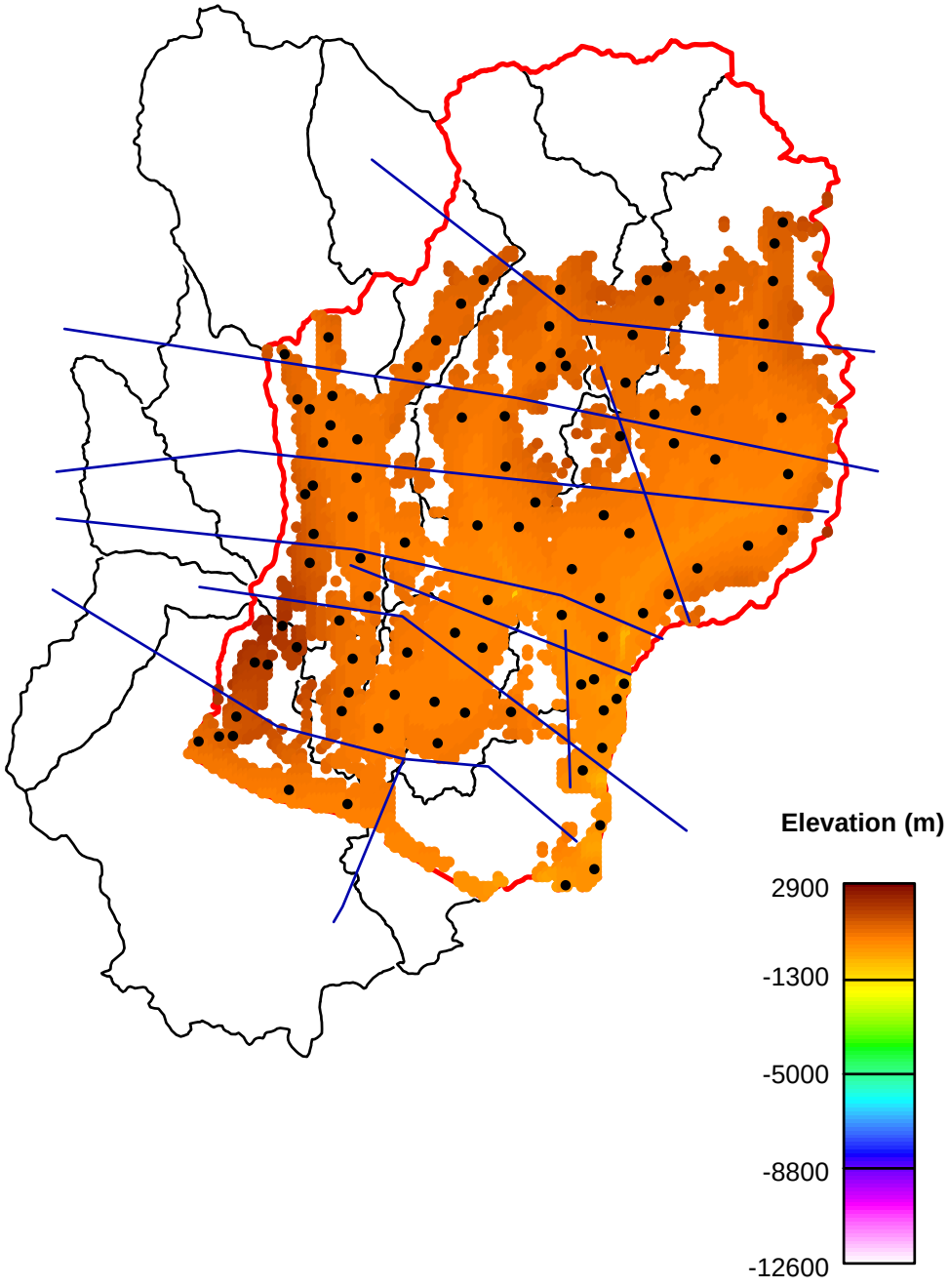
ATTACHMENT I

Distributions and Top Elevations of Hydrogeologic Units

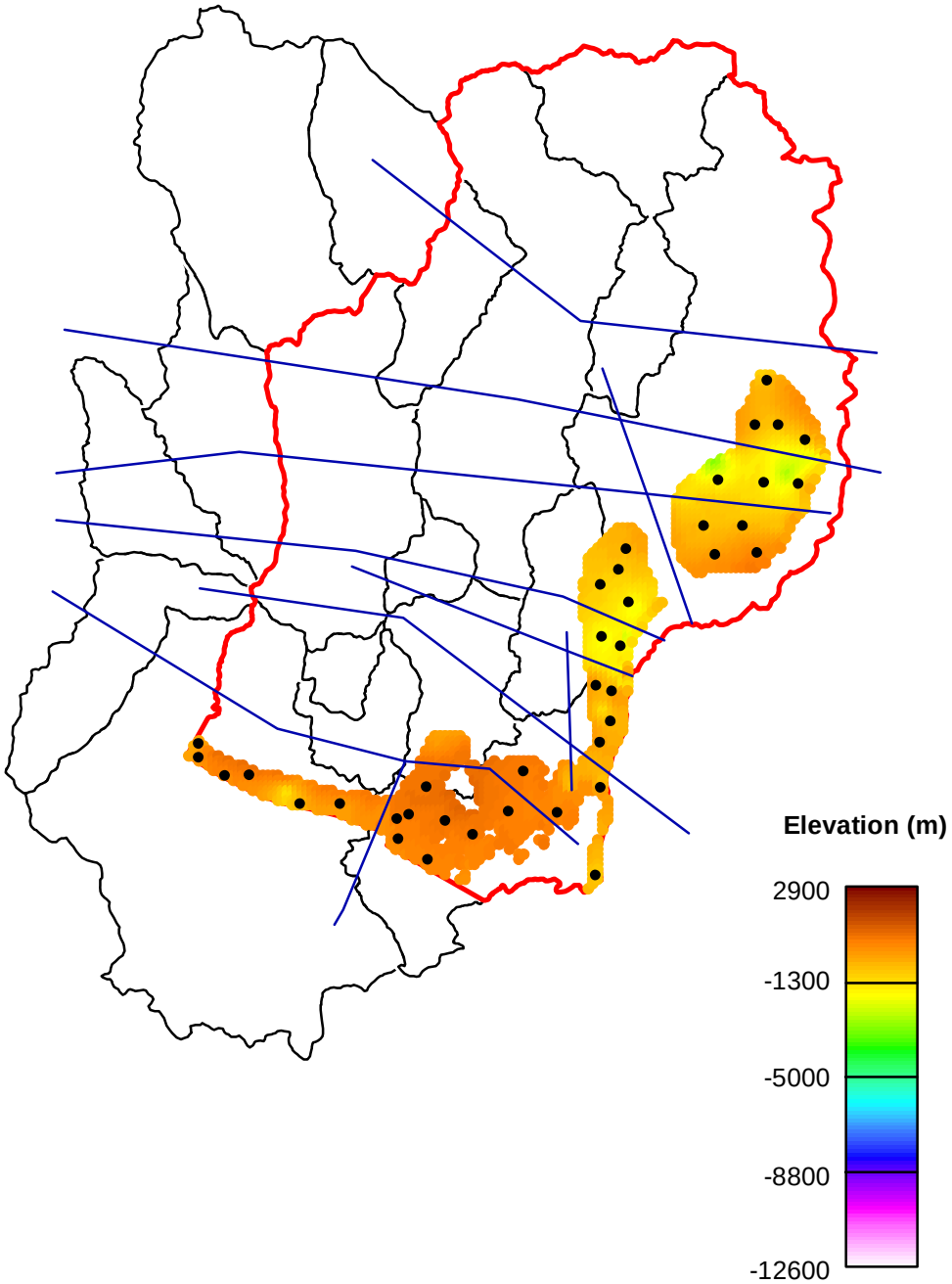
QCD



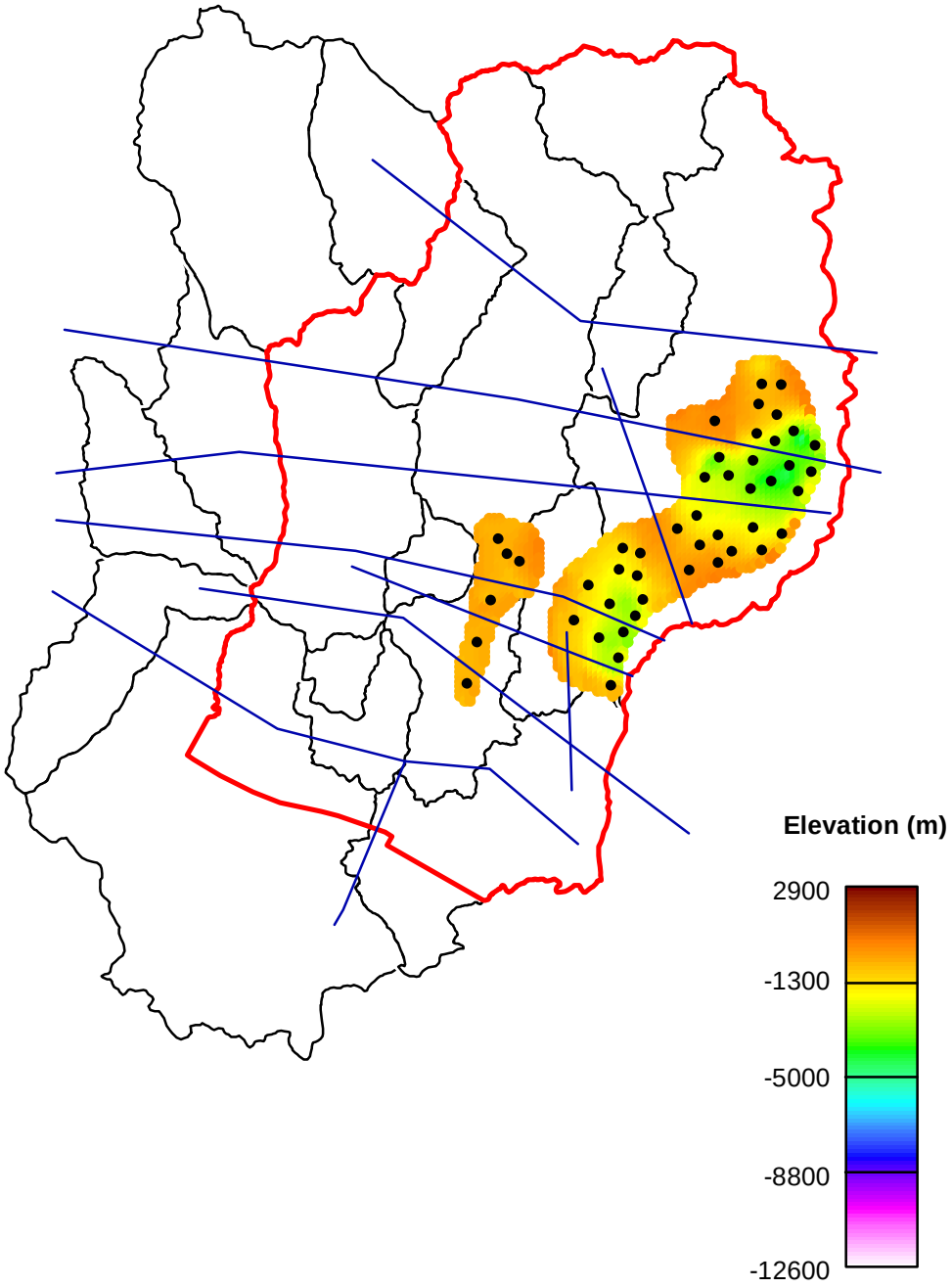
CAU



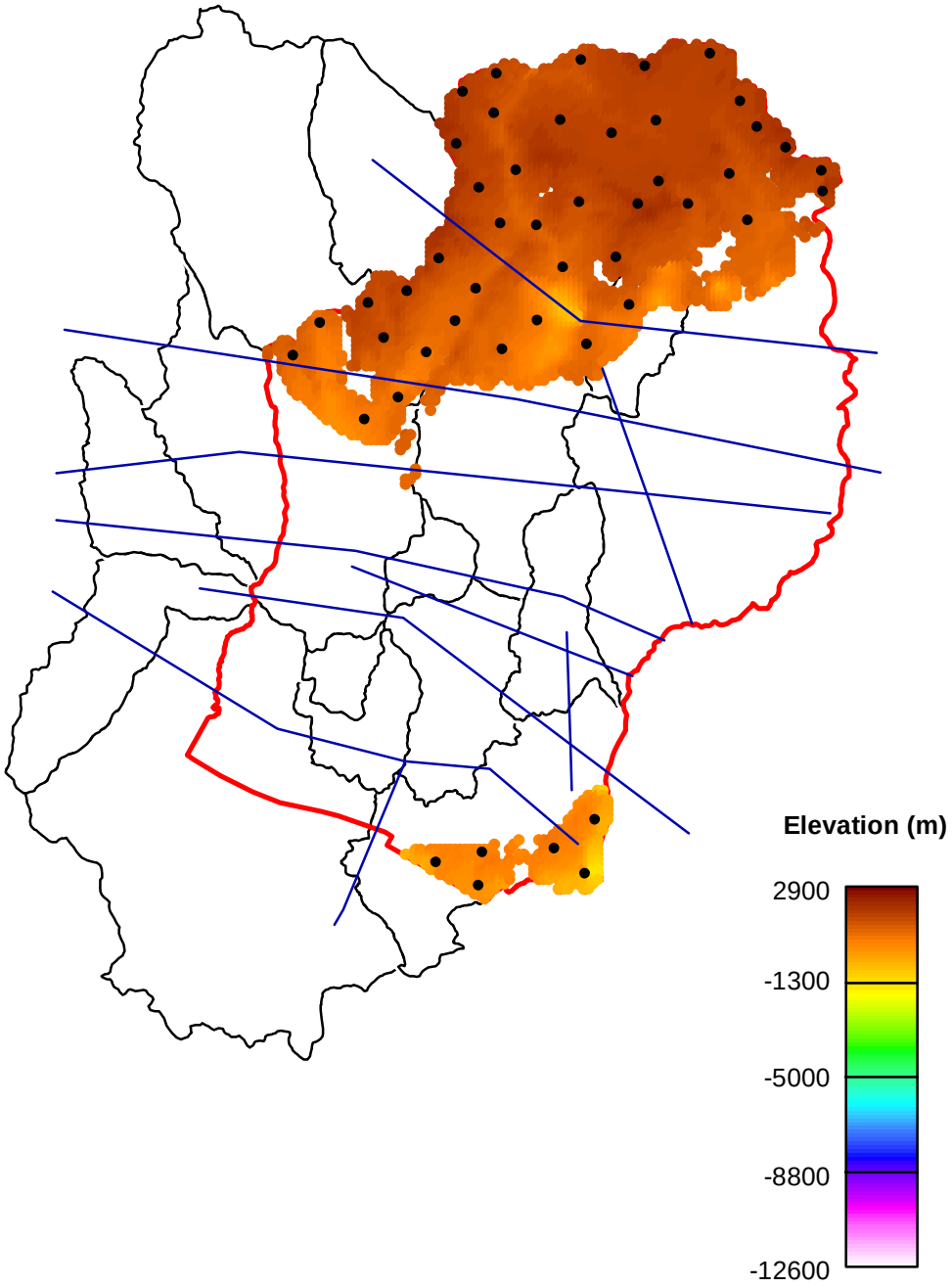
THS



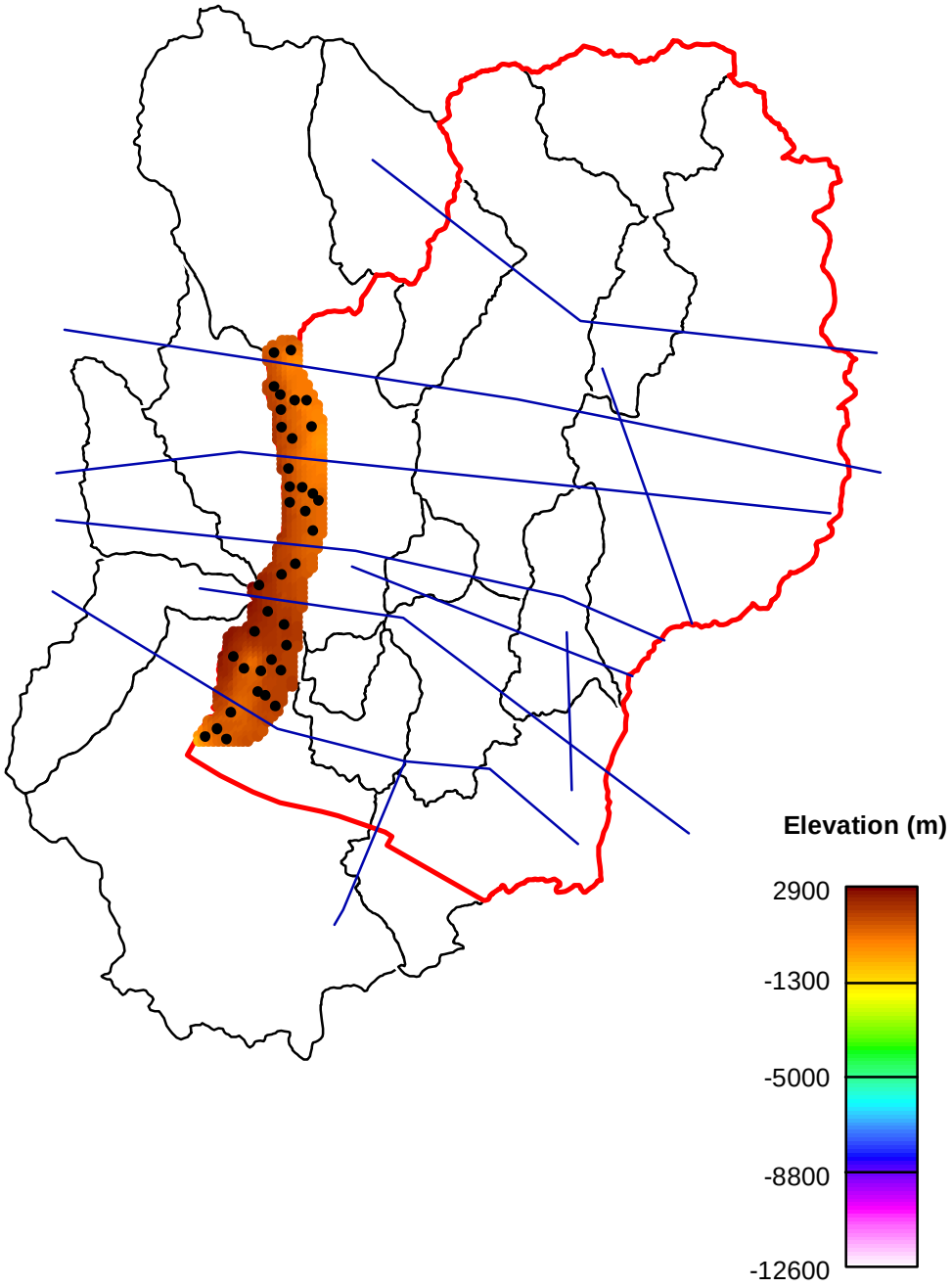
TAU



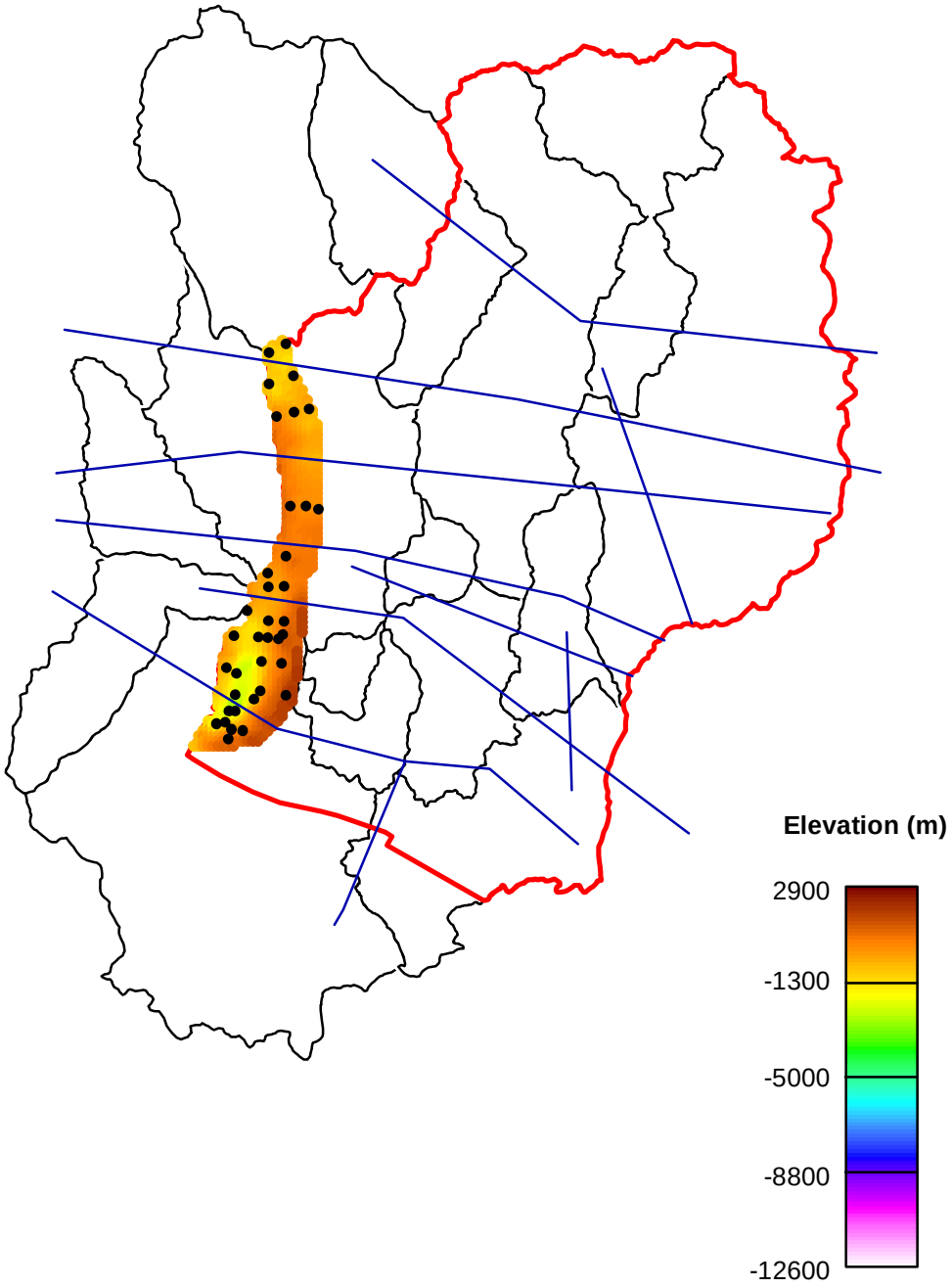
TVC



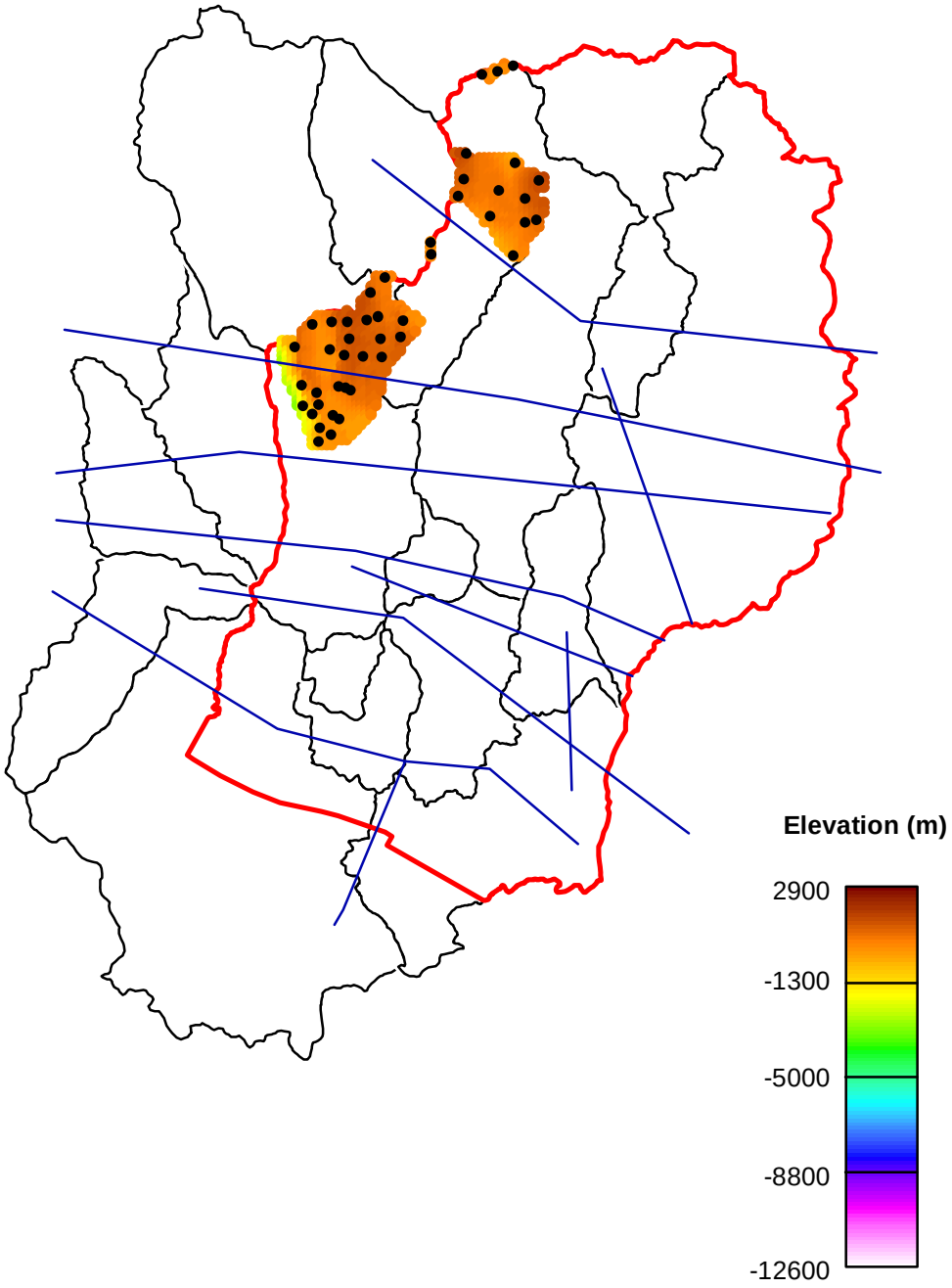
PC6



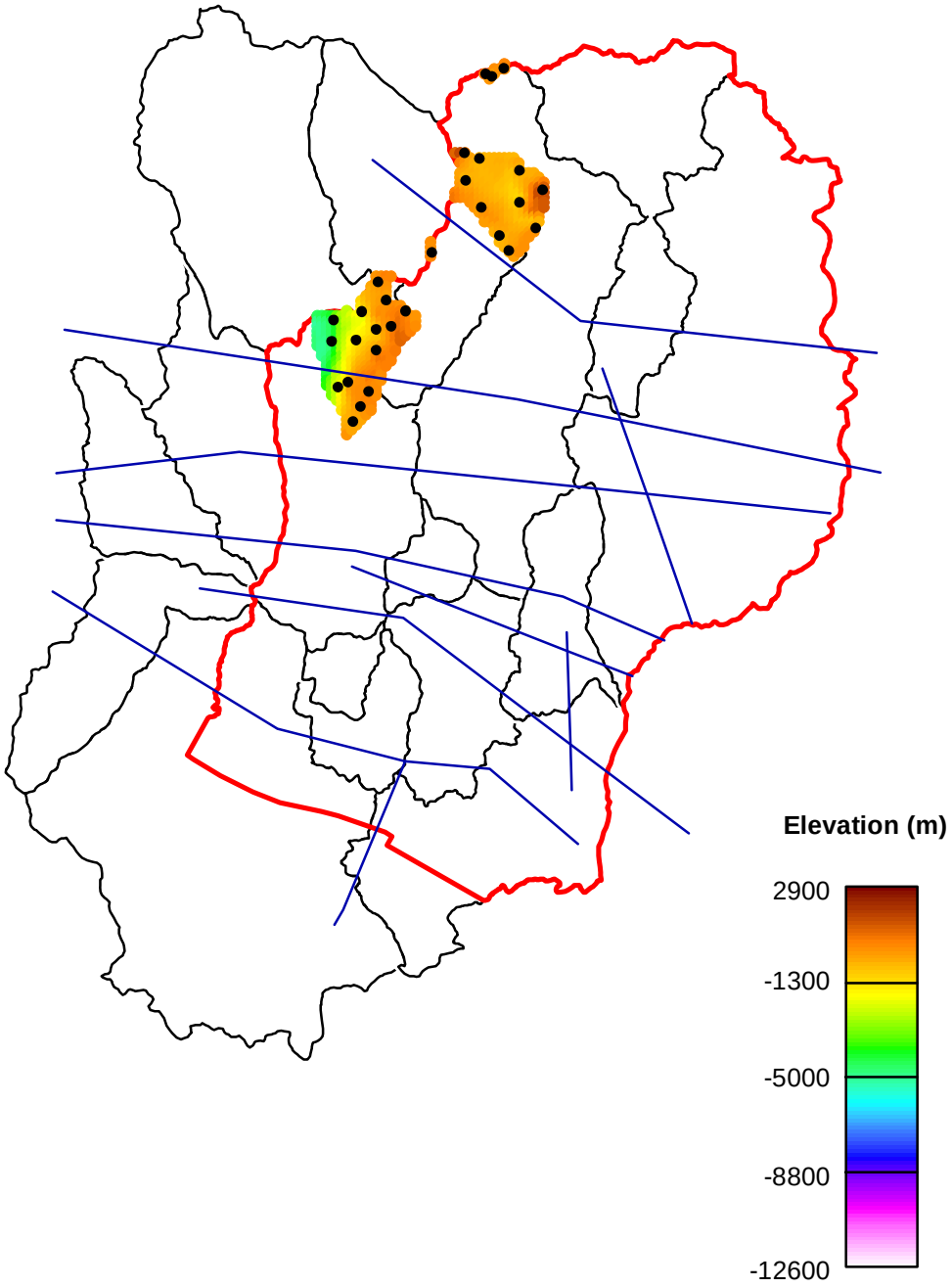
LC6



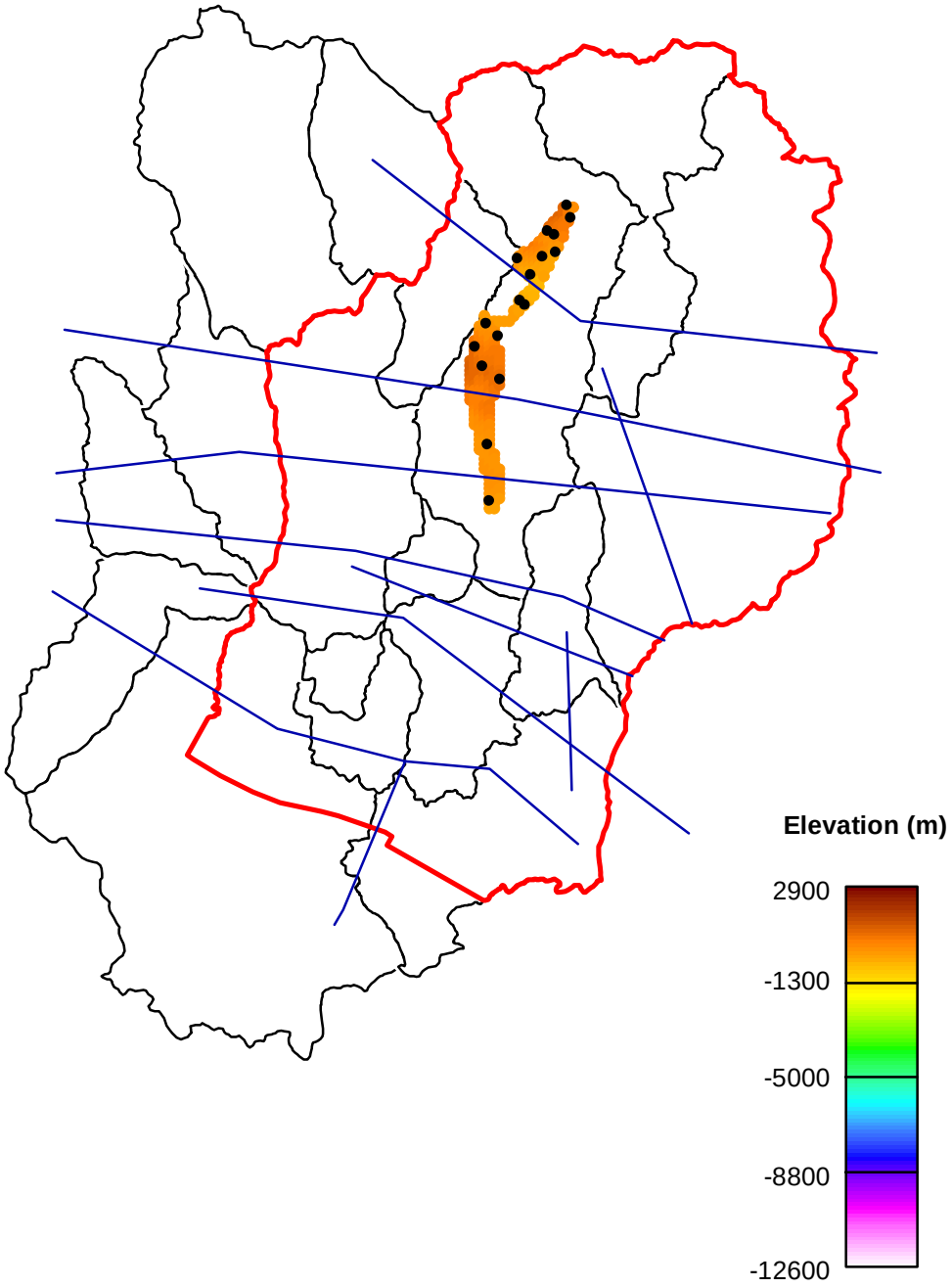
PC5



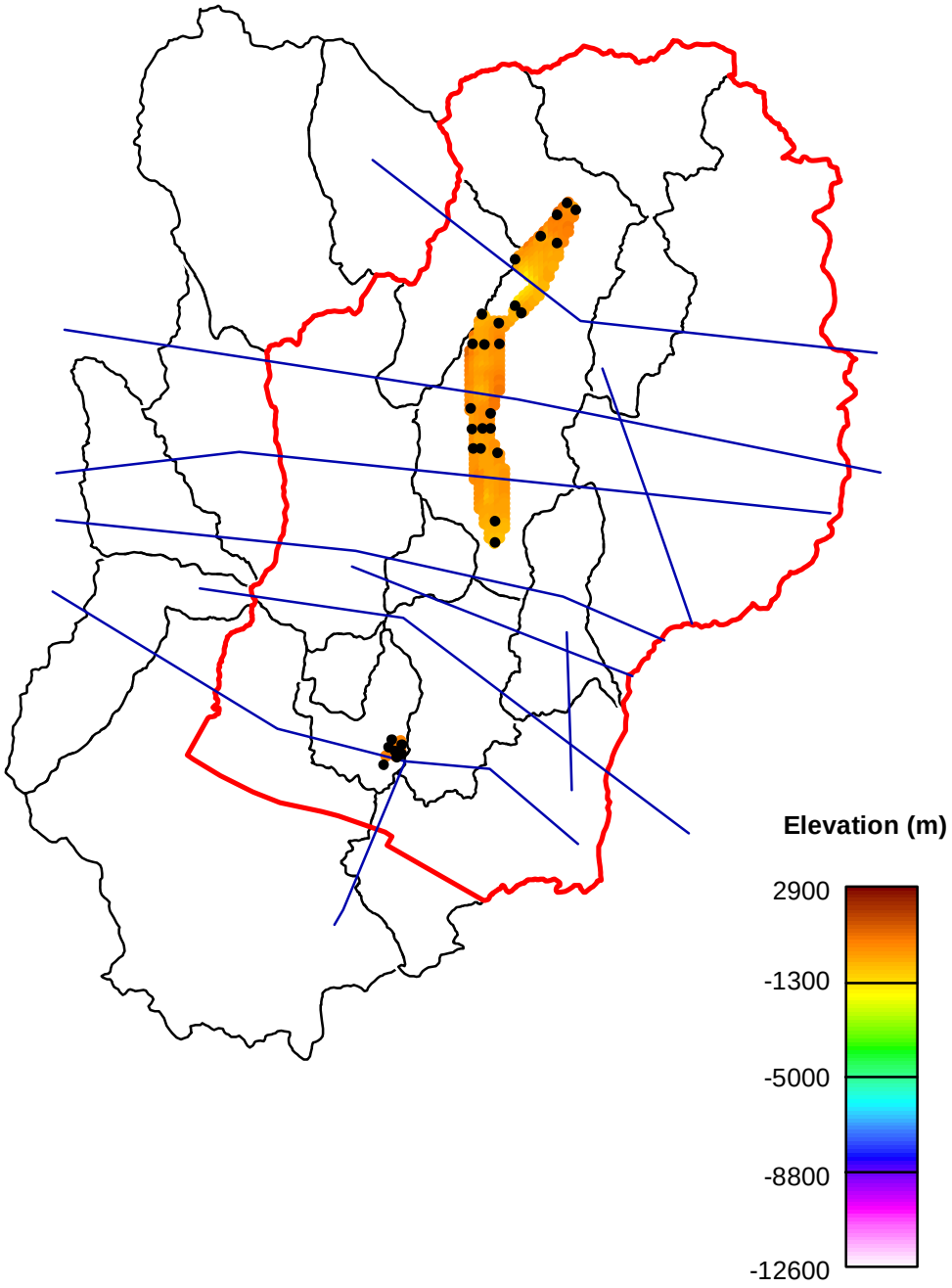
LC5



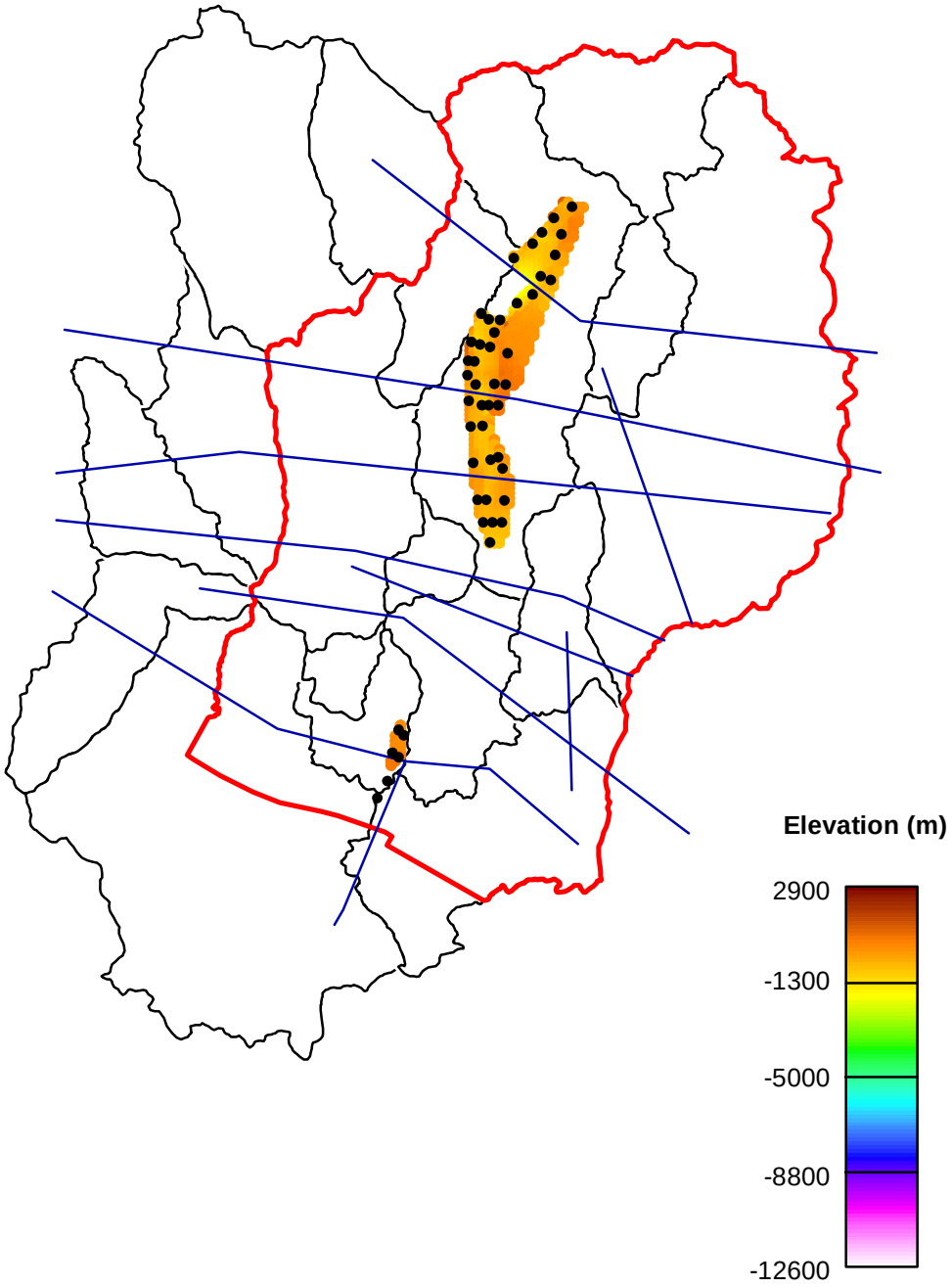
MU4



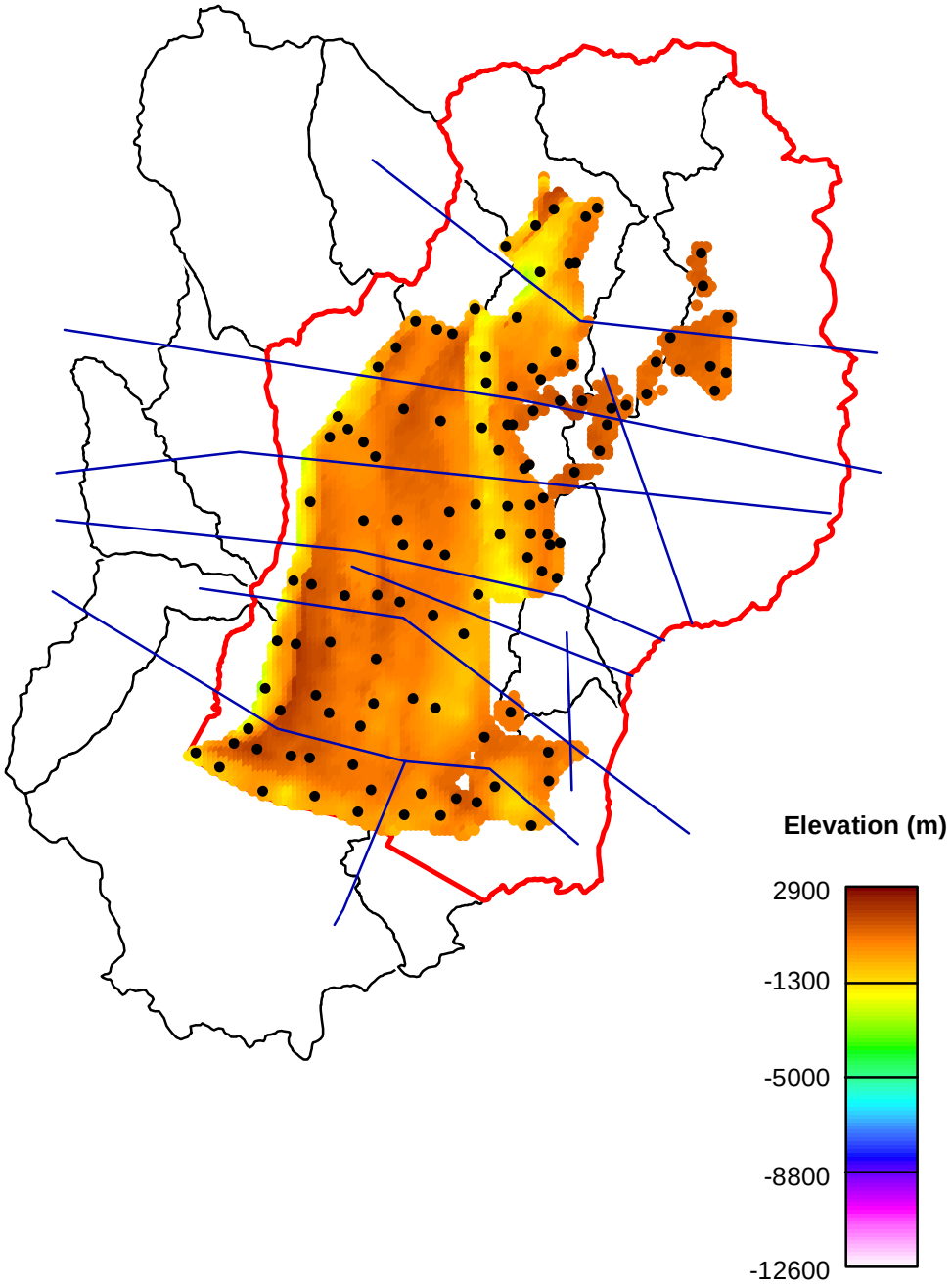
KT4



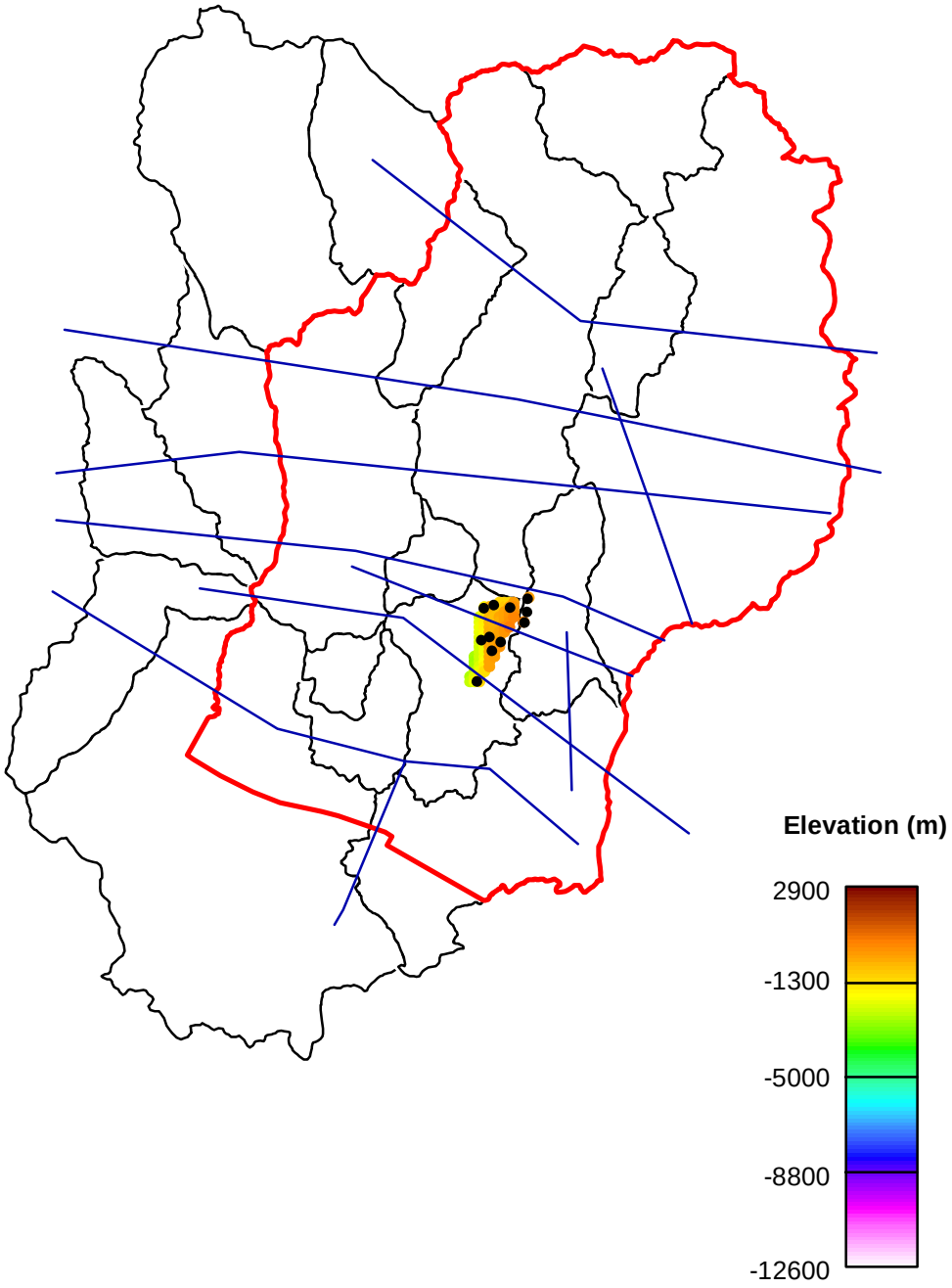
PR4



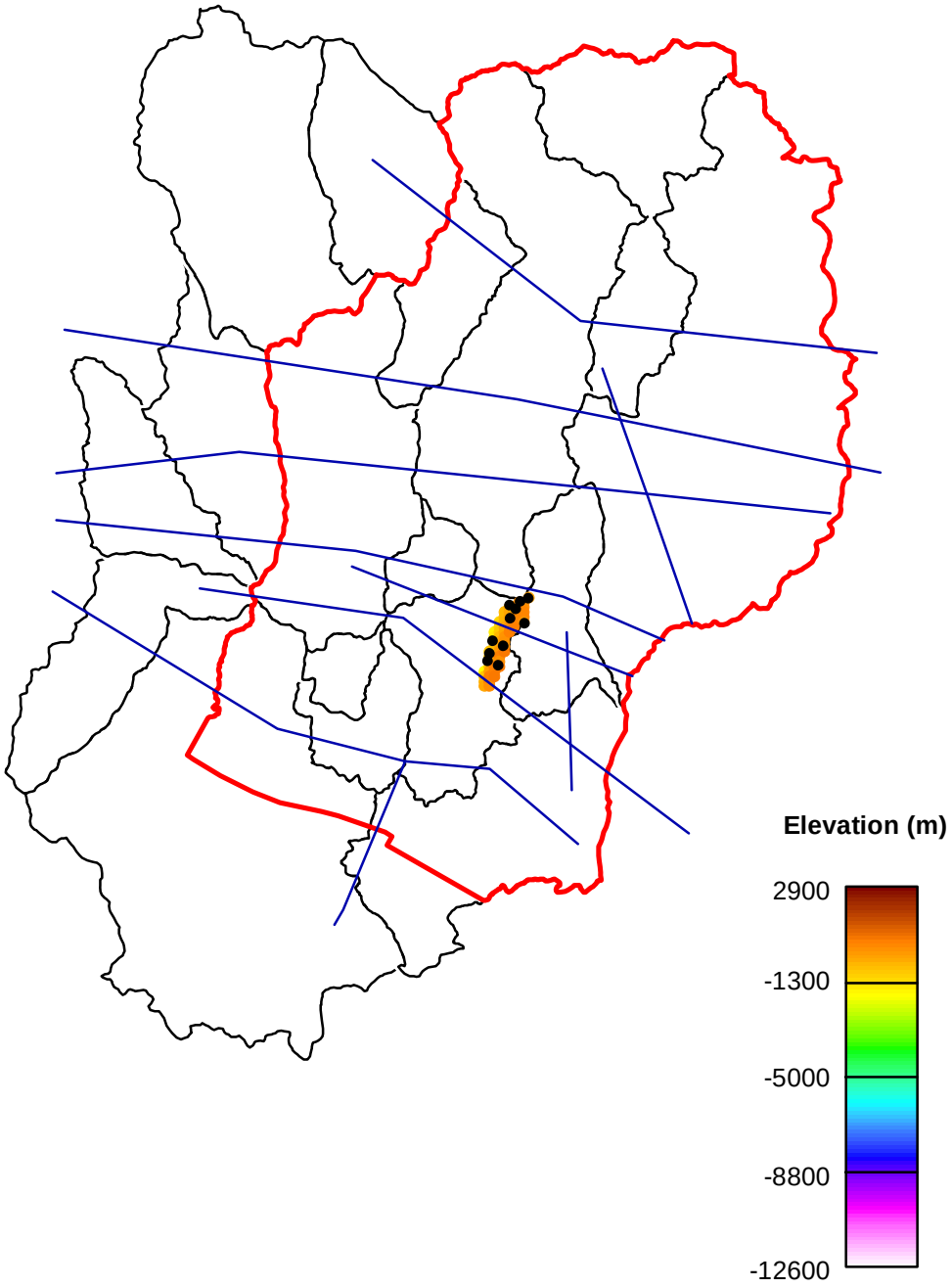
PC4



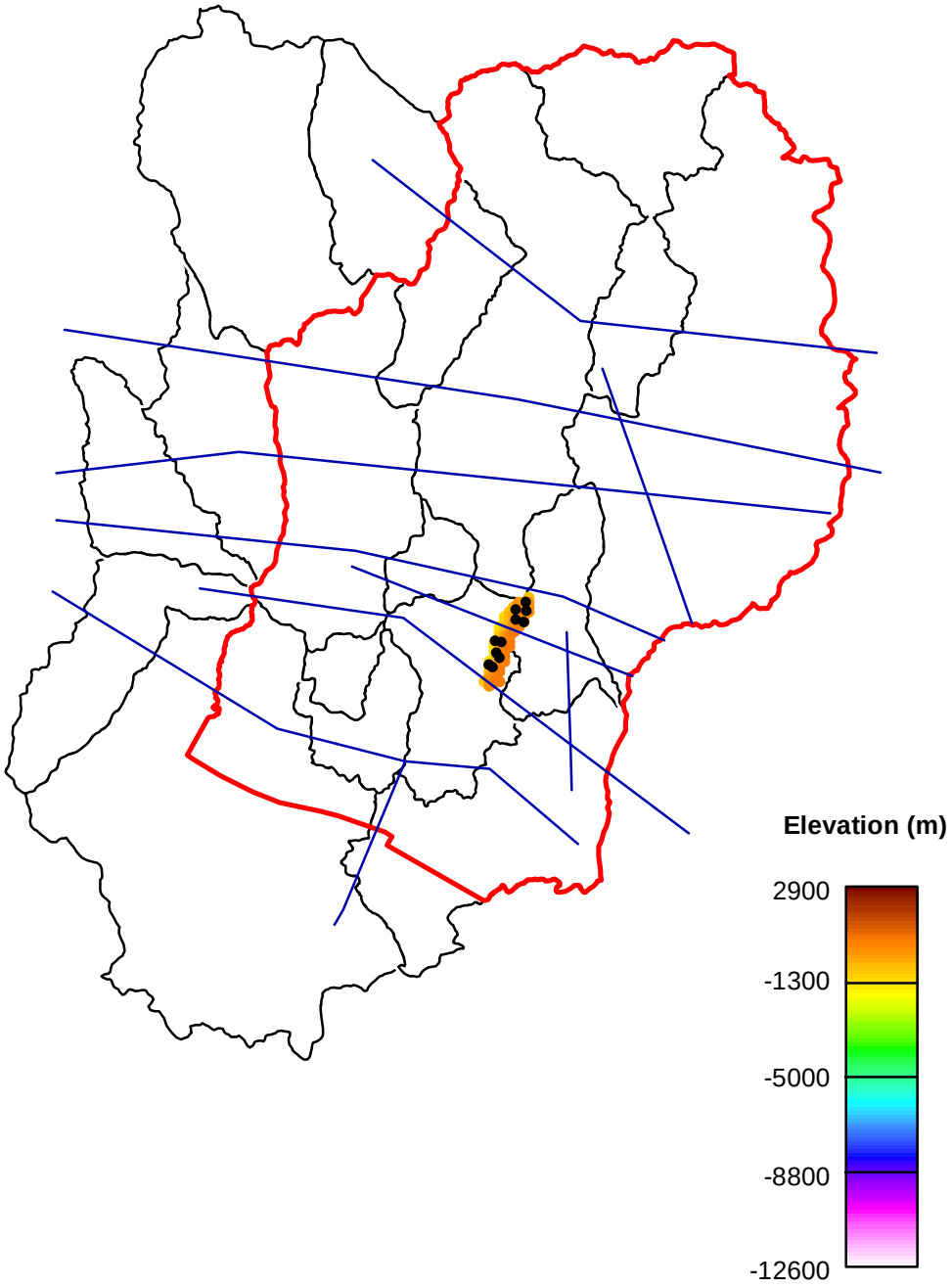
PC3



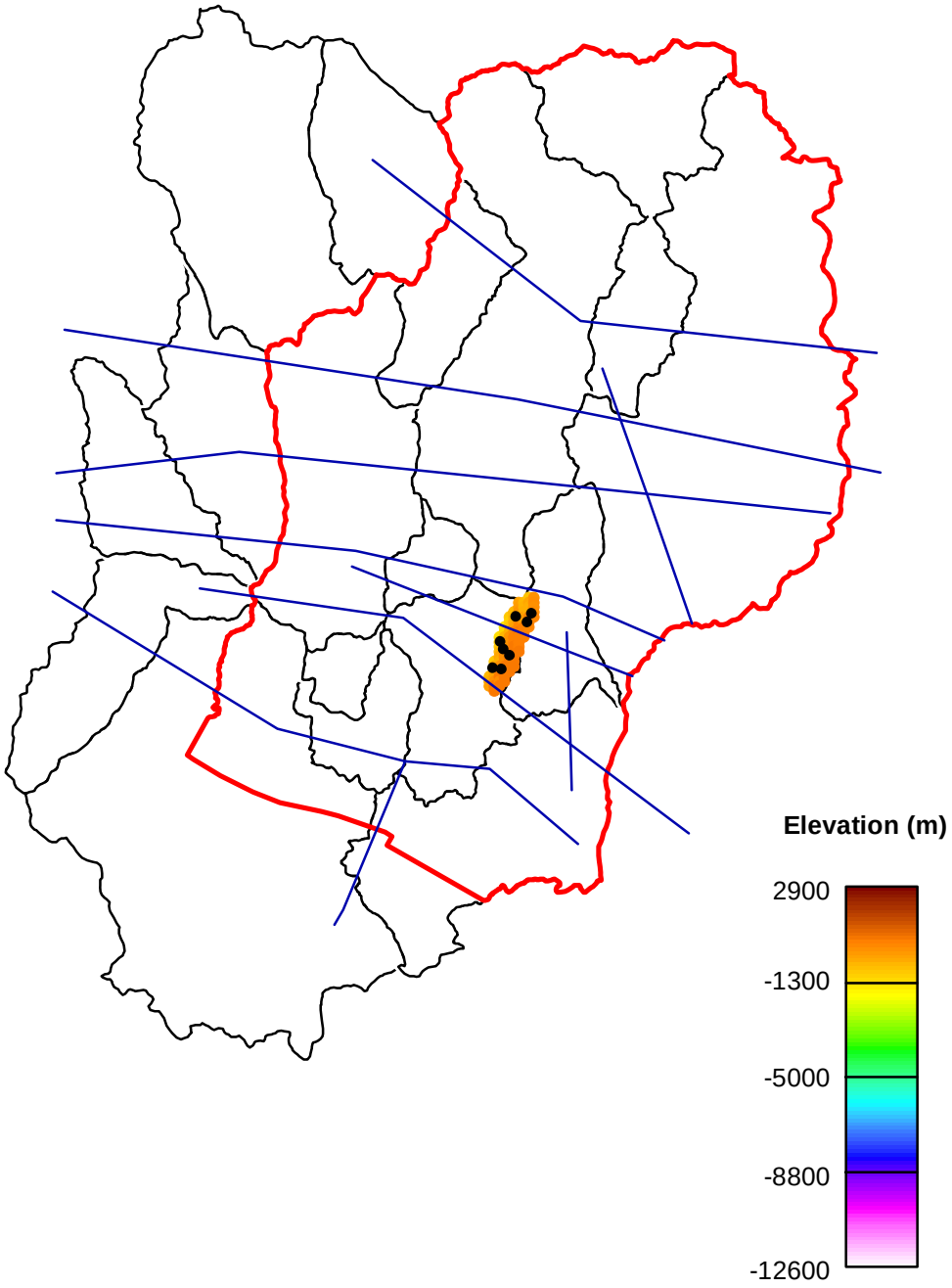
PR3



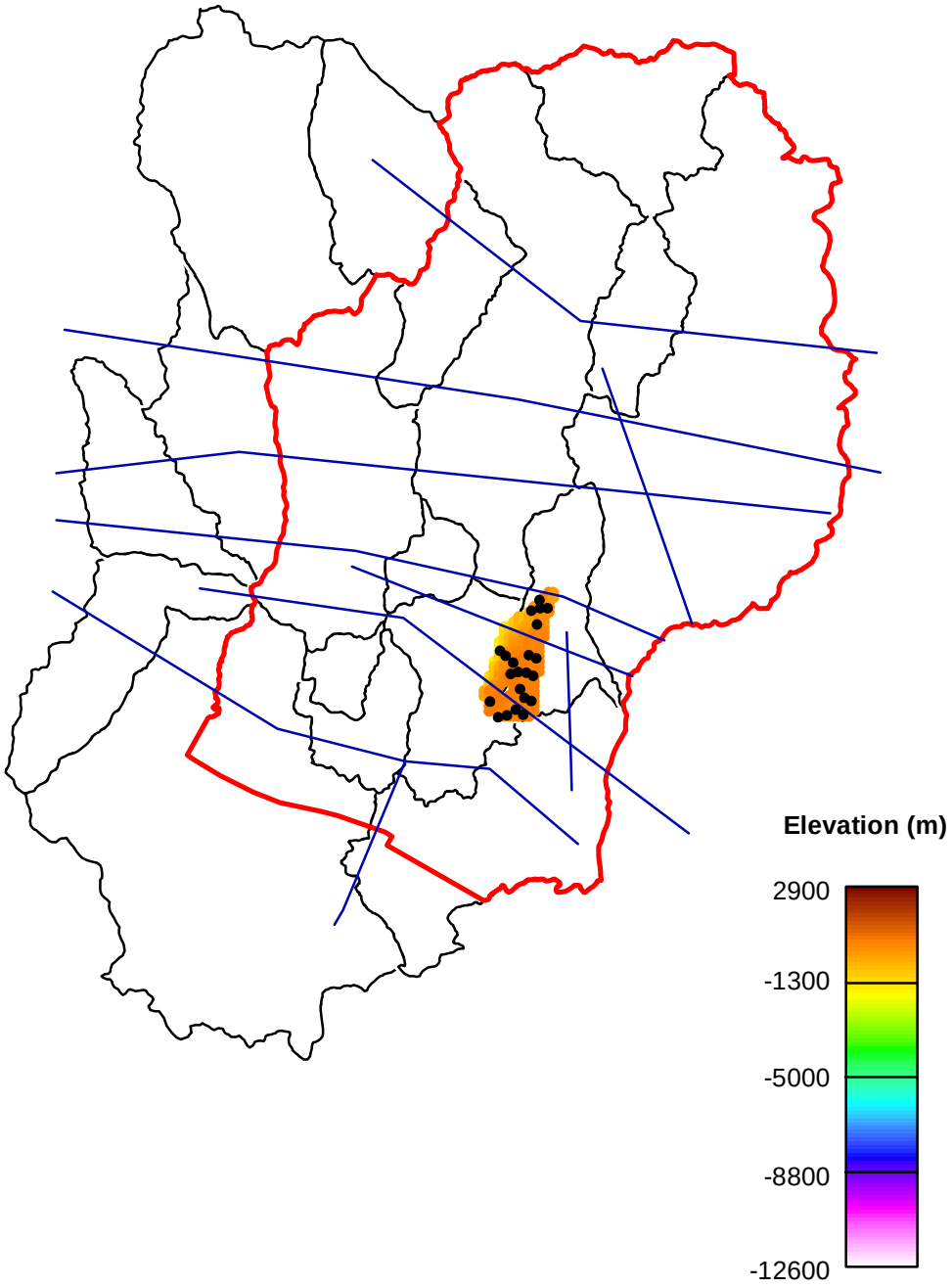
KT3



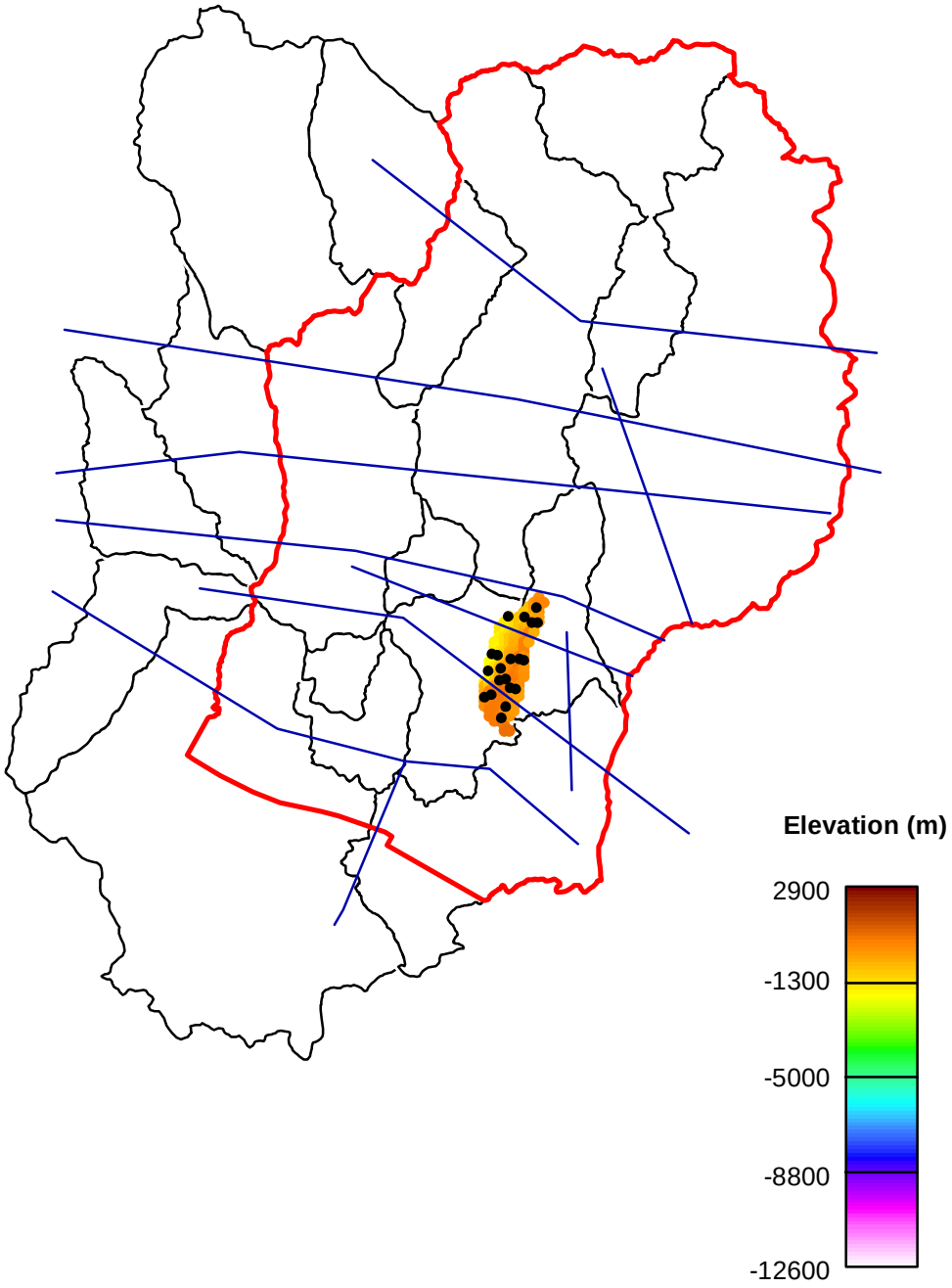
MU3



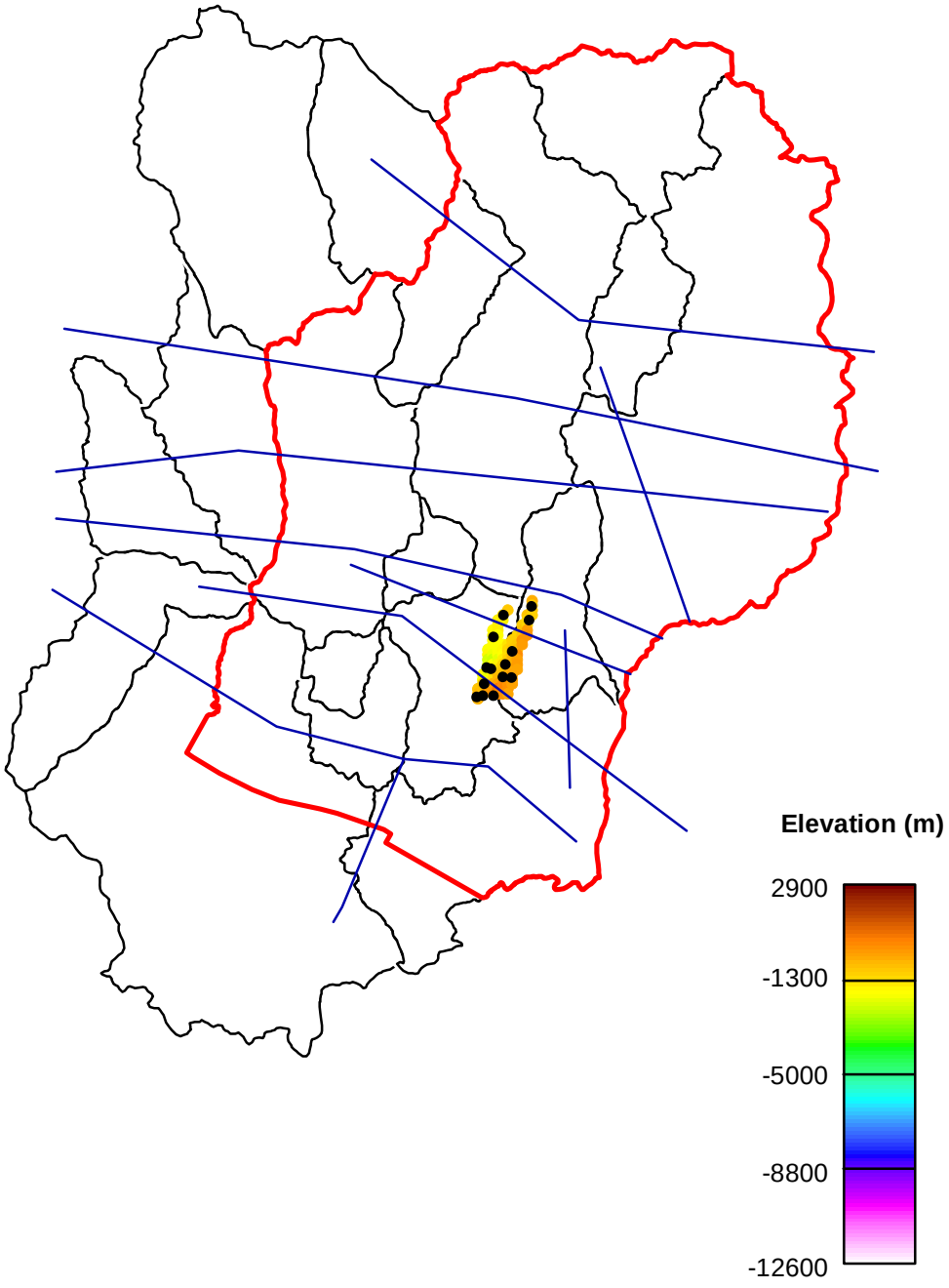
MU2



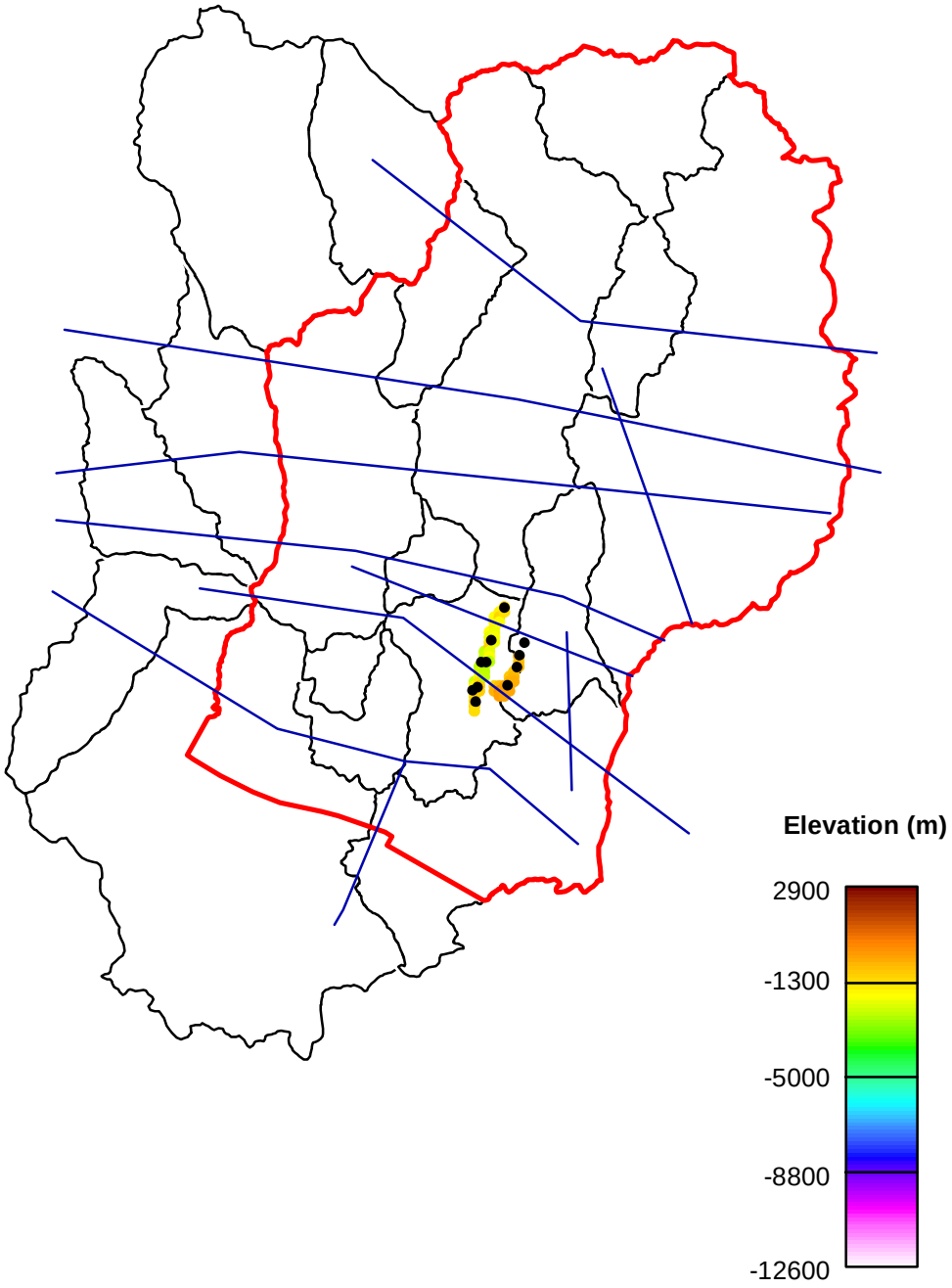
KT2



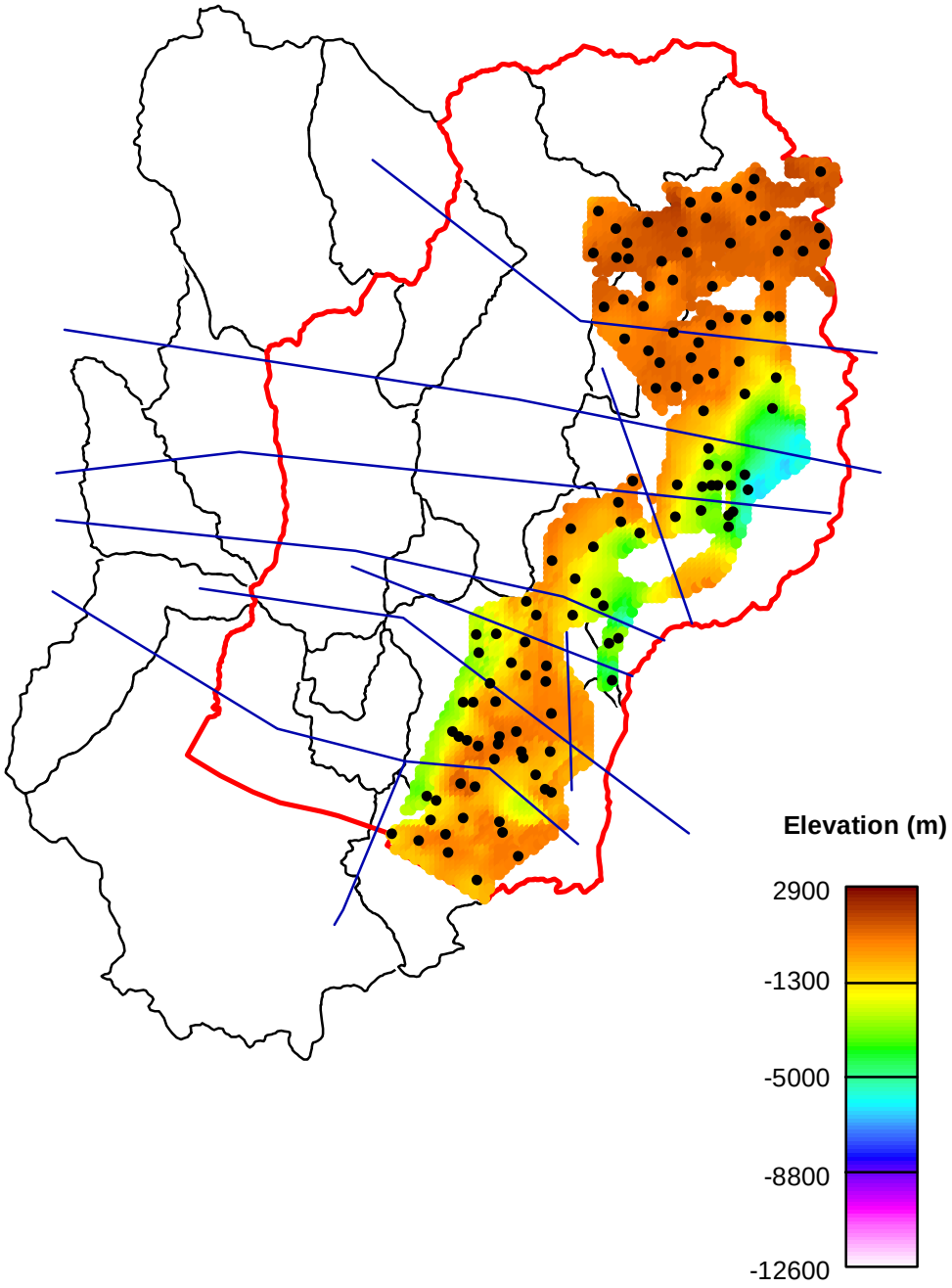
PR2



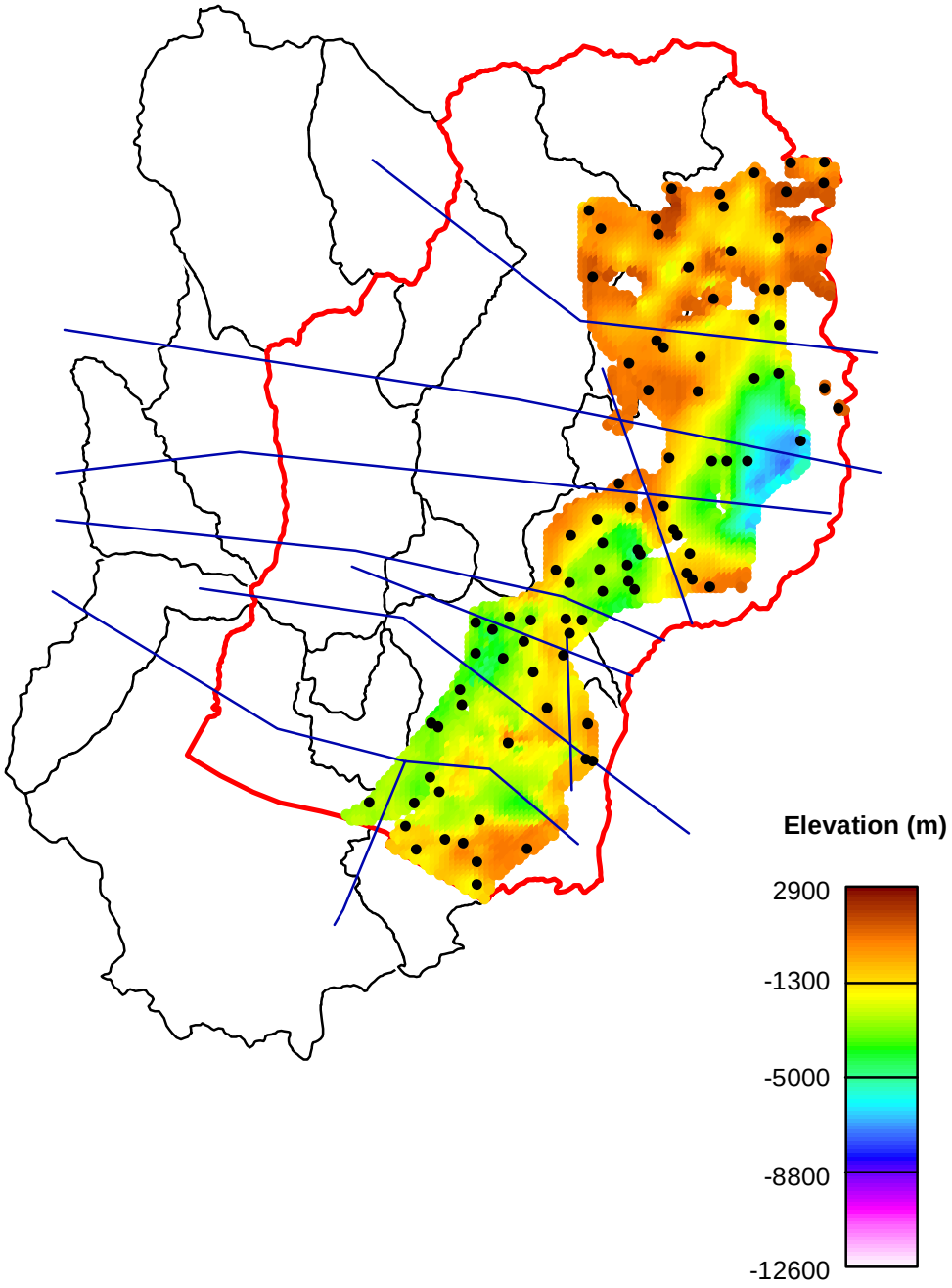
PC2



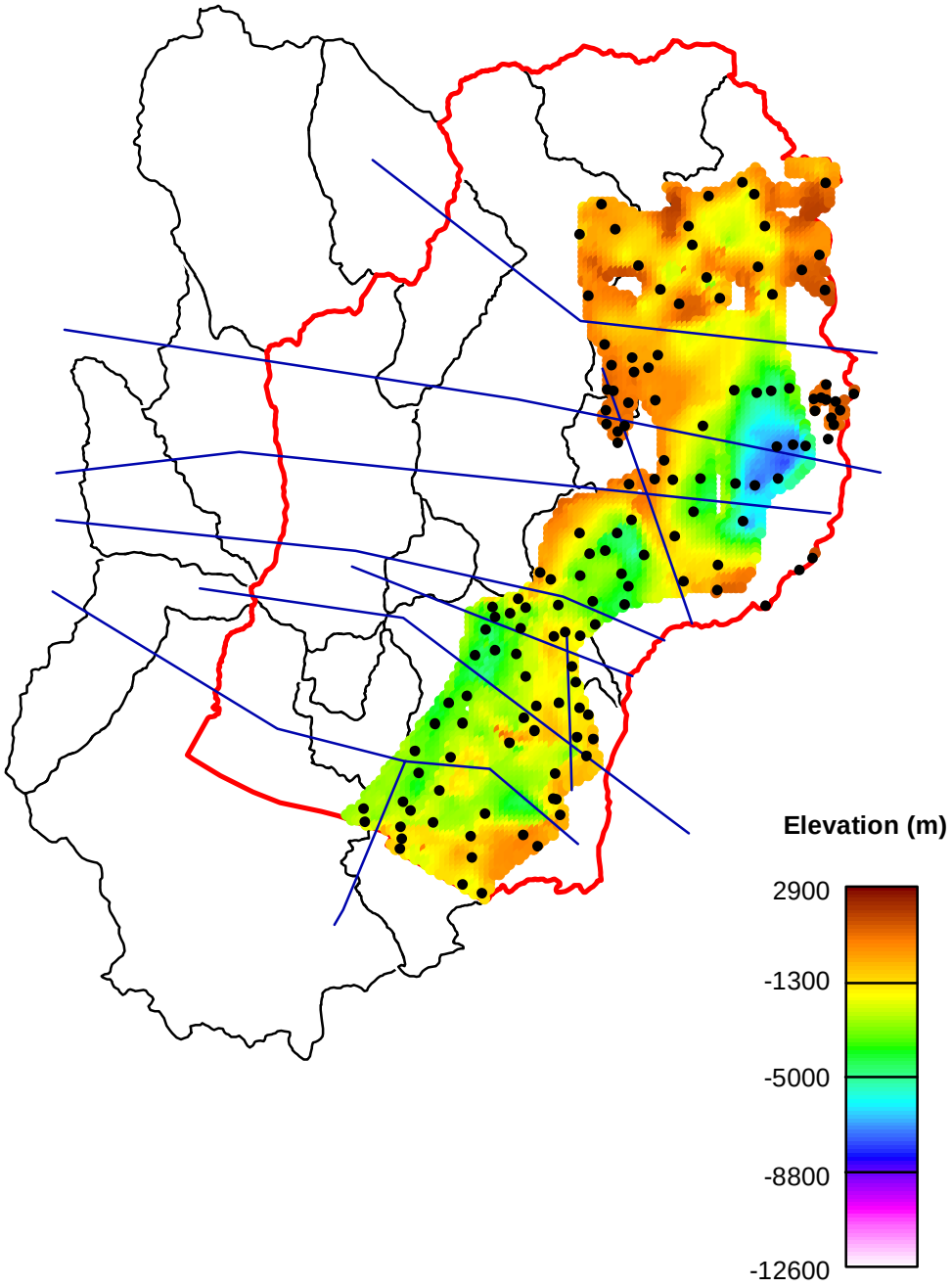
MU1



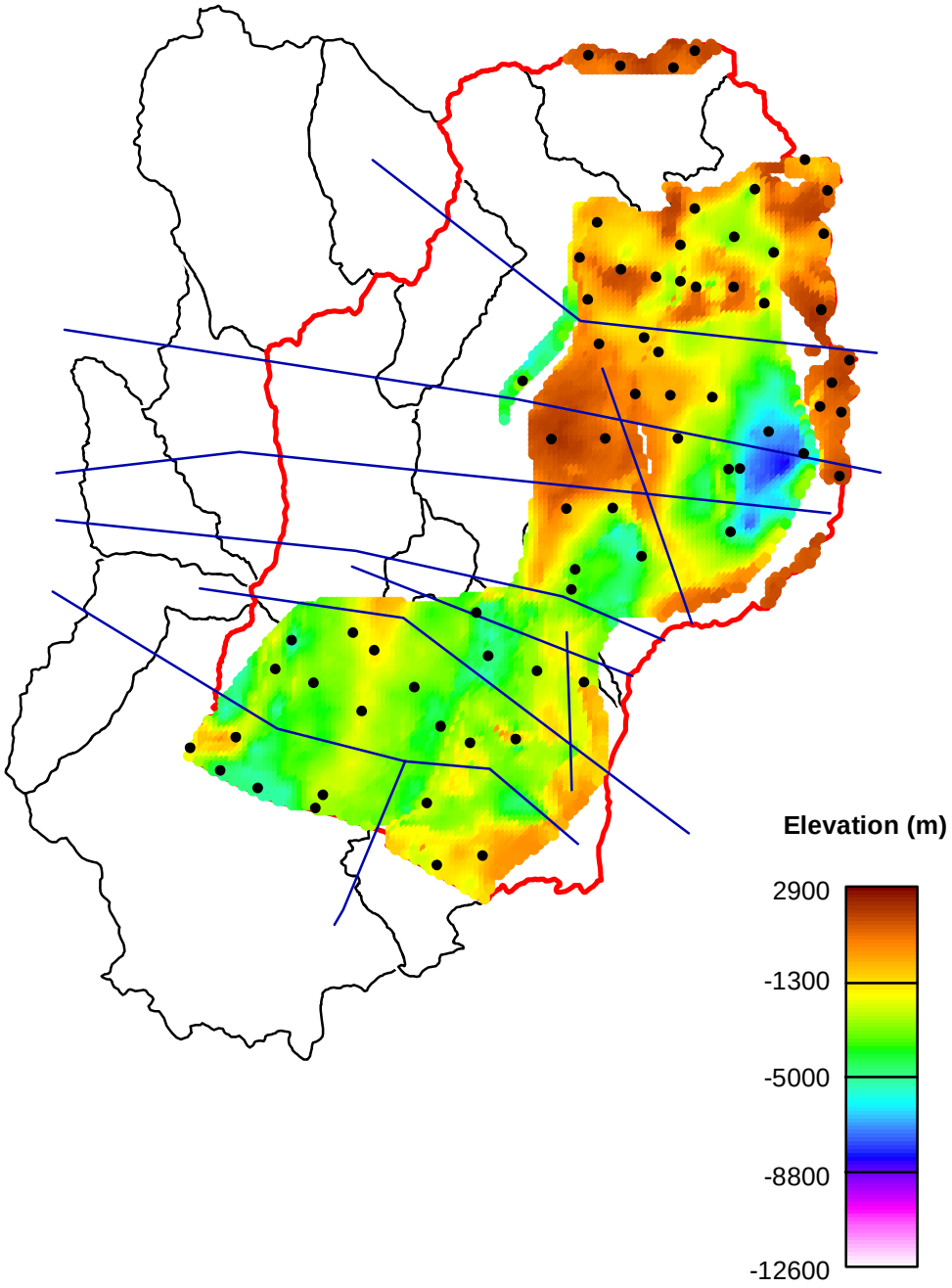
KT1



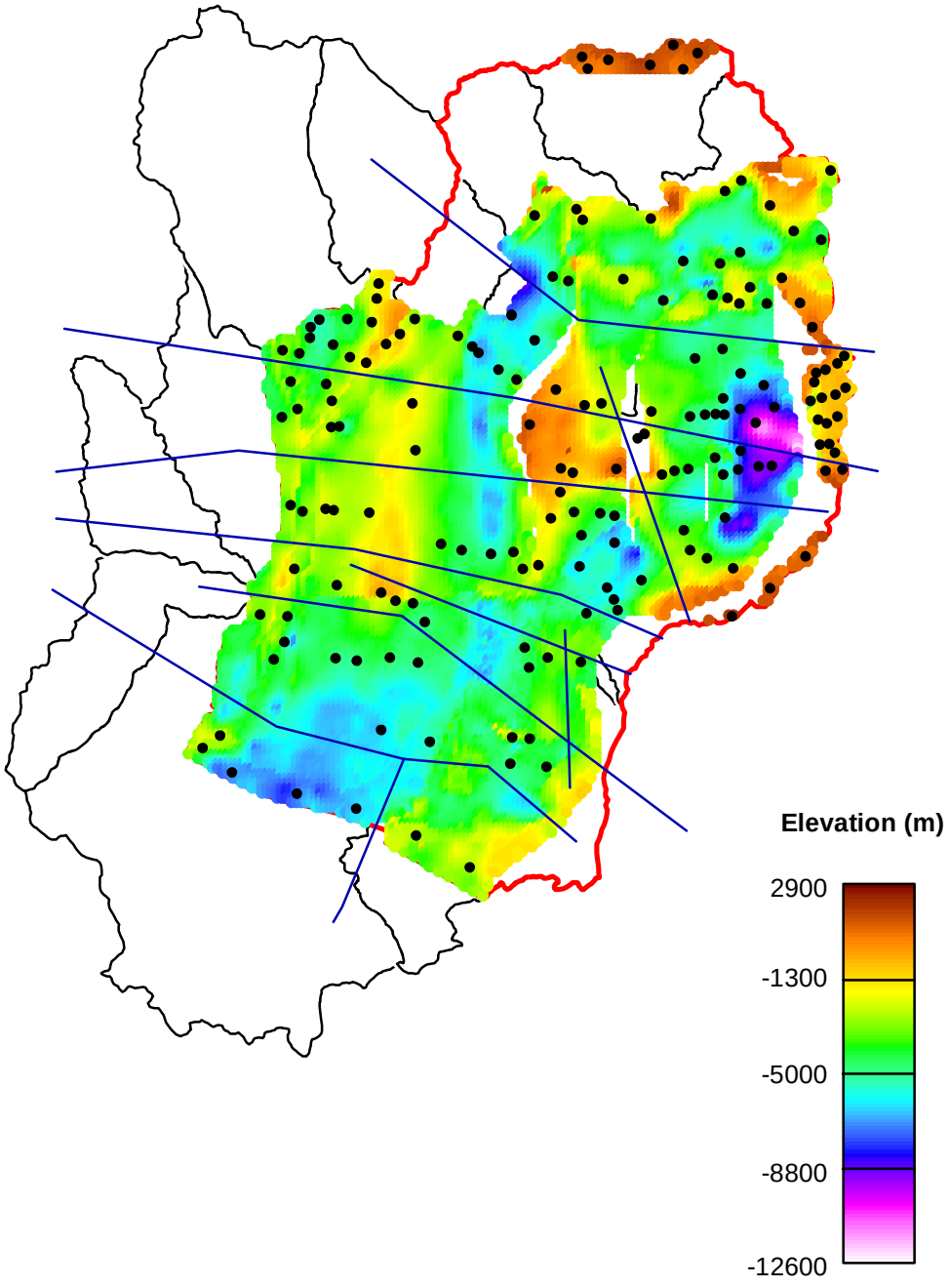
PR1



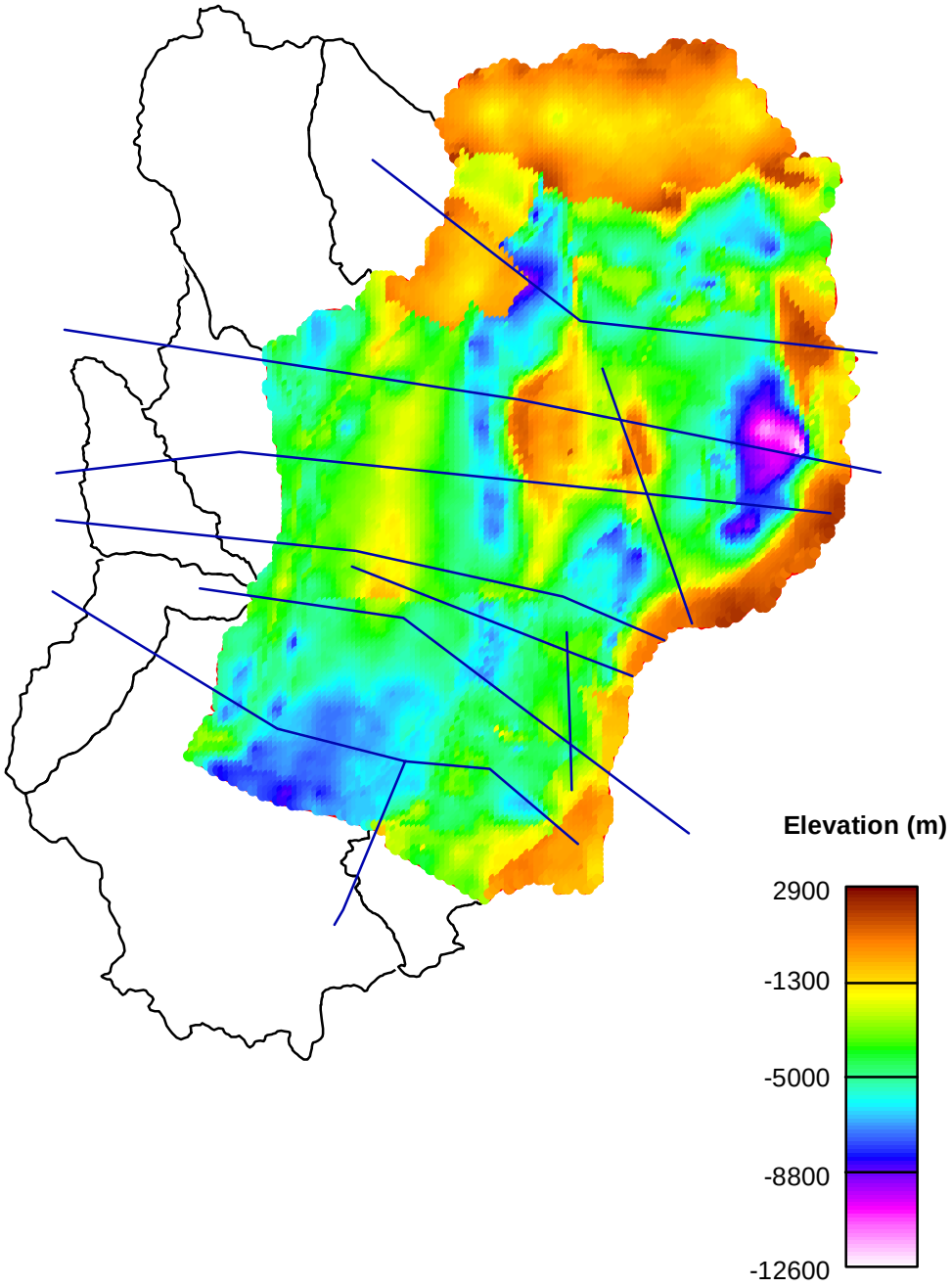
PC1



LC1

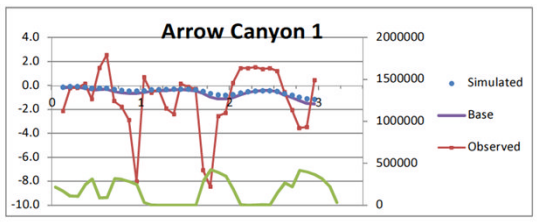


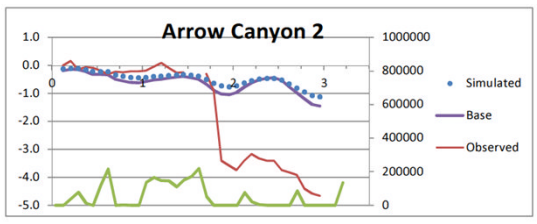
XLB

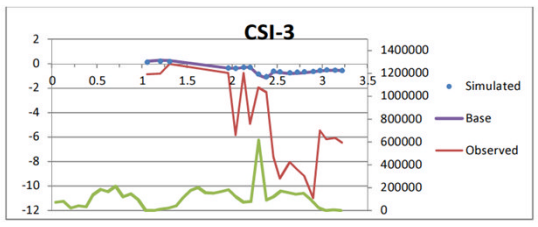


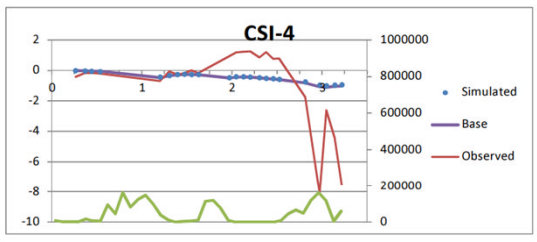
ATTACHMENT II

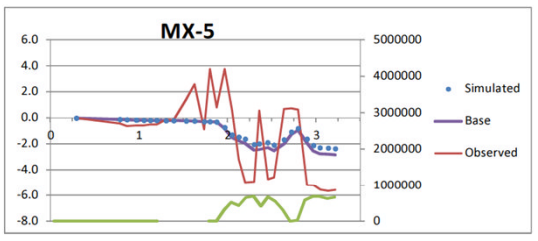
Sensitivity Testing – Simulated Drawdowns

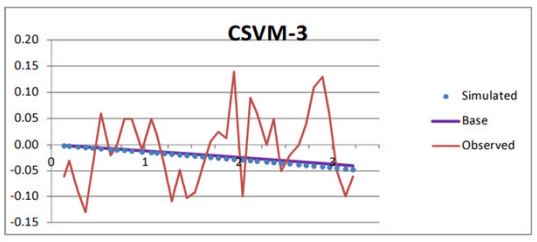


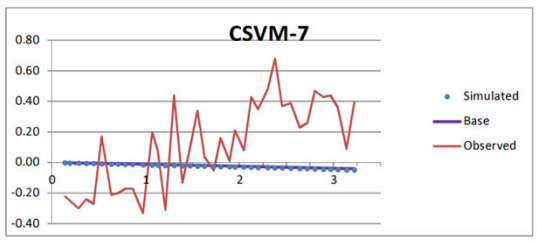


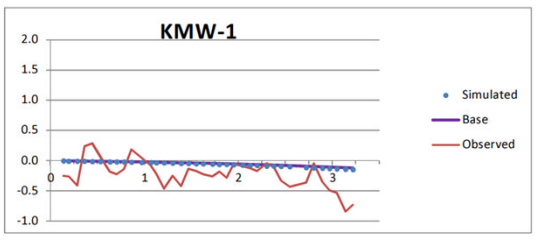


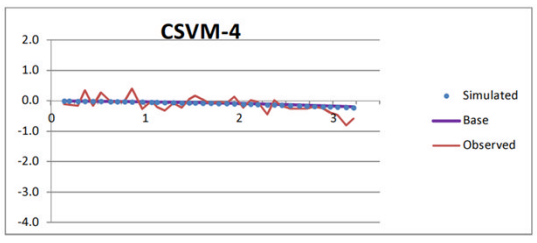


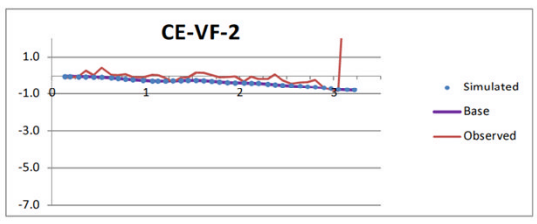


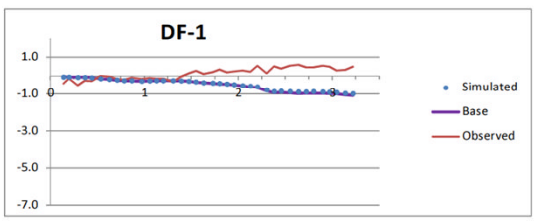


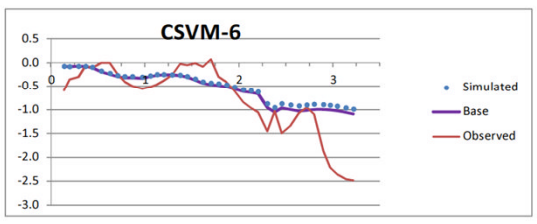


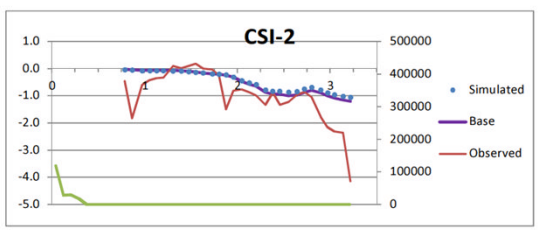


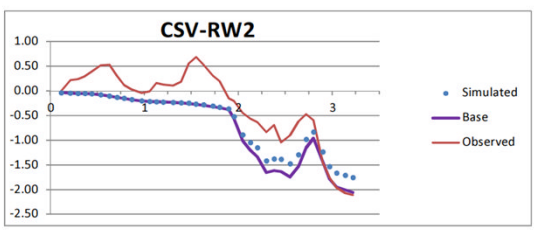


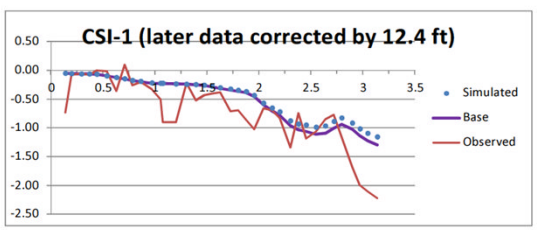


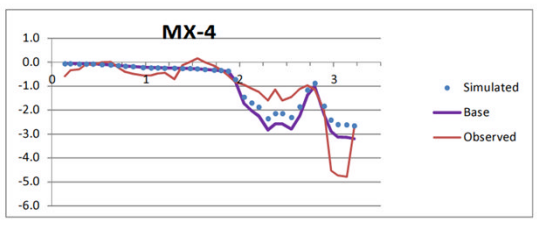


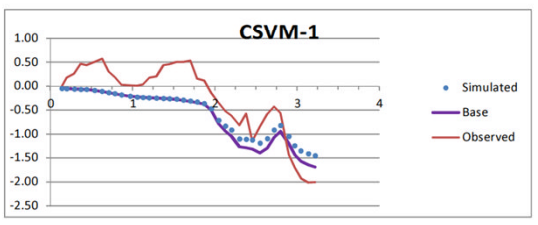


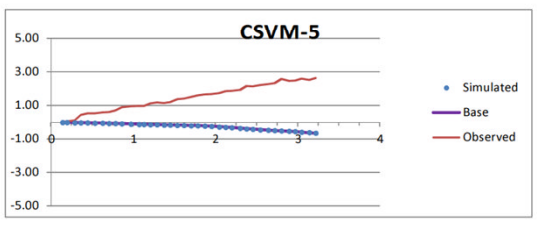


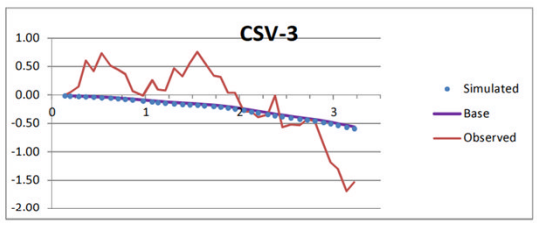


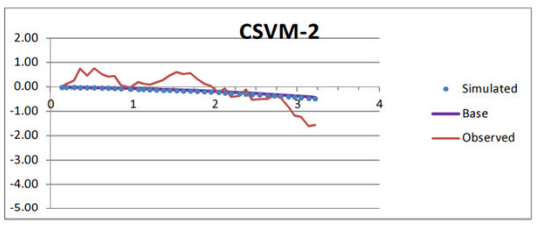


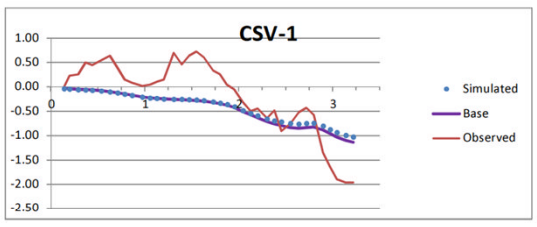


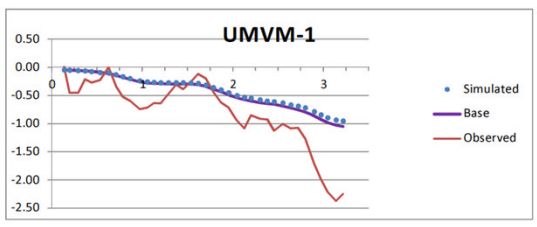


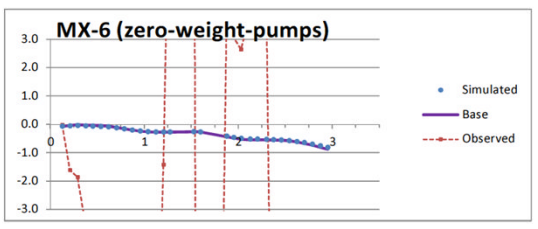


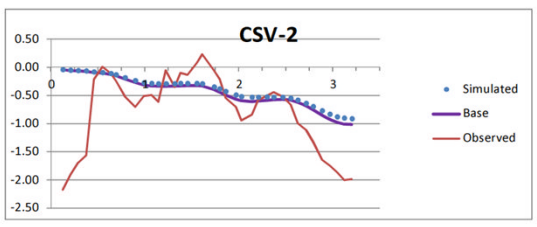


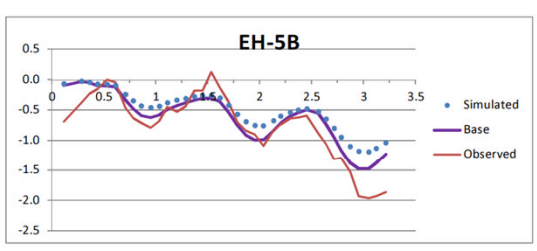


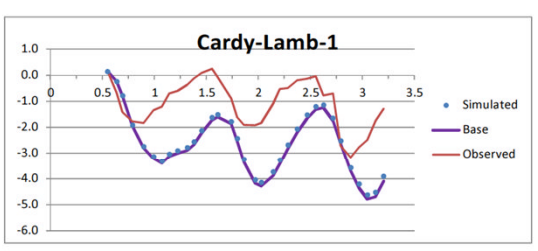


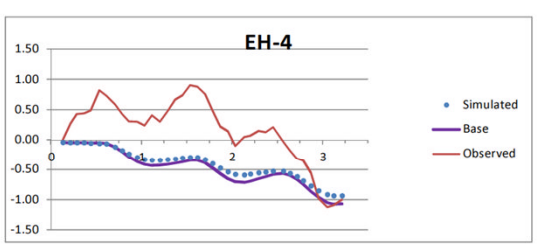


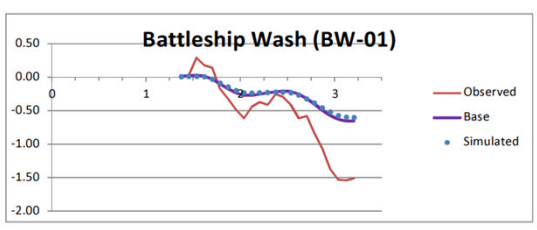


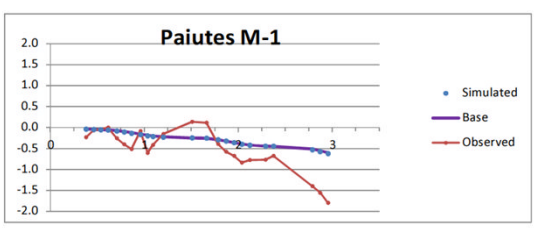


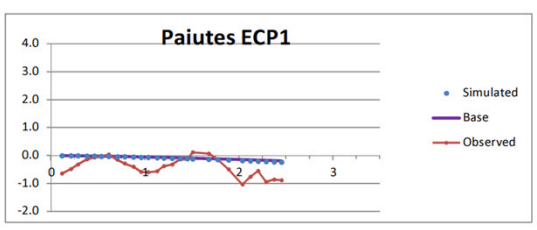


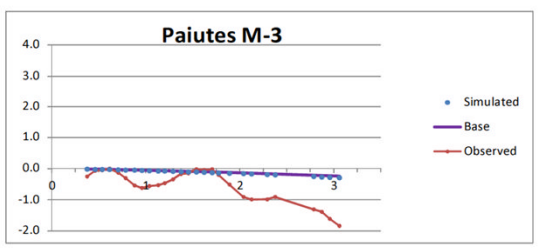


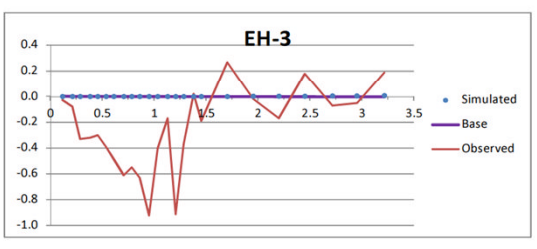


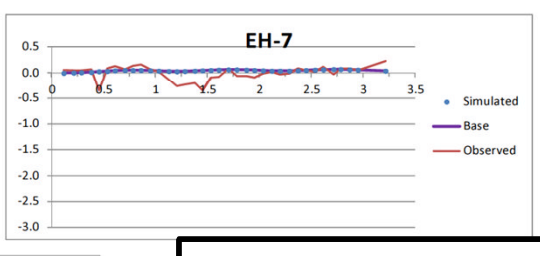


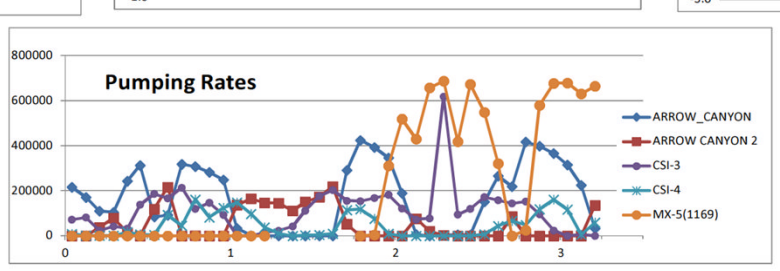








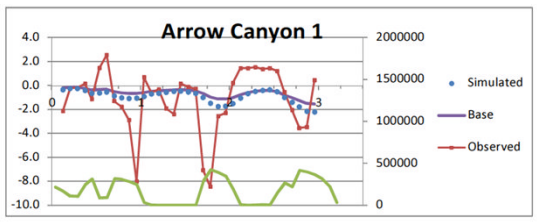


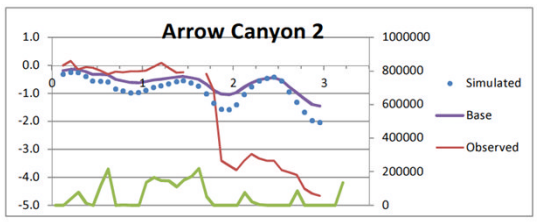


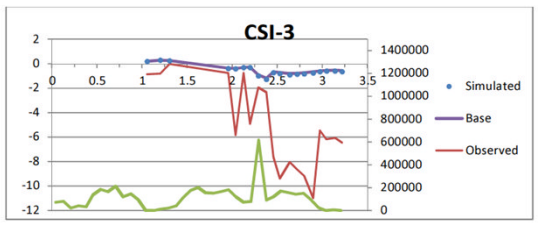
Sensitivity of Simulated Drawdown to Multiplying K_PC4_1 by 2

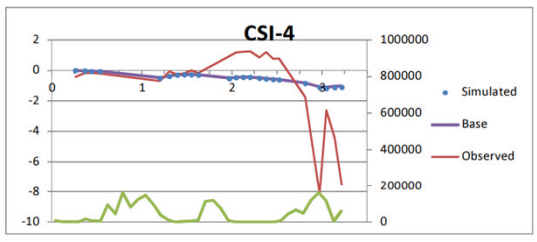
Lower Colorado River Flow System

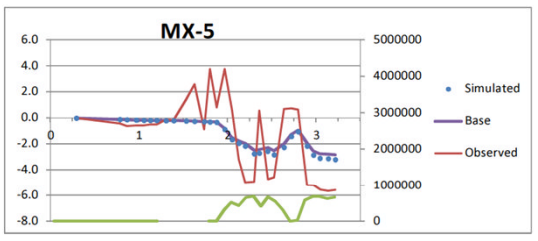
TETRA TECH GEO

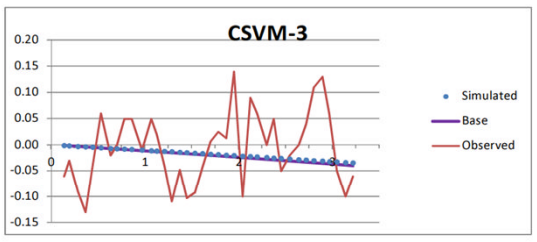


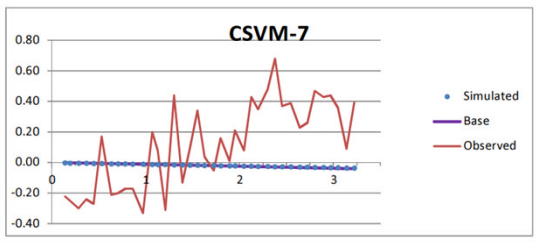


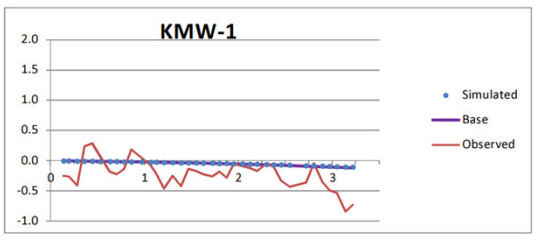


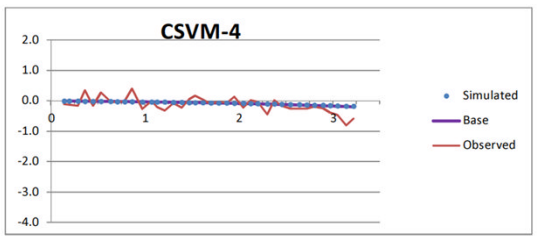


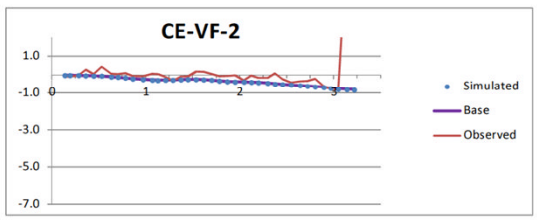


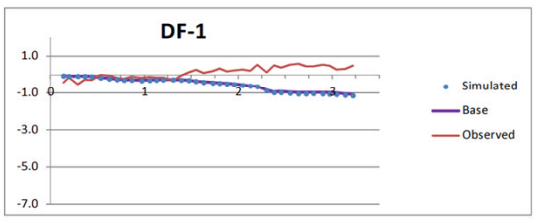


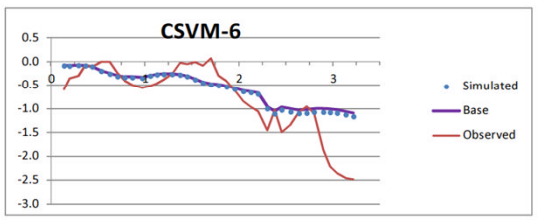


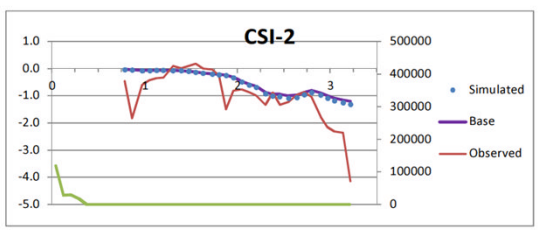


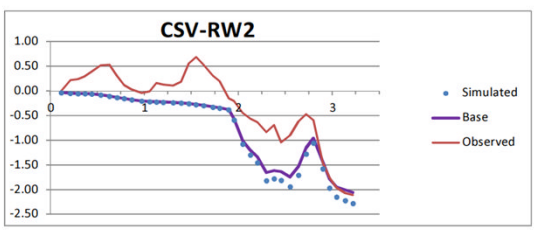


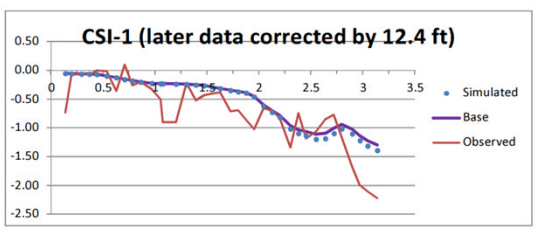


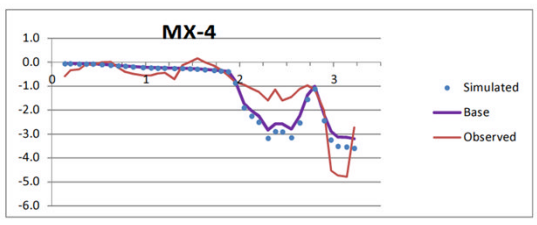


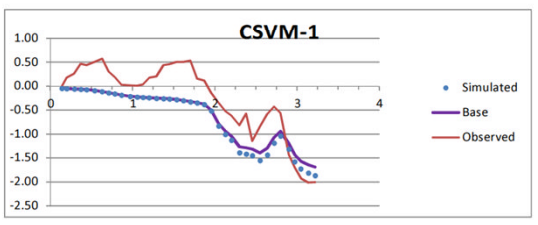


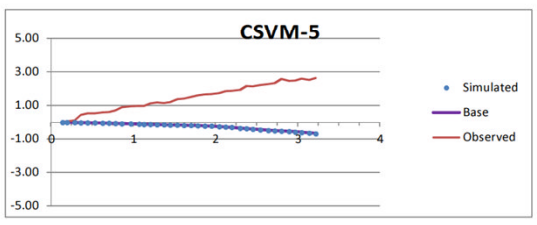


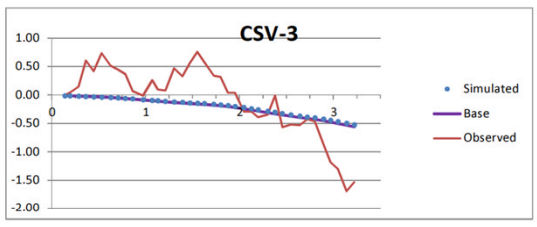


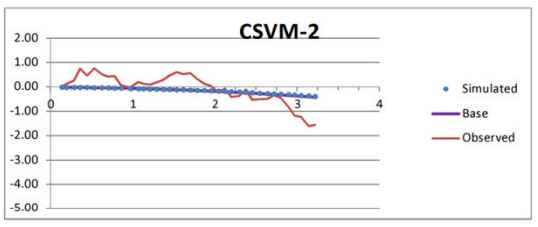


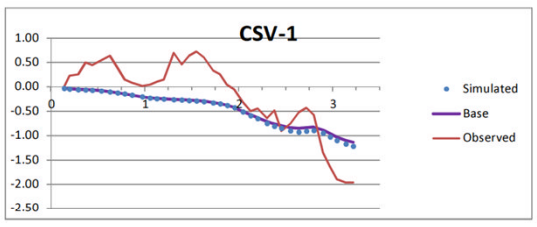


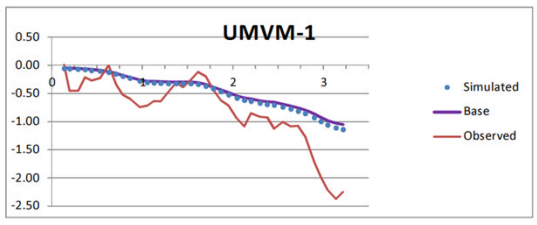


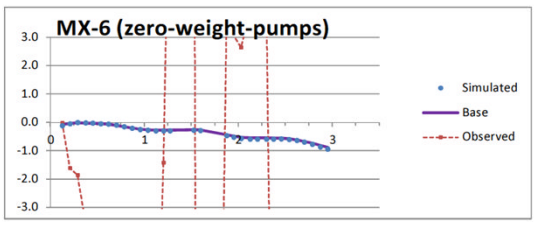


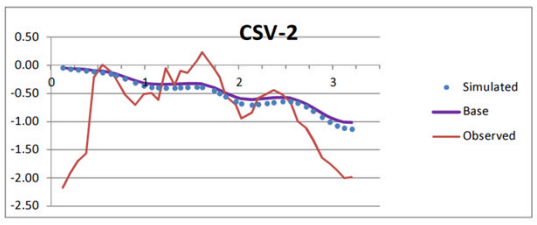


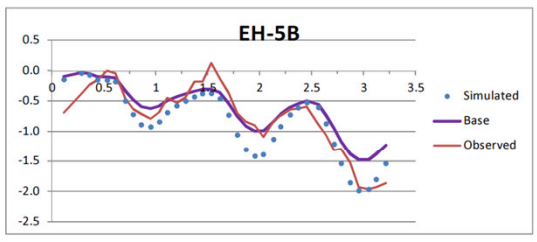


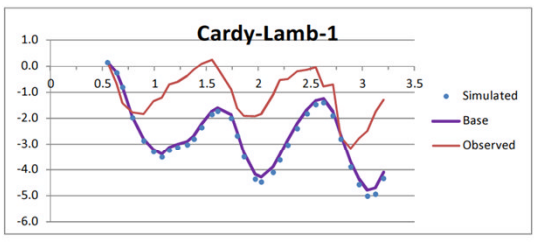


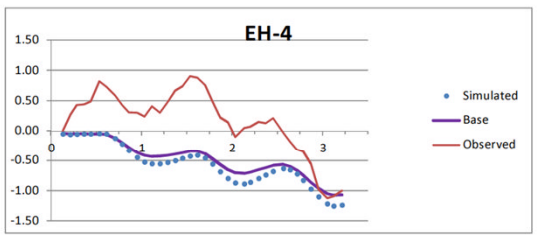


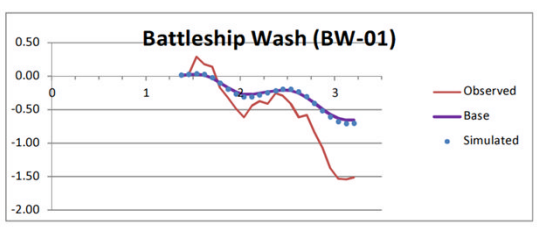


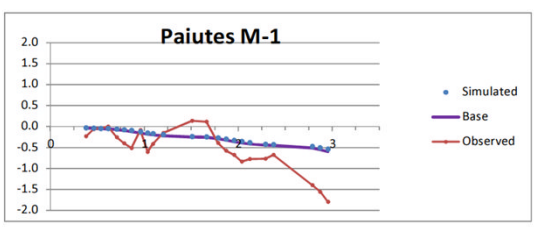


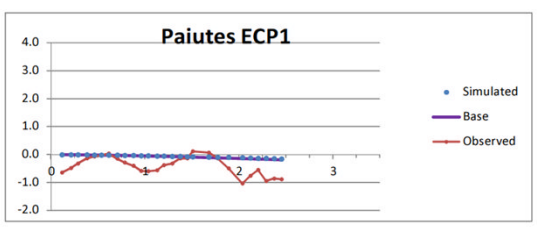


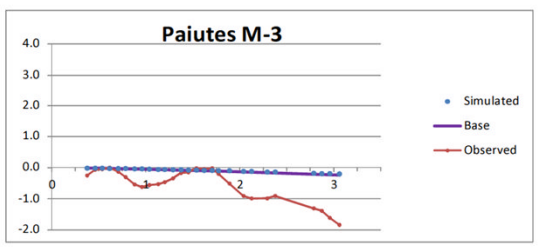


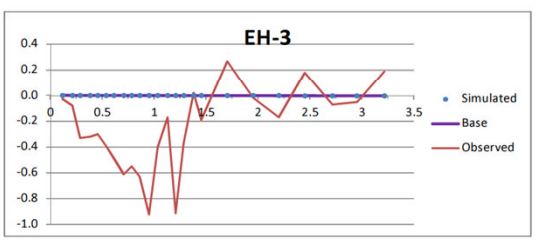


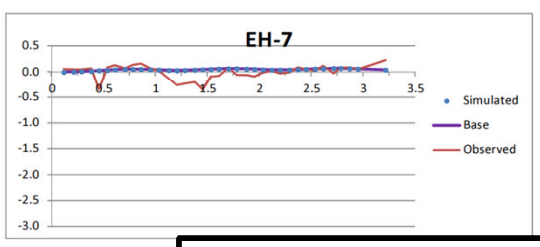


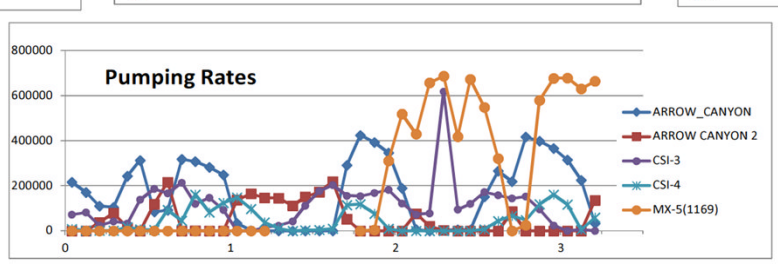








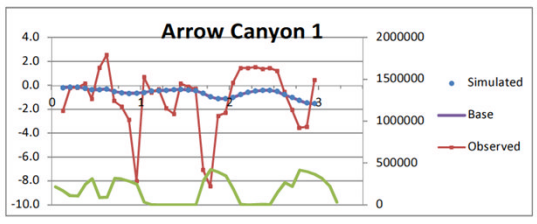


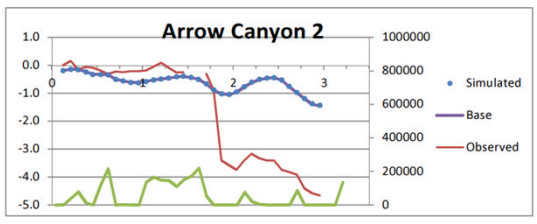


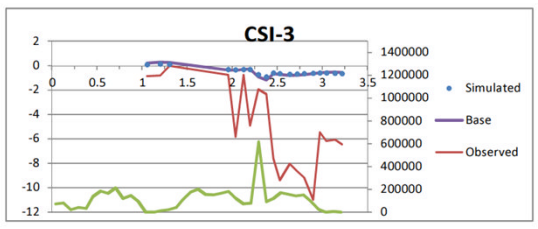
Sensitivity of Simulated Drawdown to Dividing K_PC4_1 by 2

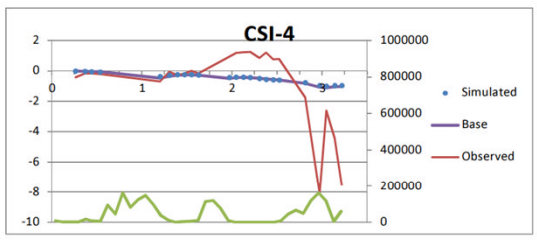
Lower Colorado River Flow System

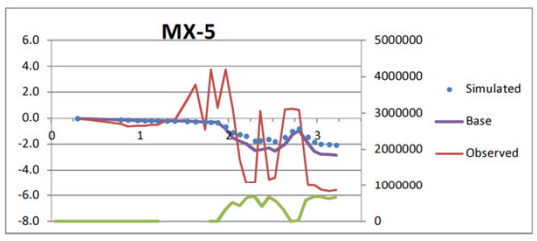
TETRA TECH GEO

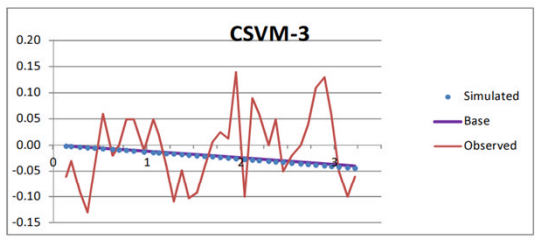


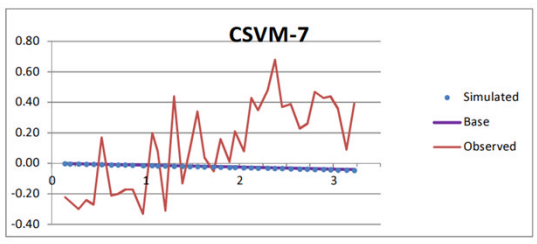


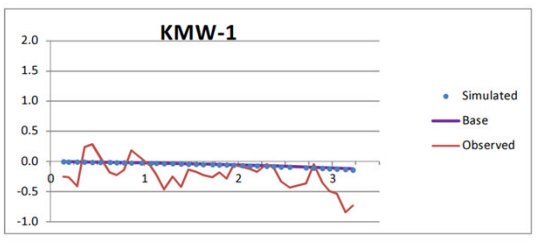


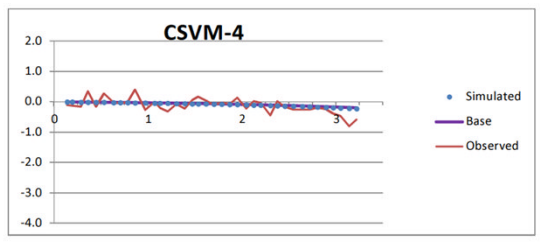


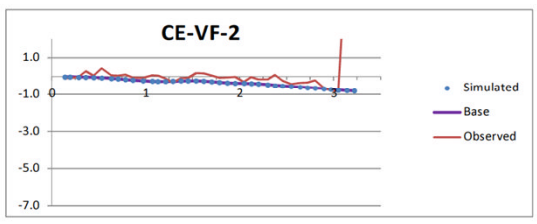


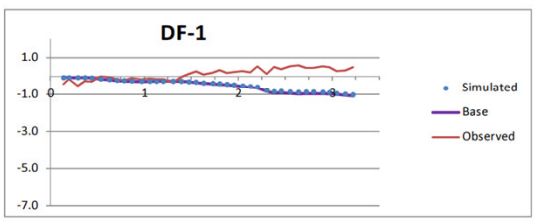


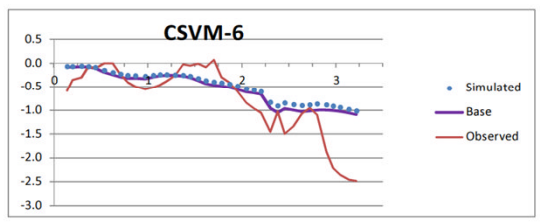


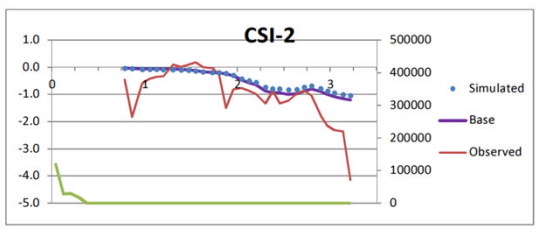


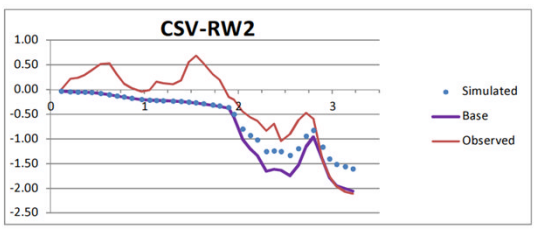


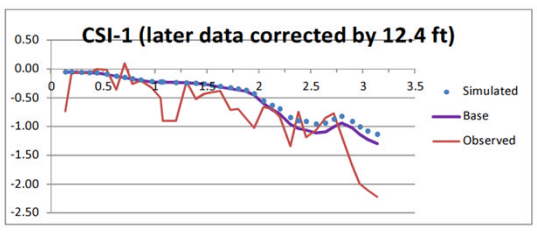


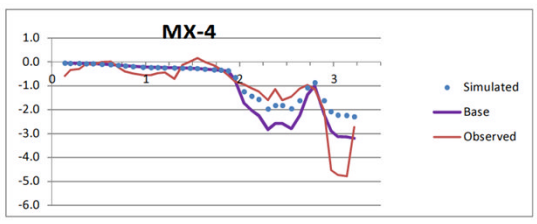


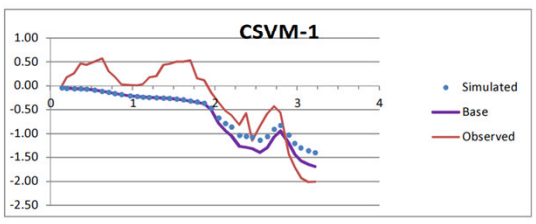


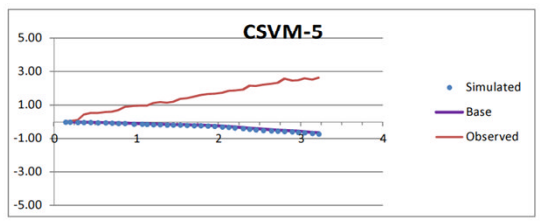


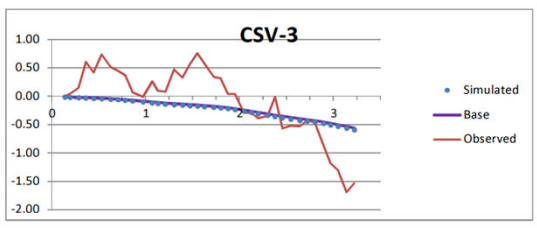


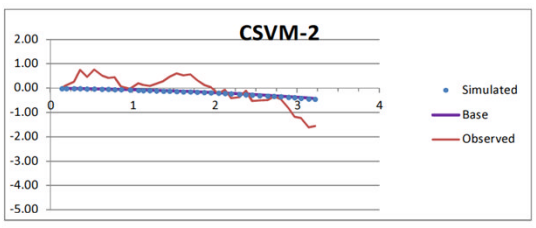


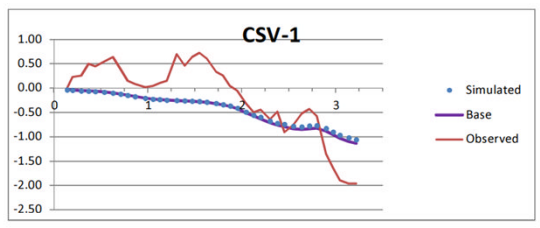


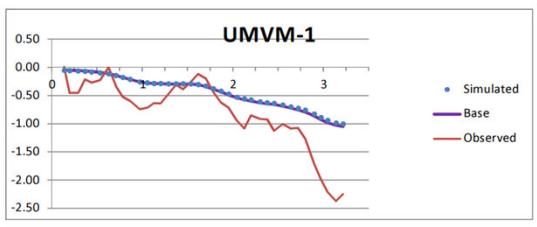


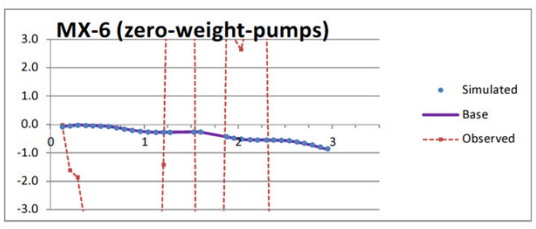


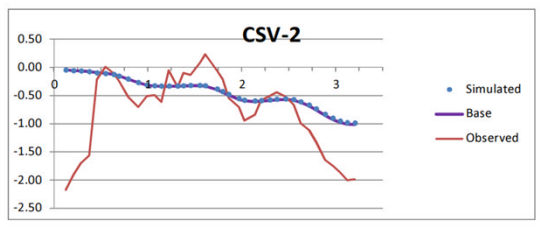


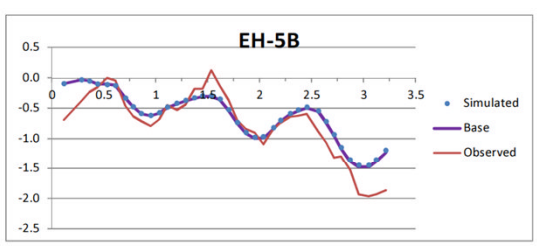


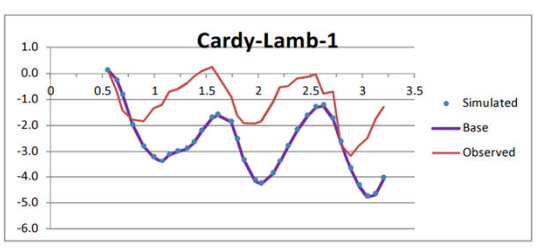


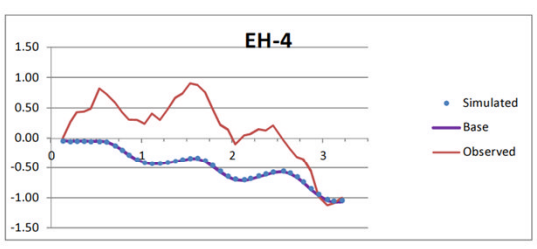


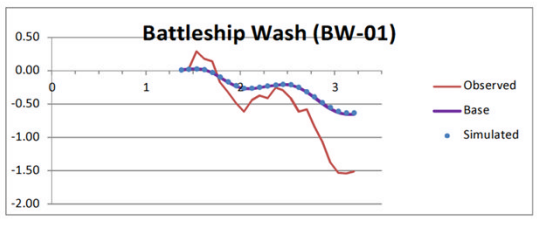


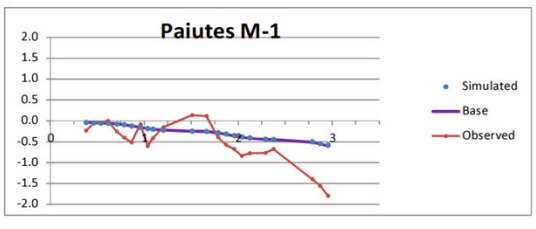


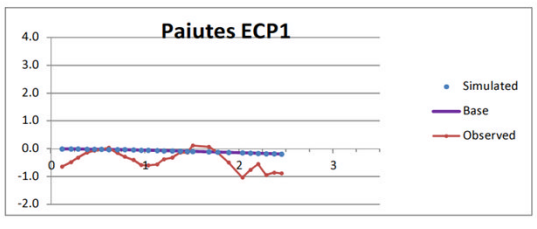


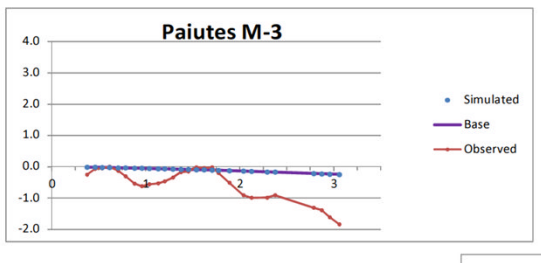


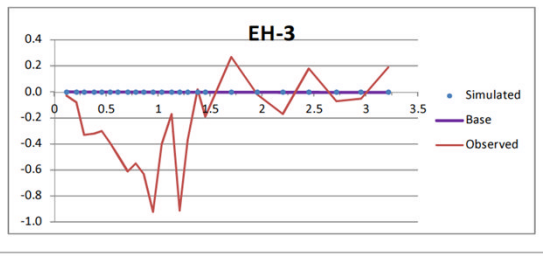


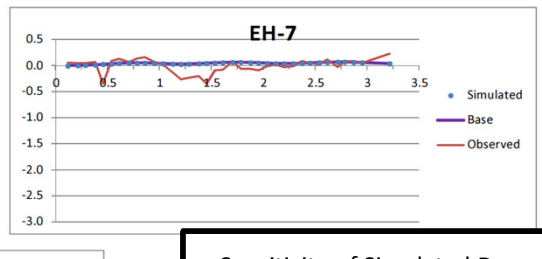


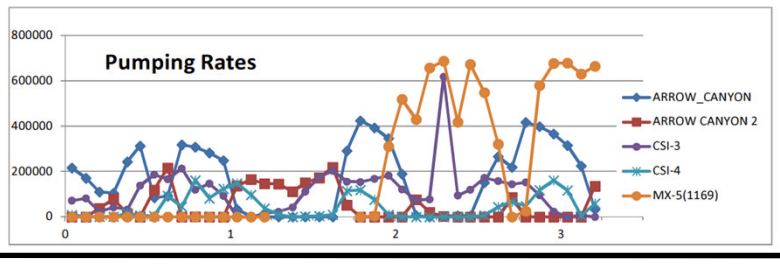








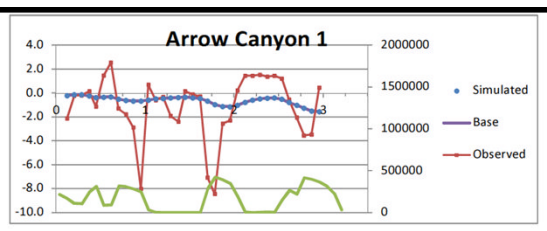


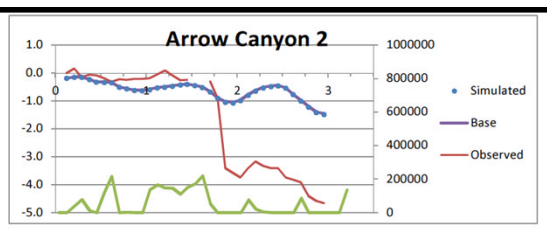


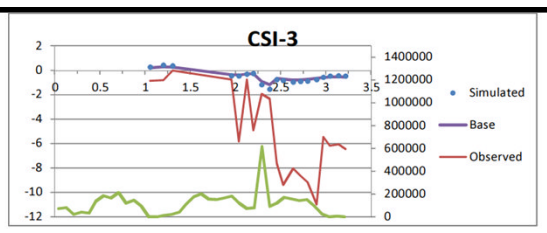
Sensitivity of Simulated Drawdown to Multiplying K_PC4_2 by 2

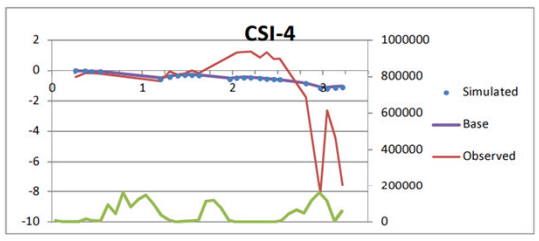
Lower Colorado River Flow System

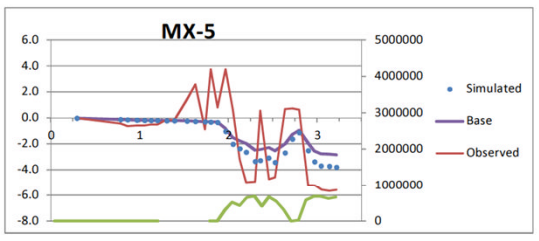
TETRA TECH GEO

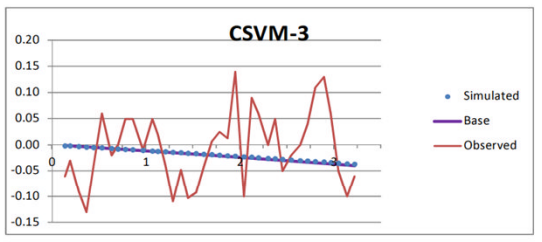


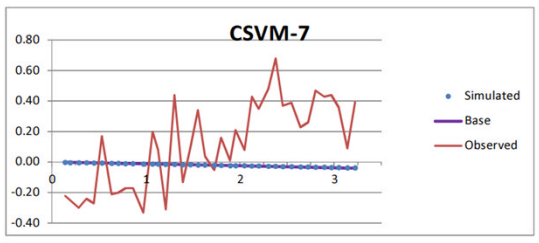


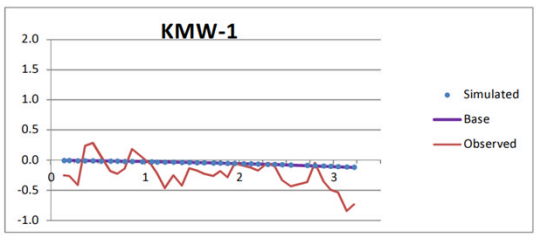


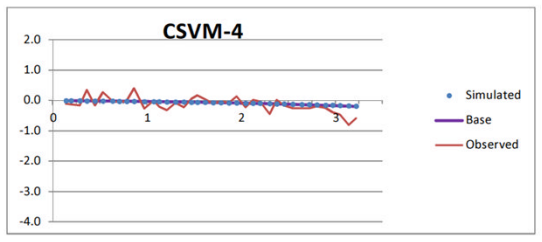


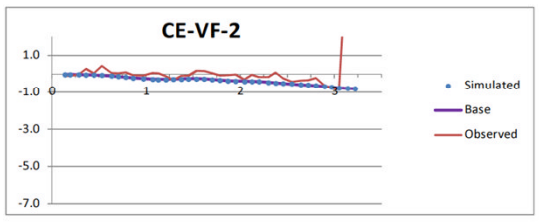


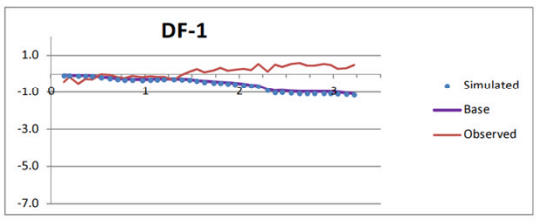


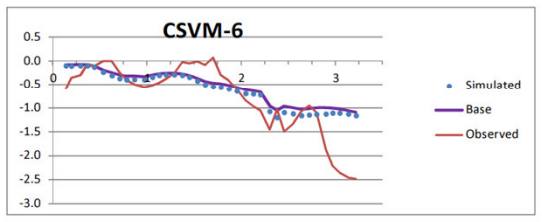


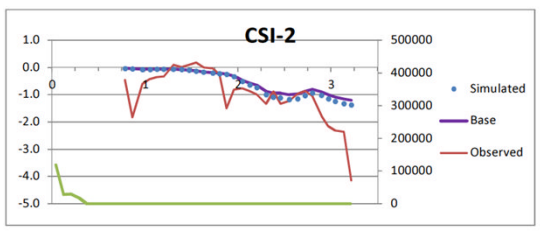


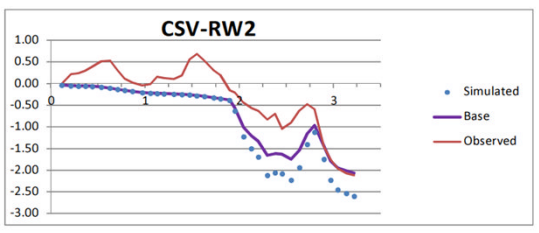


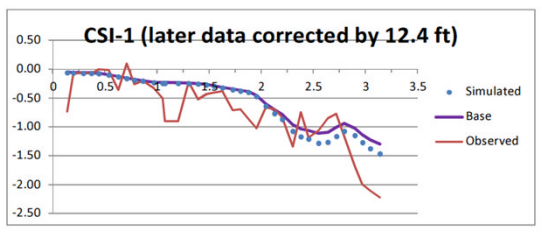


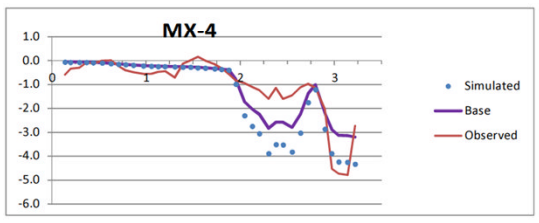


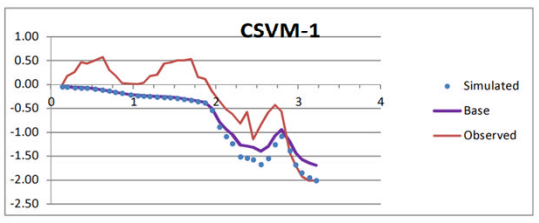


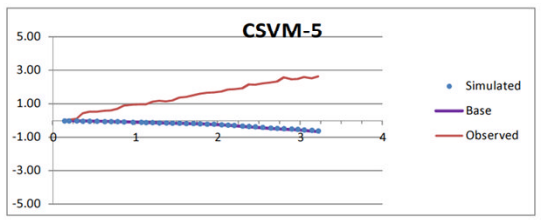


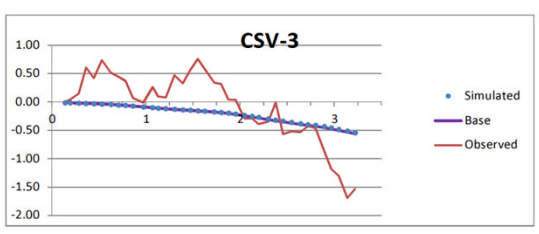


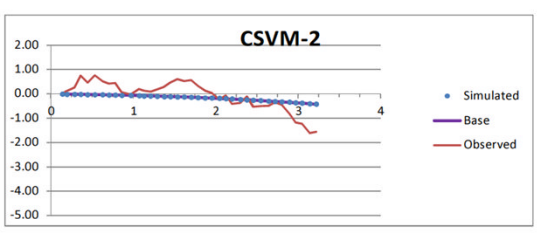


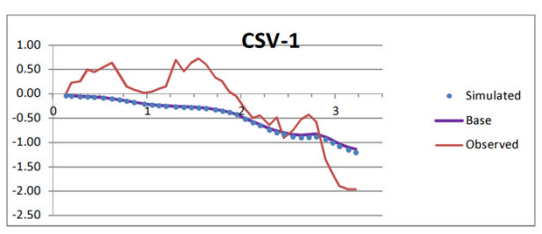


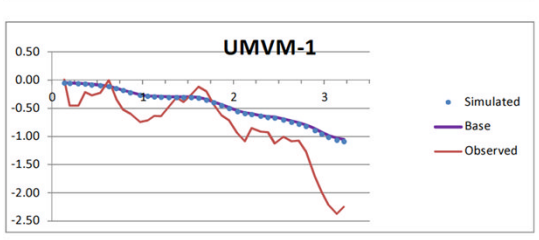


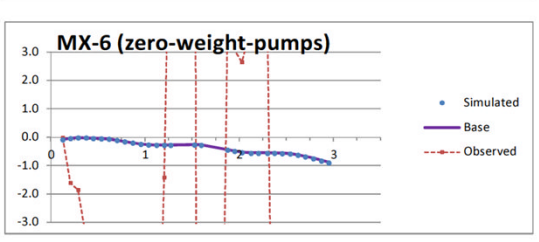


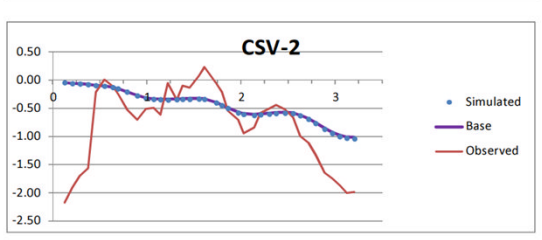


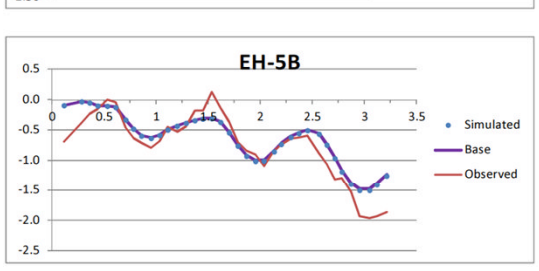


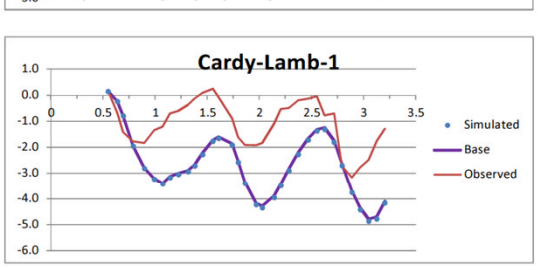


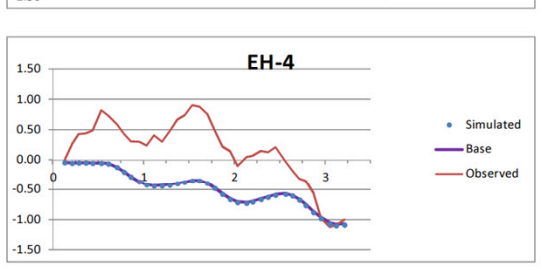


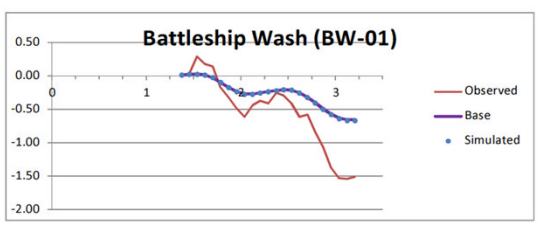


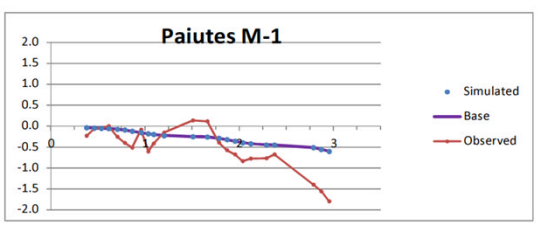


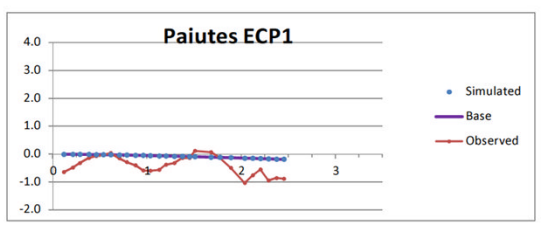


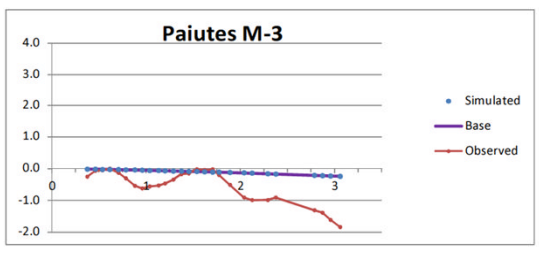


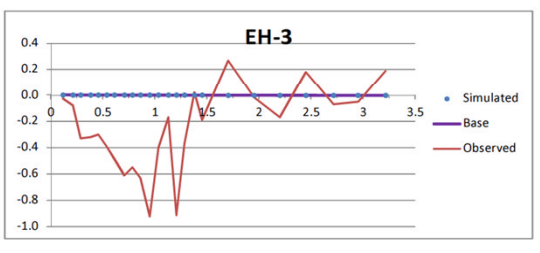


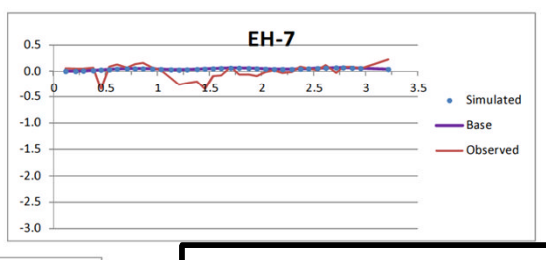


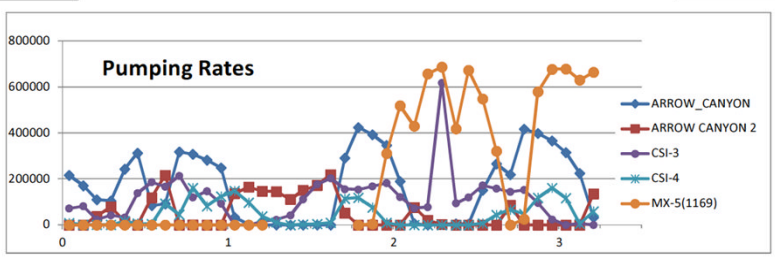








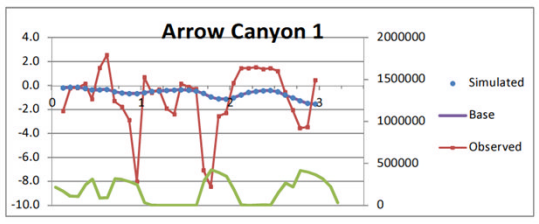


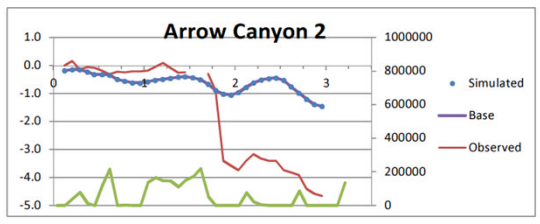


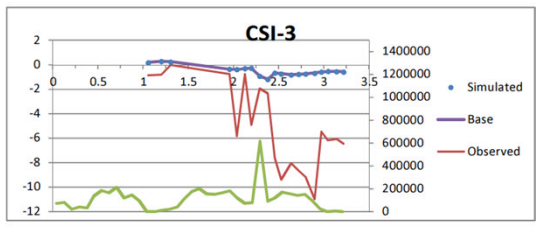
Sensitivity of Simulated Drawdown to Dividing K_PC4_2 by 2

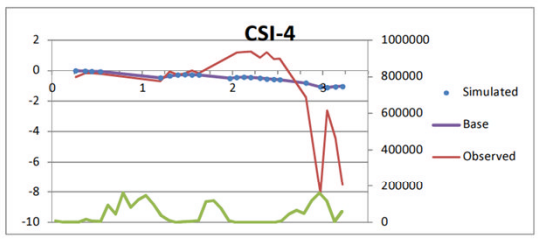
Lower Colorado River Flow System

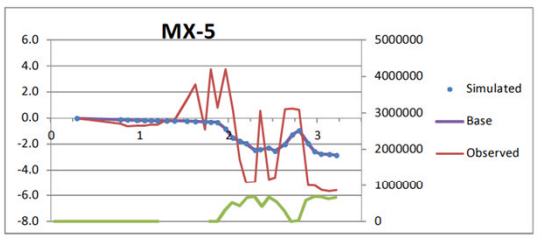
TETRA TECH GEO

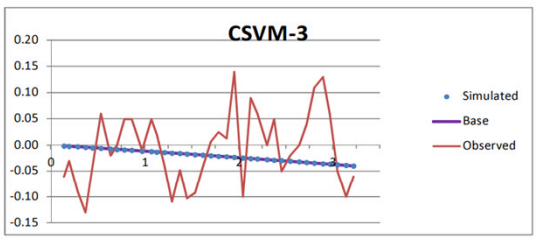


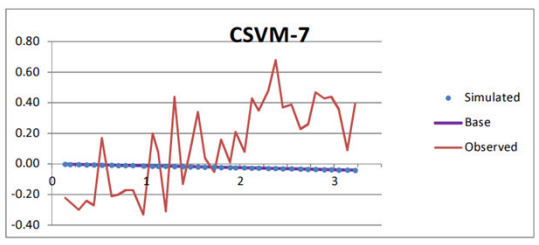


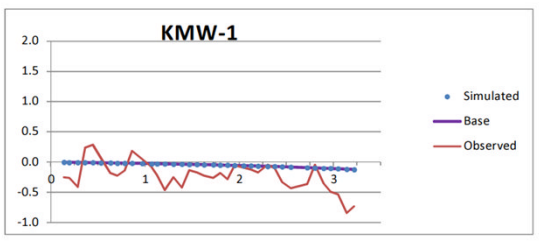


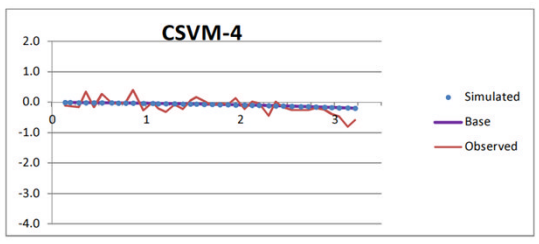


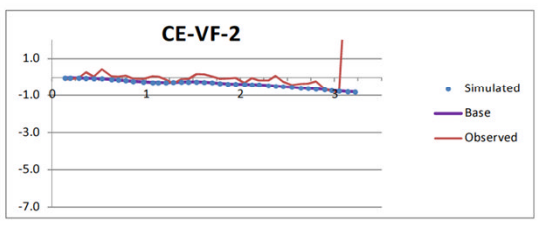


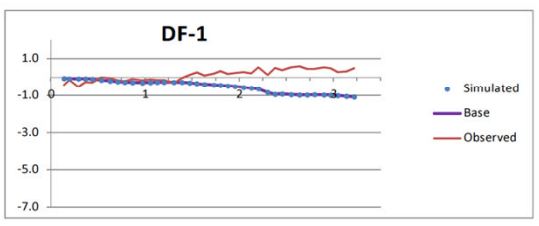


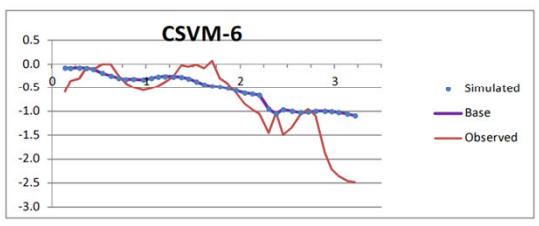


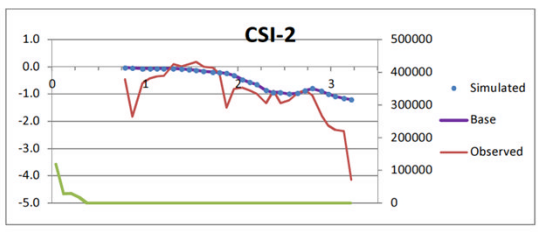


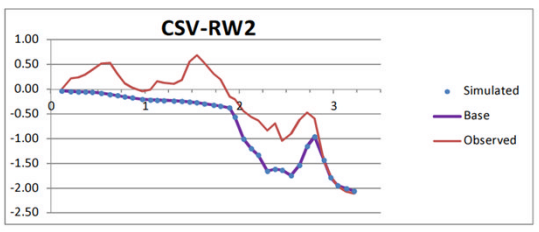


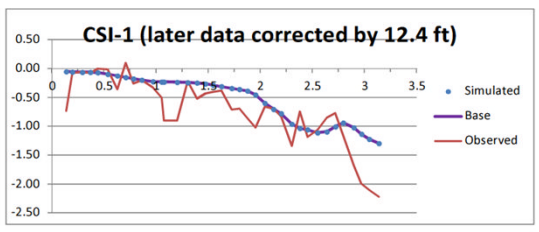


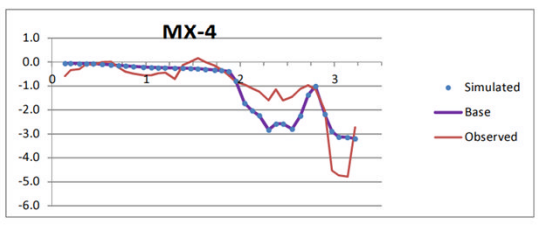


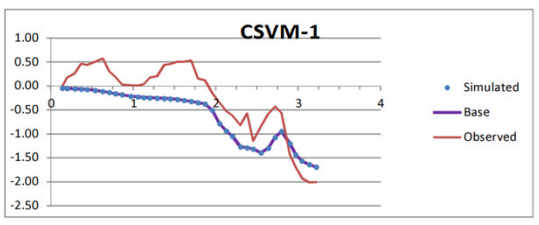


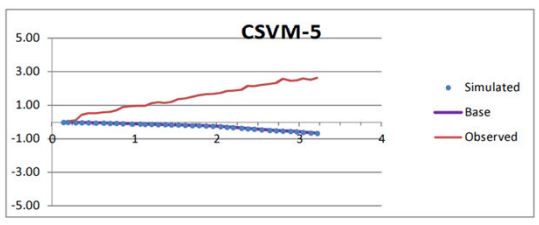


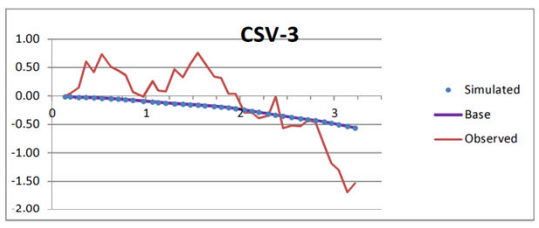


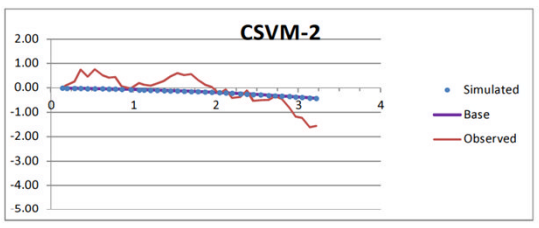


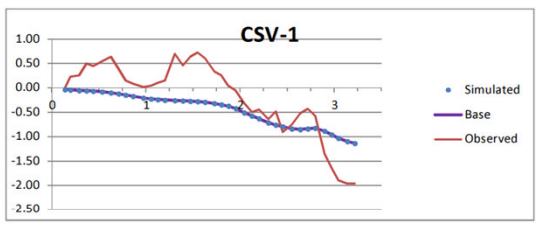


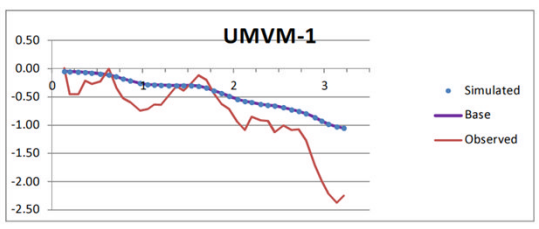


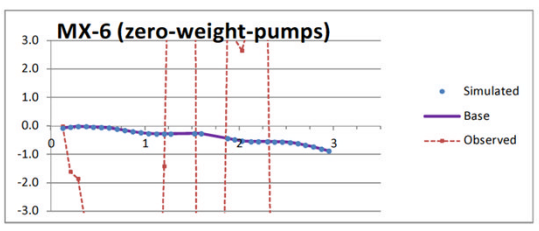


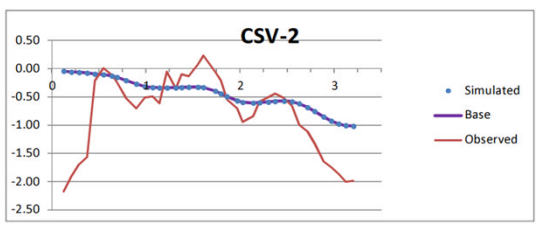


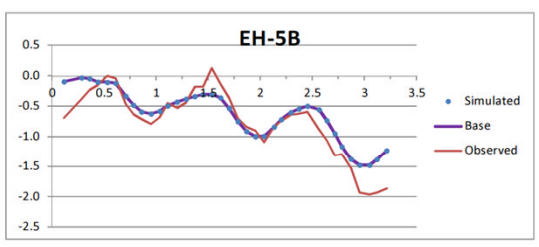


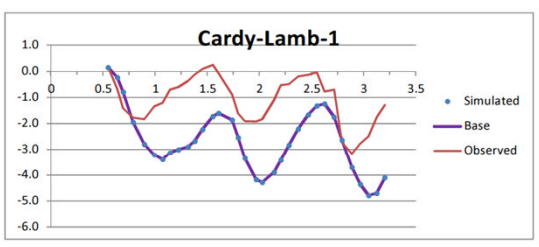


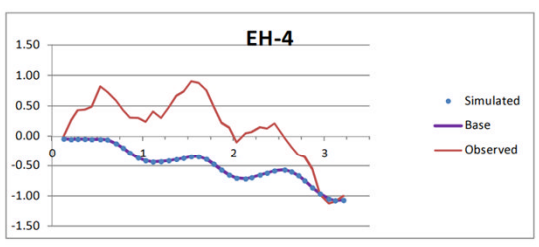


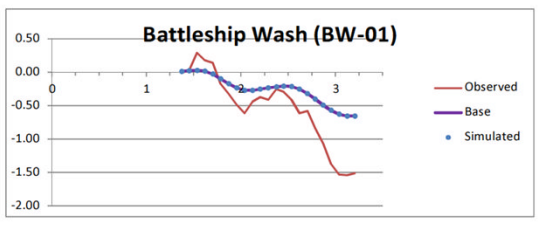


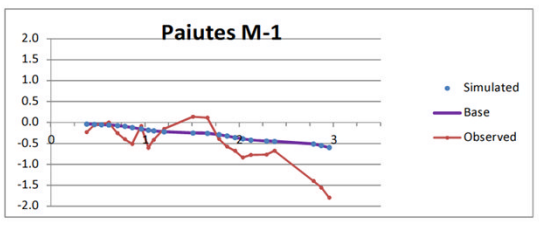


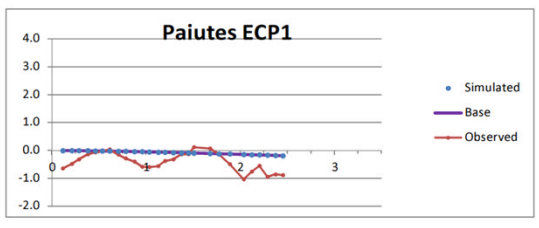


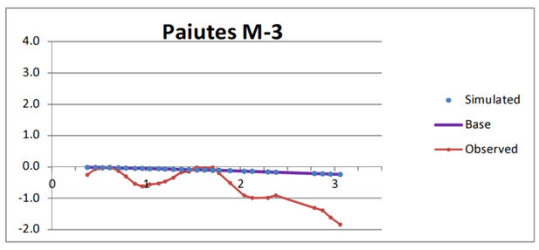


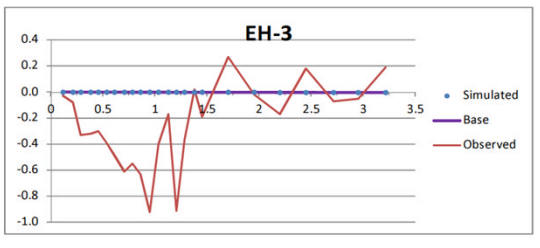


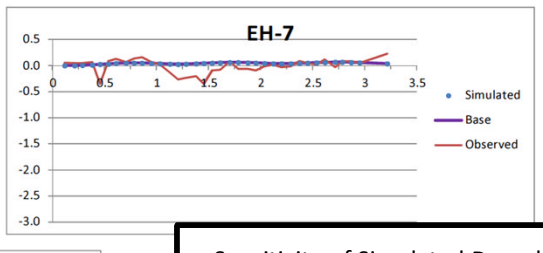


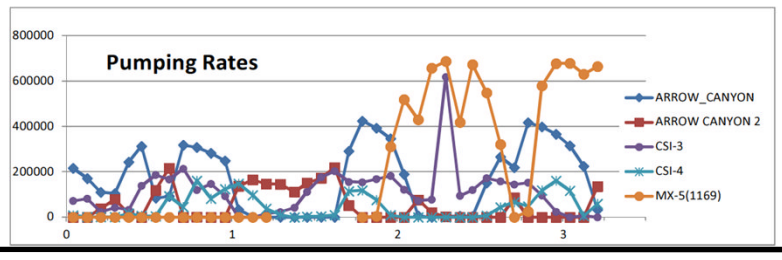








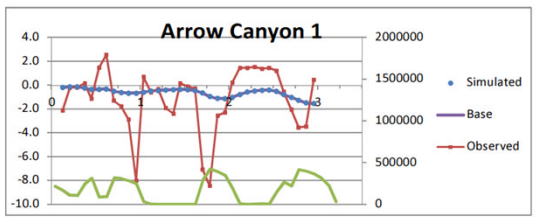


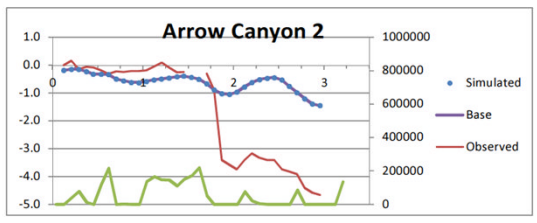


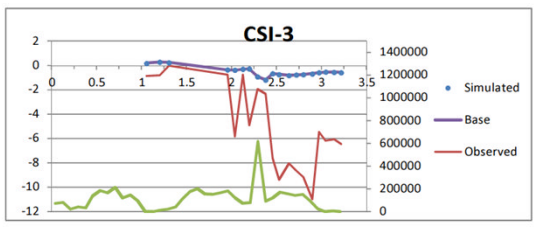
Sensitivity of Simulated Drawdown to Multiplying K_PC4_6 by 2

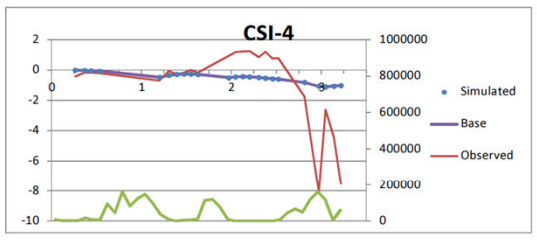
Lower Colorado River Flow System

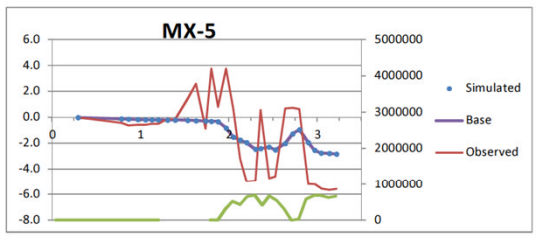
TETRA TECH GEO

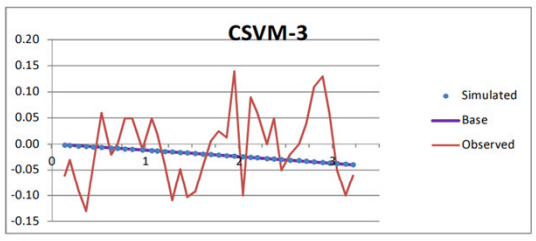


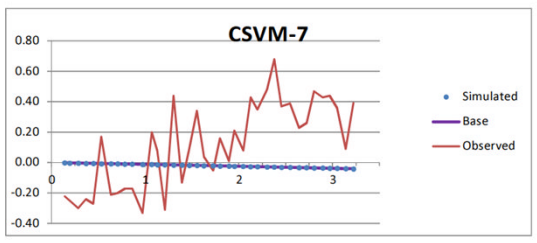


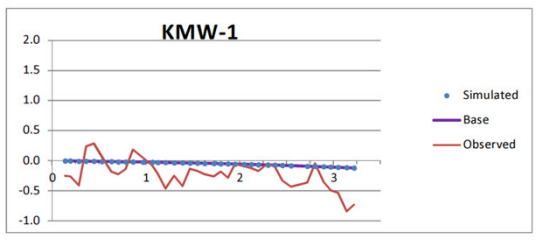


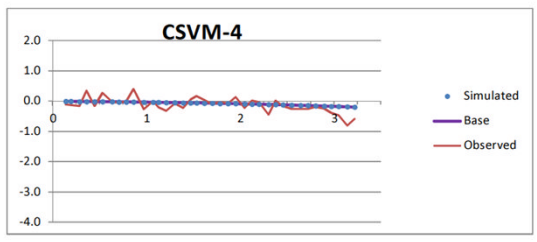


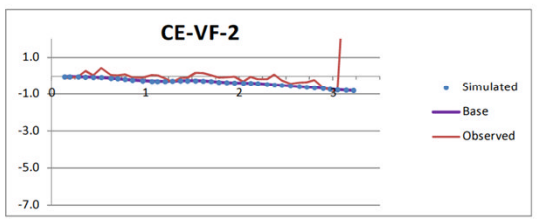


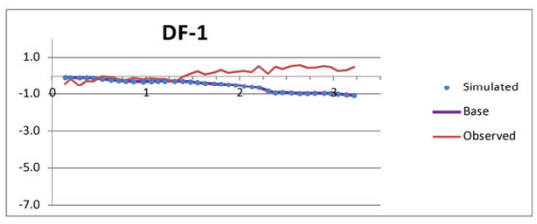


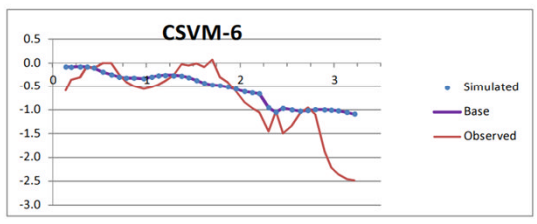


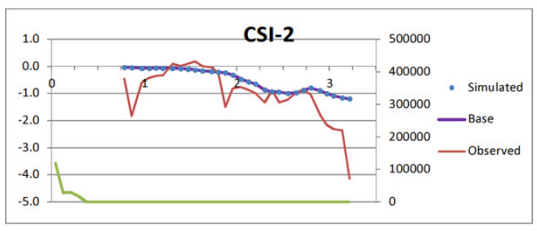


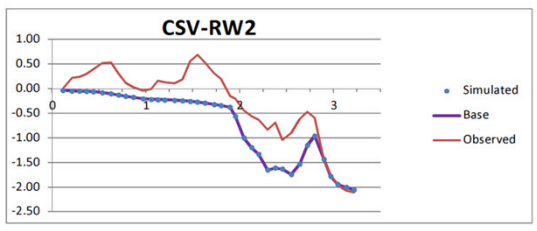


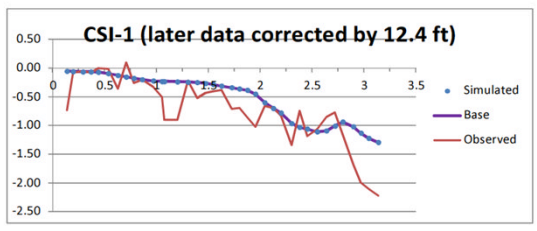


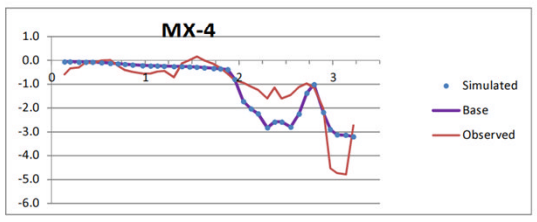


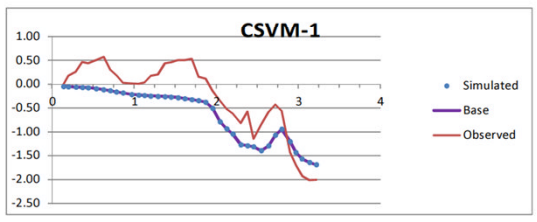


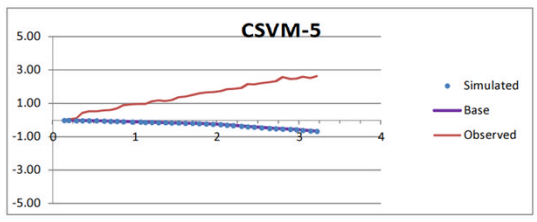


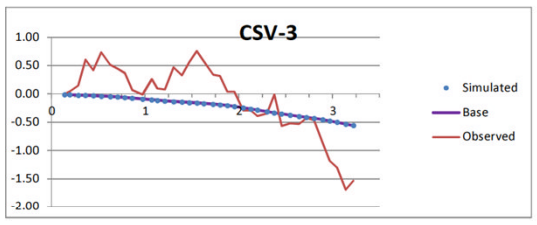


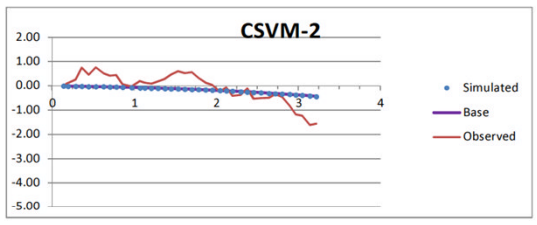


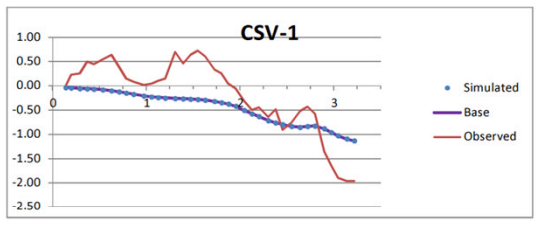


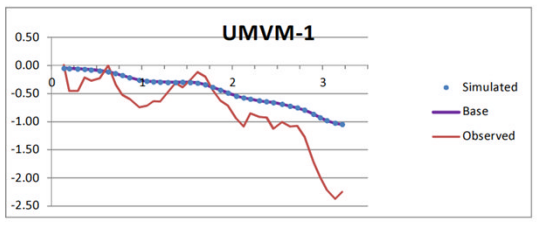


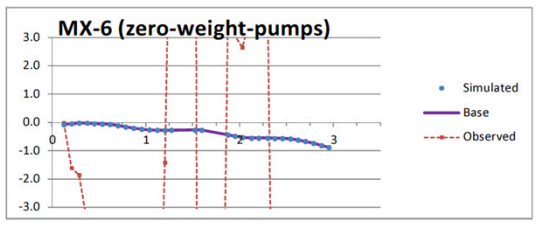


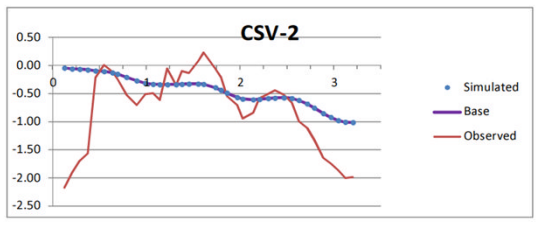


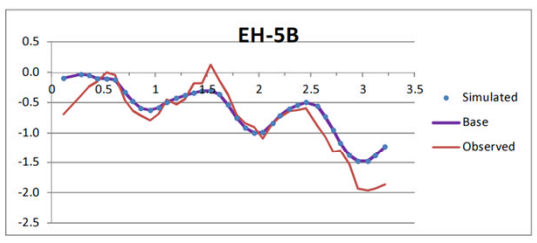


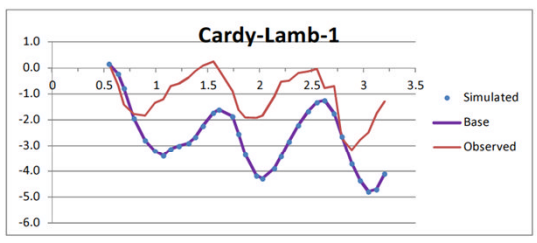


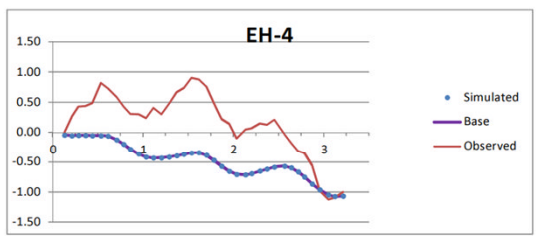


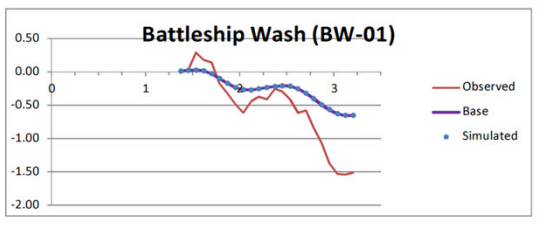


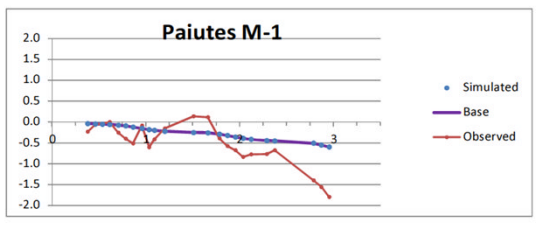


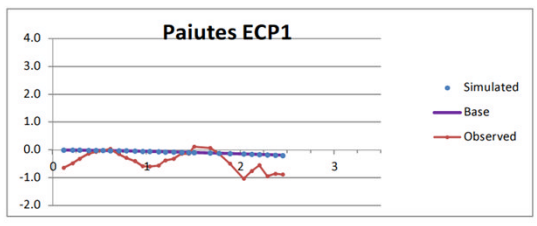


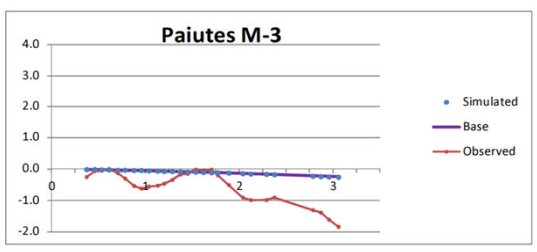


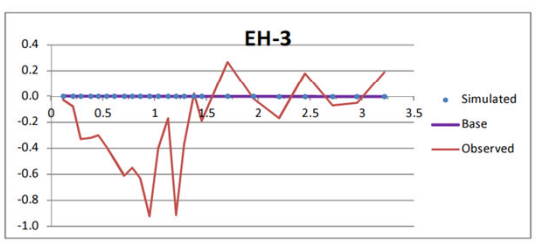


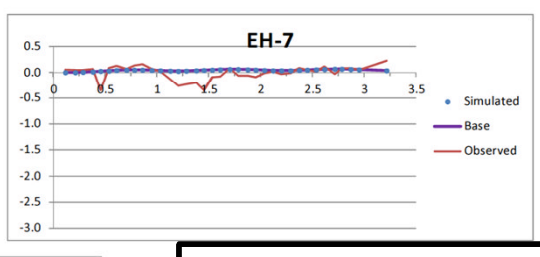


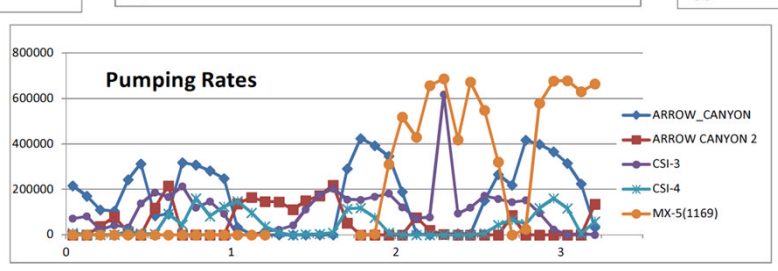








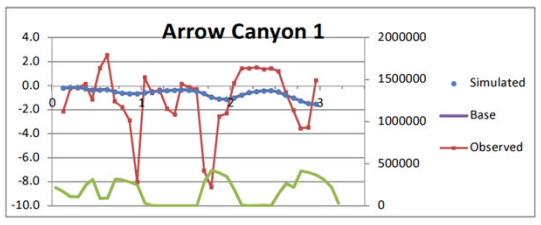


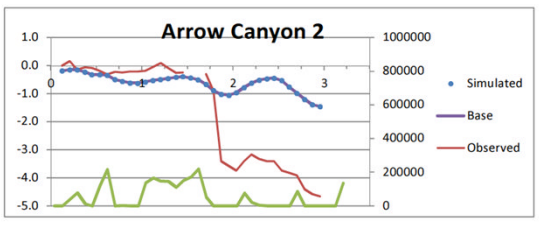


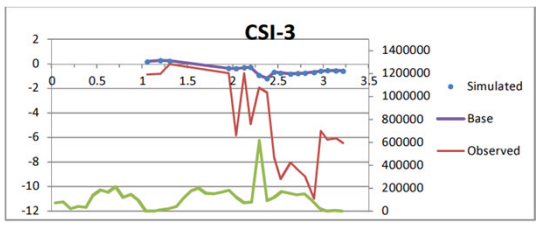
Sensitivity of Simulated Drawdown to Multiplying K_PC4_14 by 2

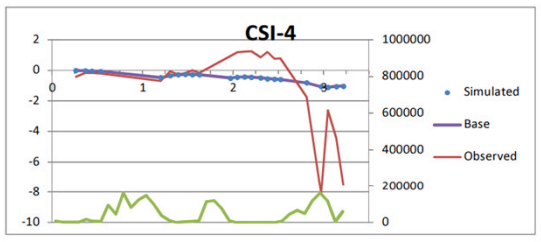
Lower Colorado River Flow System

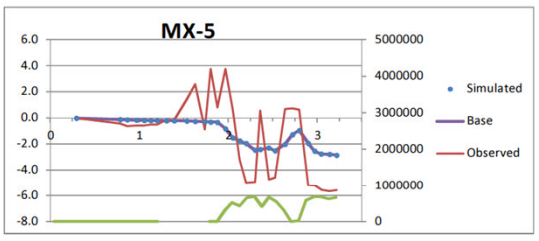
TETRA TECH GEO

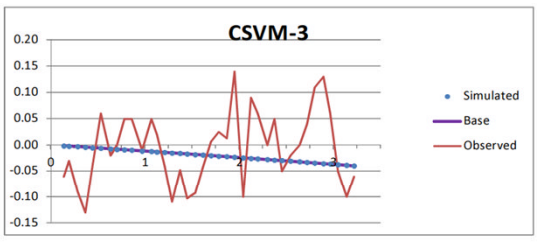


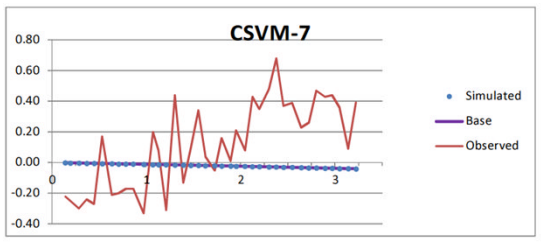


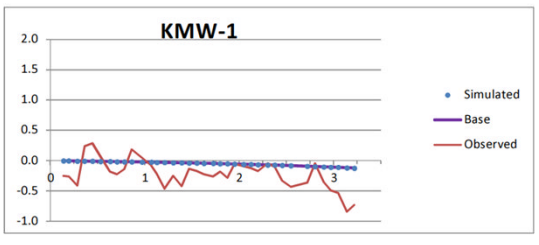


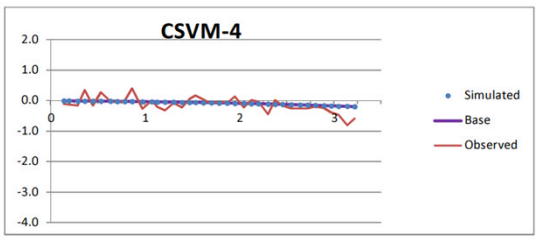


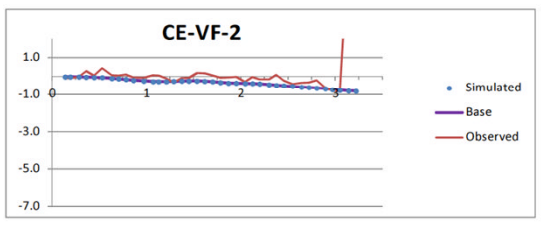


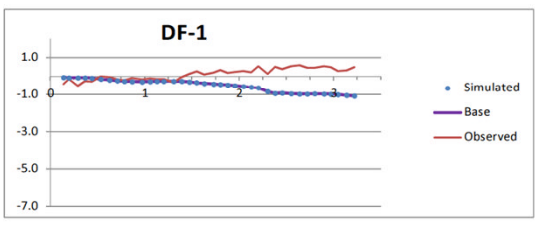


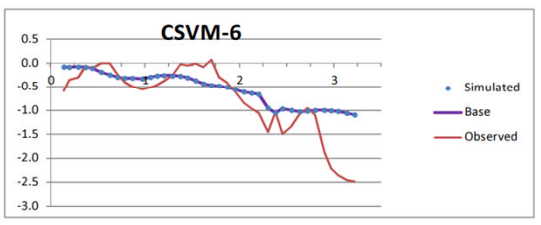


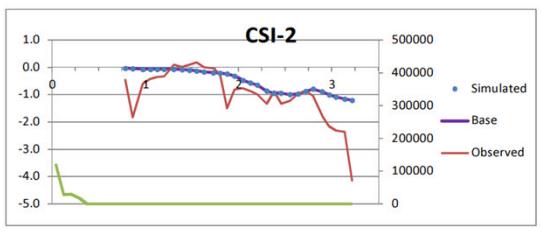


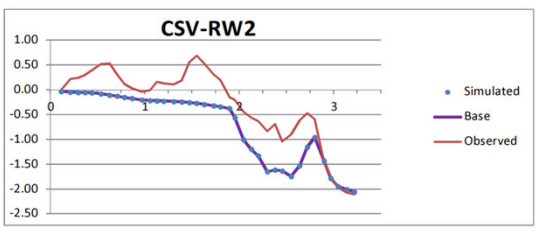


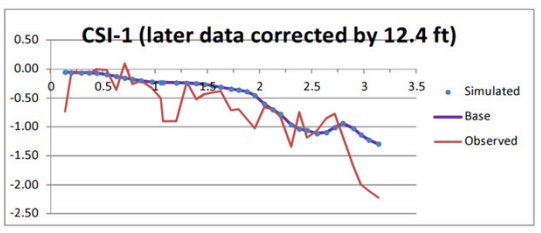


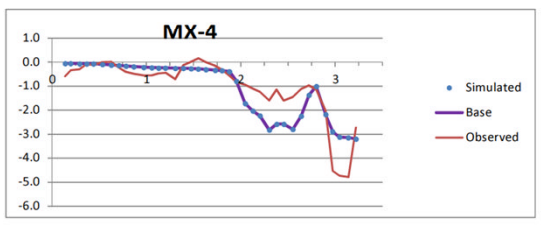


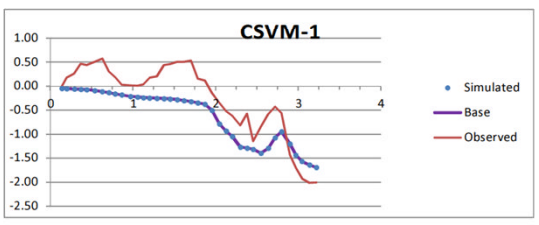


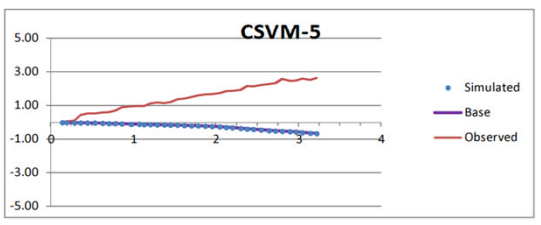


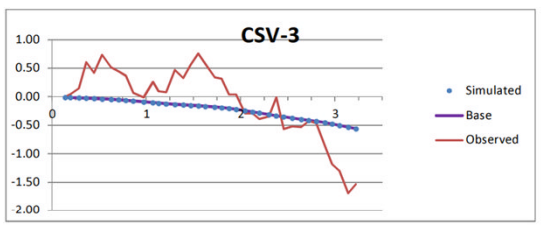


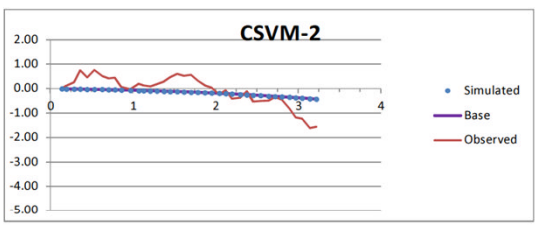


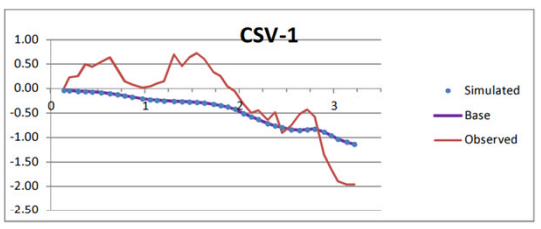


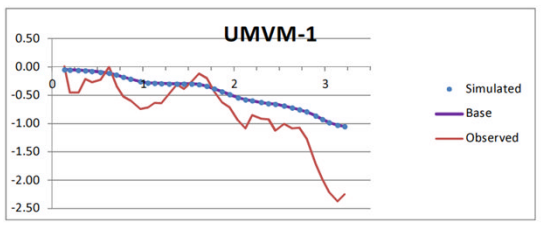


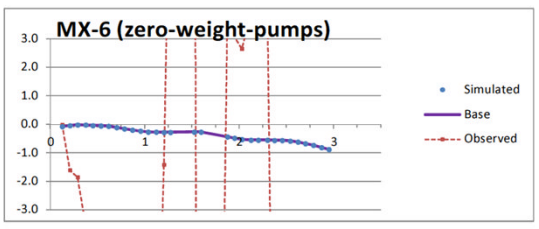


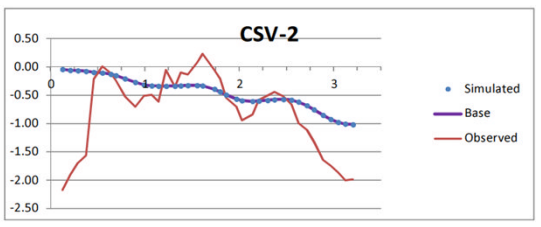


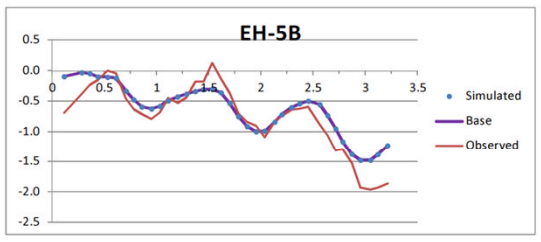


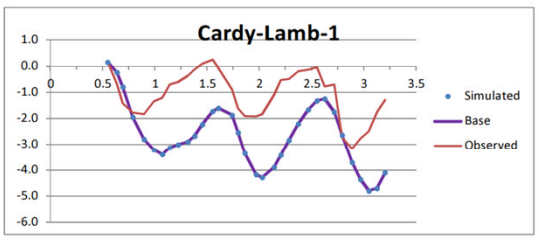


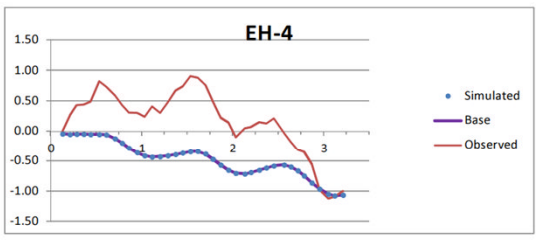


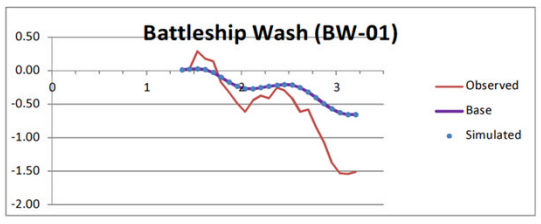


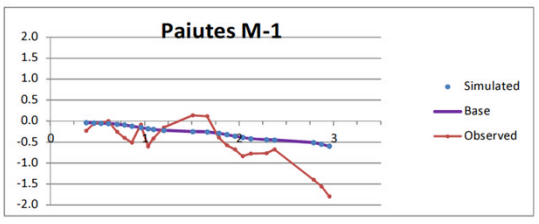


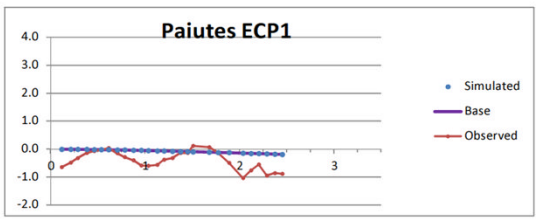


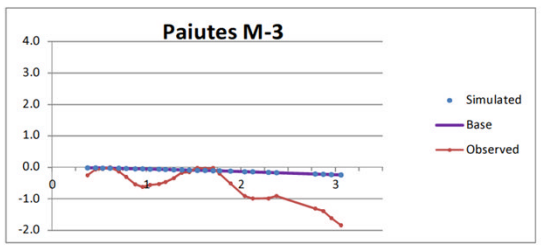


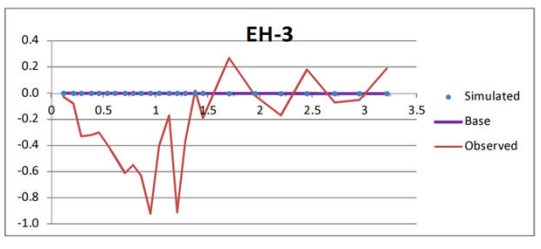


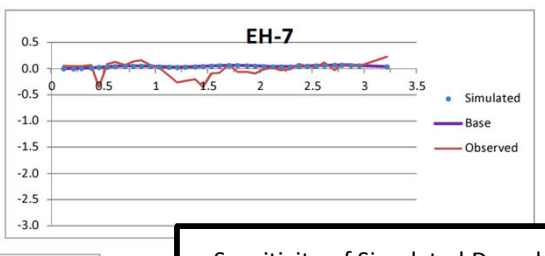


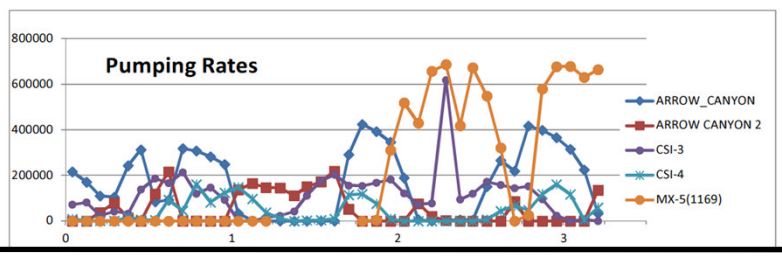








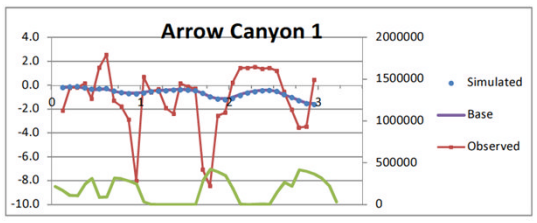


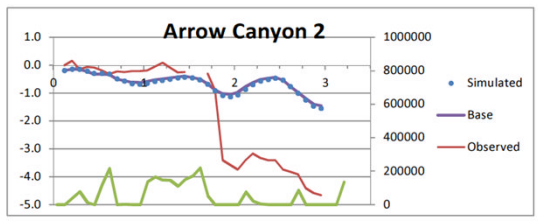


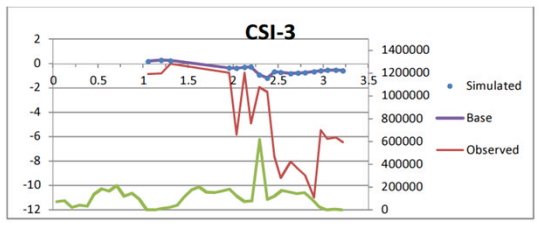
Sensitivity of Simulated Drawdown to Multiplying K_PC4_24 by 2

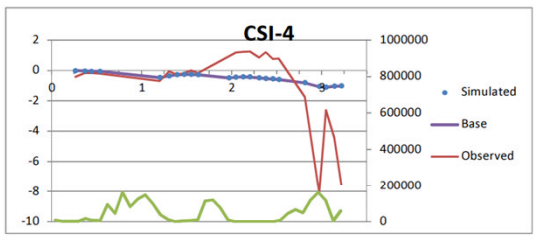
Lower Colorado River Flow System

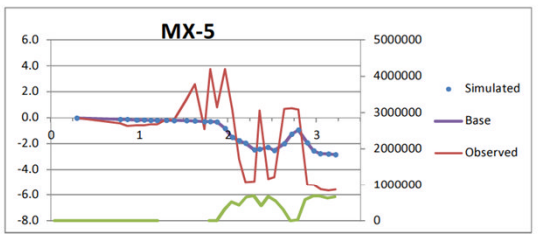
TETRA TECH GEO

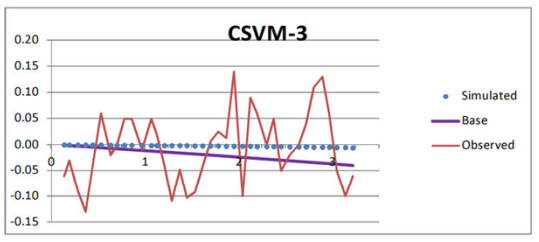


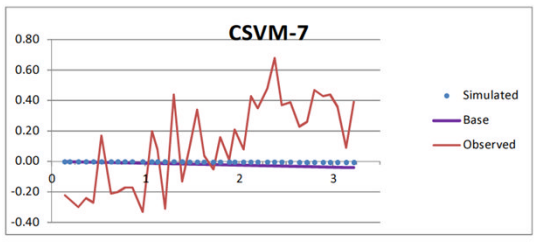


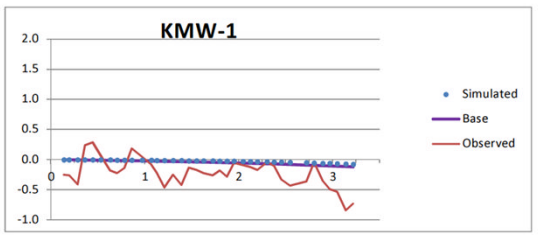


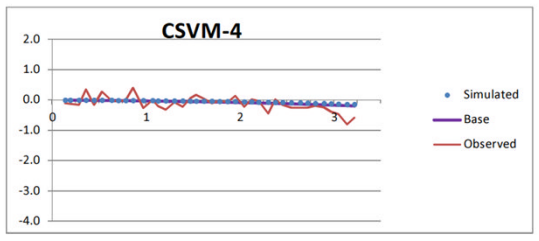


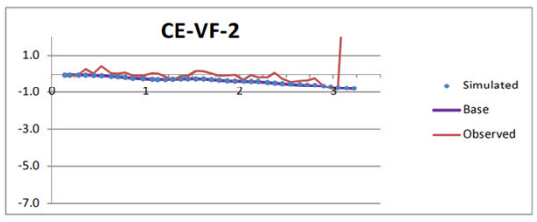


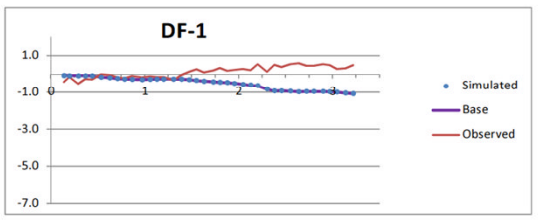


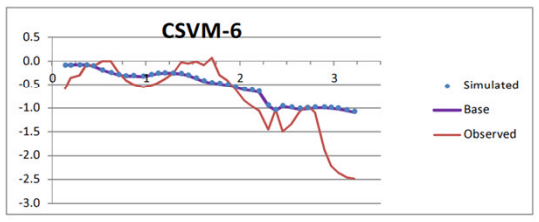


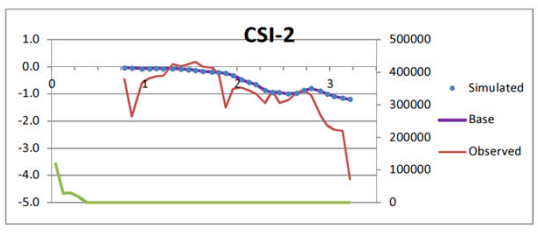


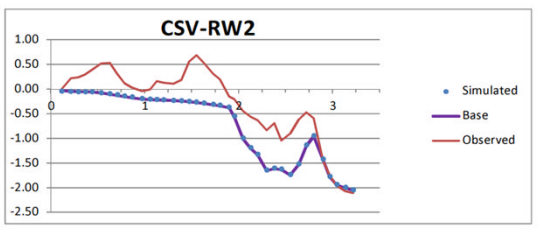


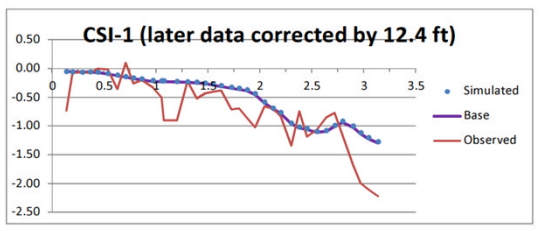


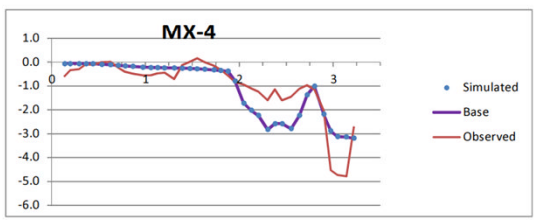


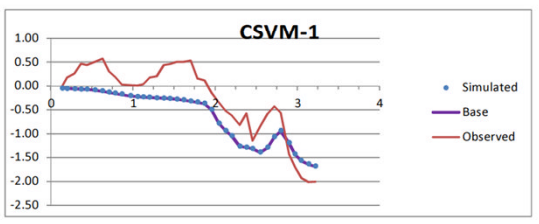


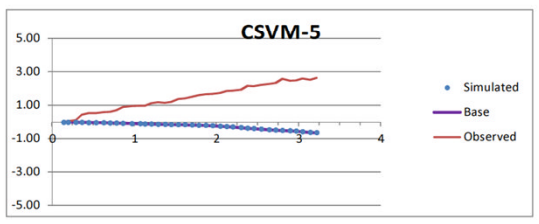


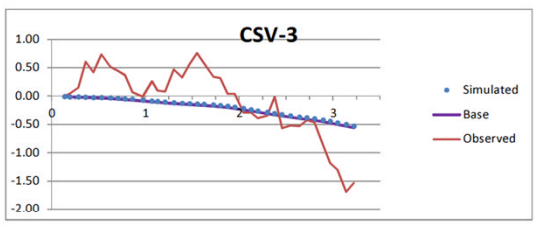


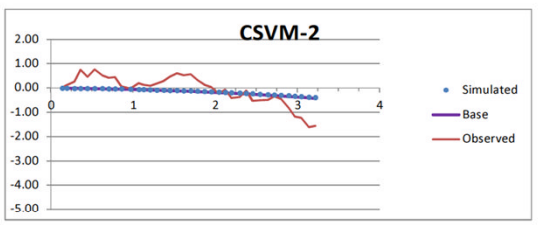


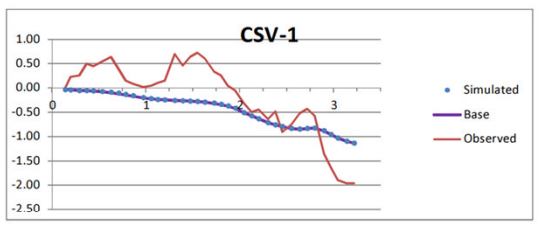


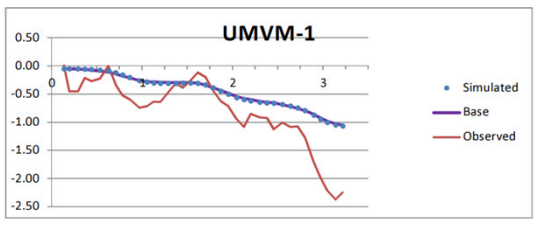


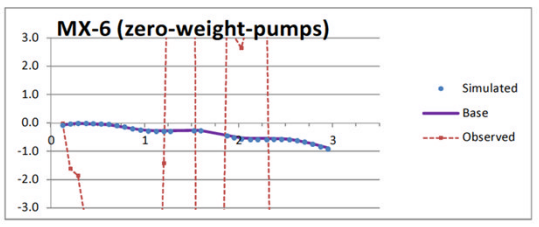


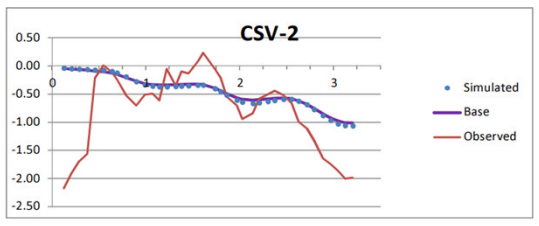


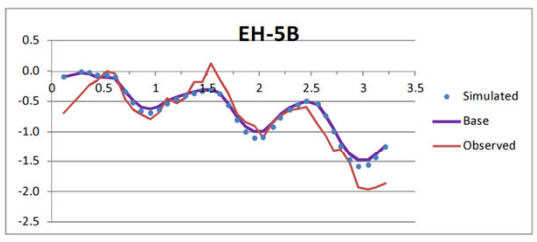


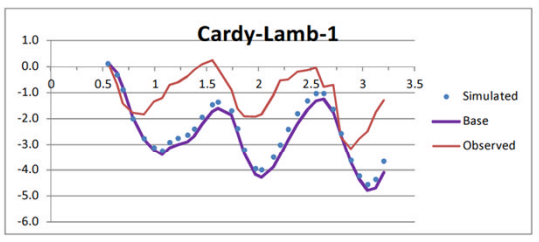


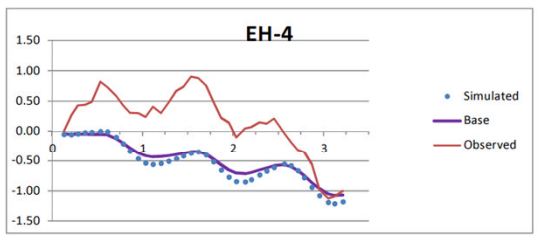


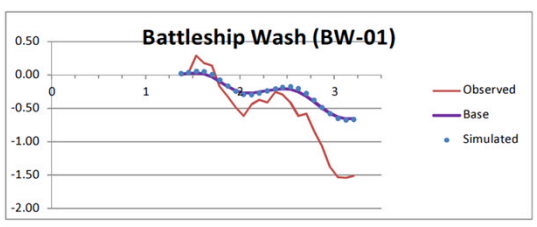


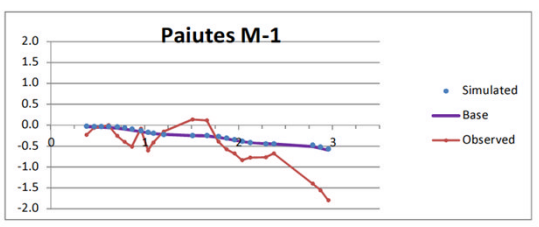


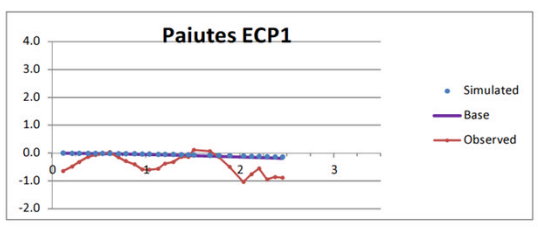


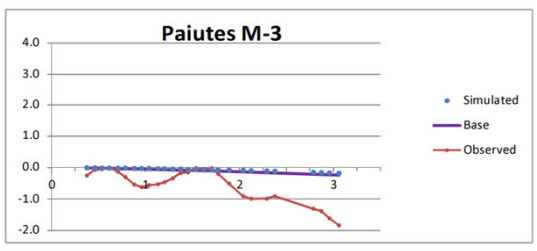


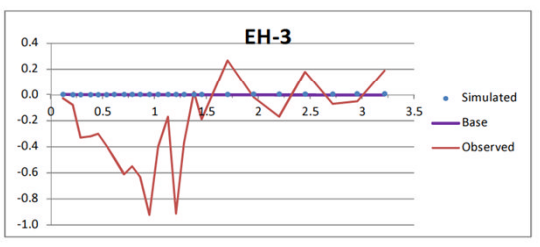


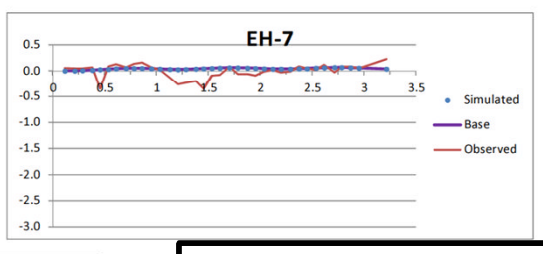


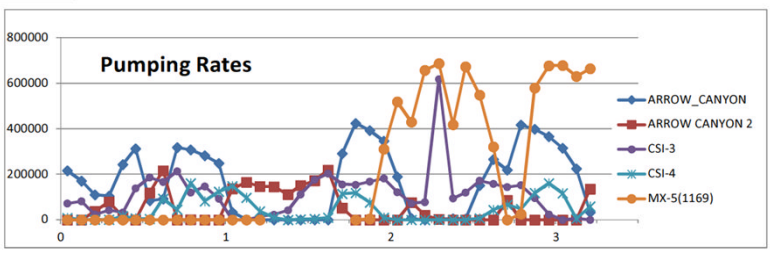








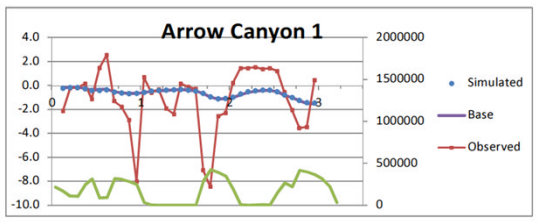


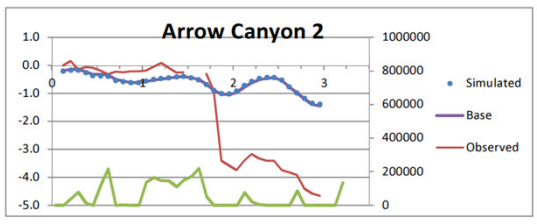


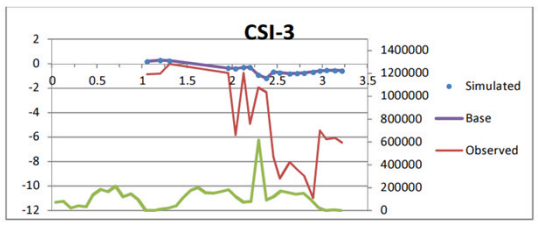
Sensitivity of Simulated Drawdown to Multiplying KX_CAU_3 by 2

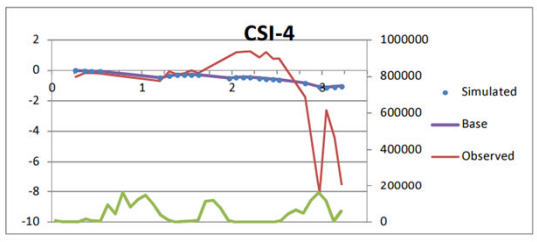
Lower Colorado River Flow System

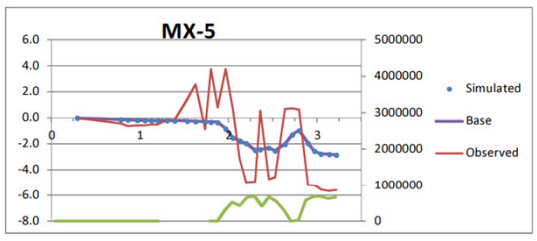
TETRA TECH GEO

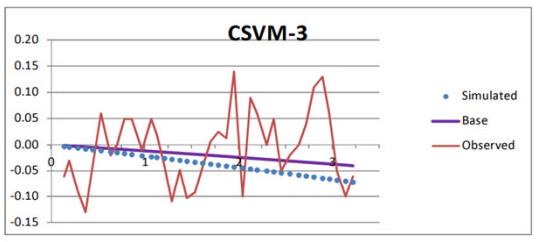


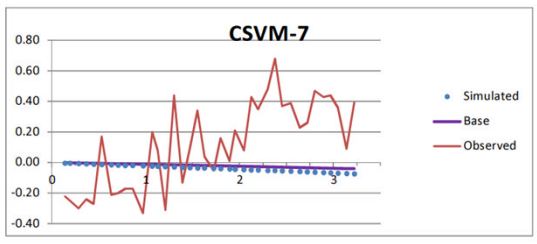


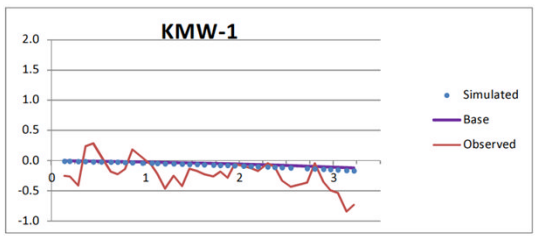


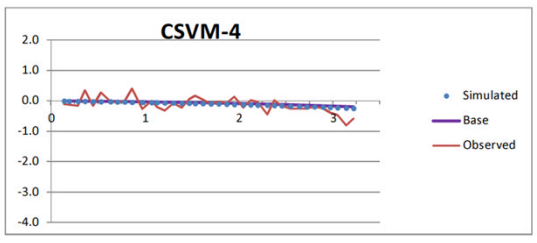


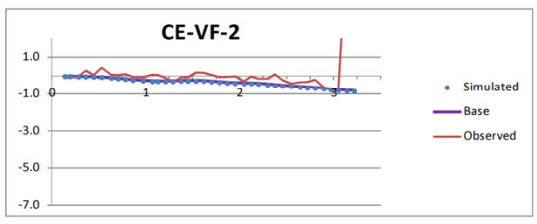


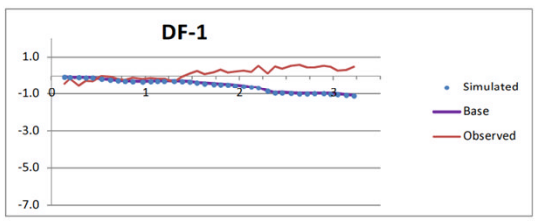


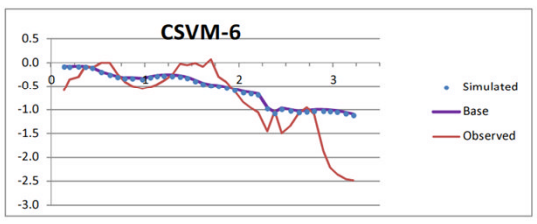


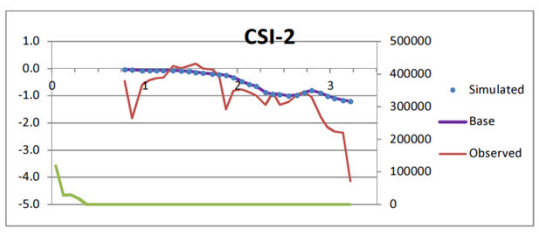


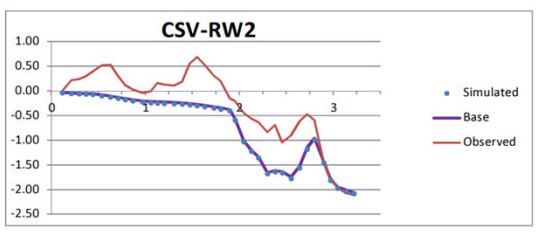


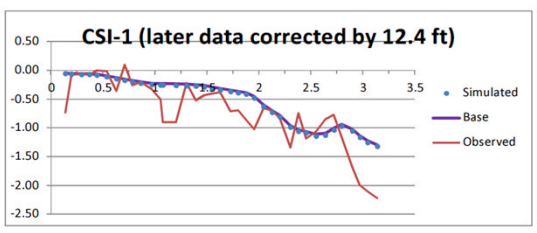


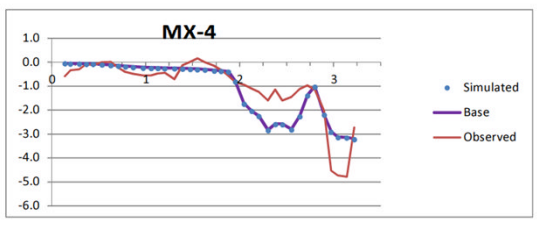


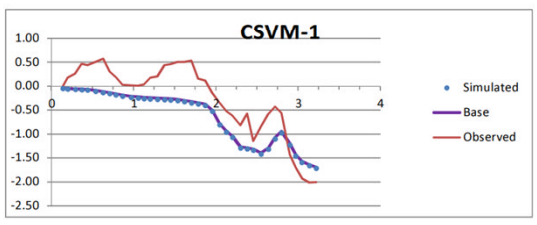


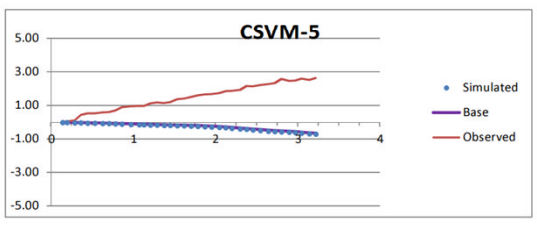


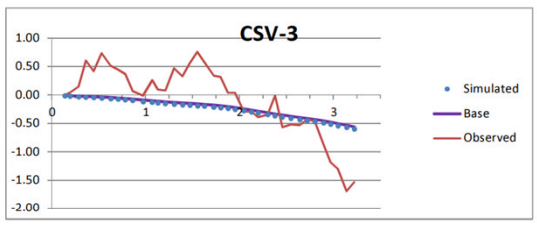


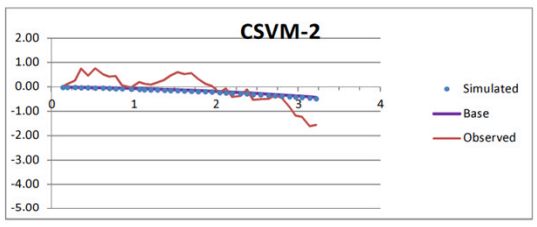


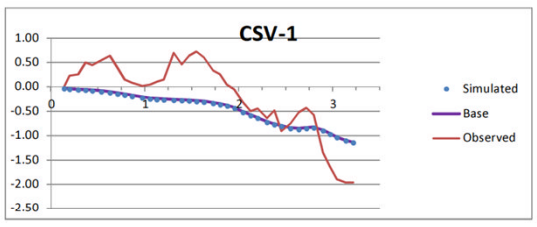


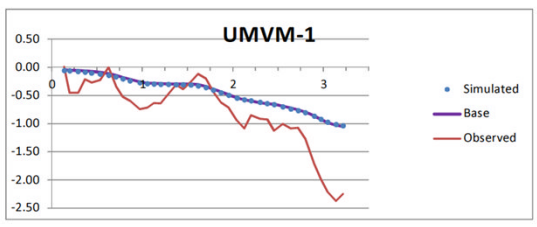


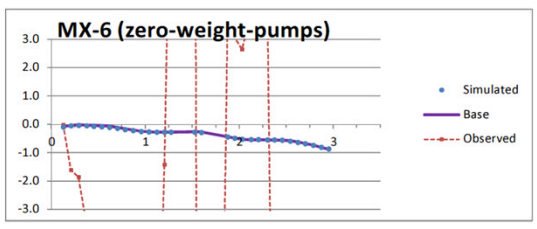


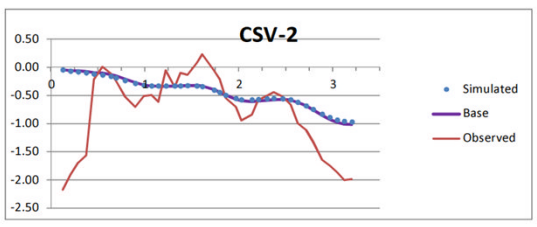


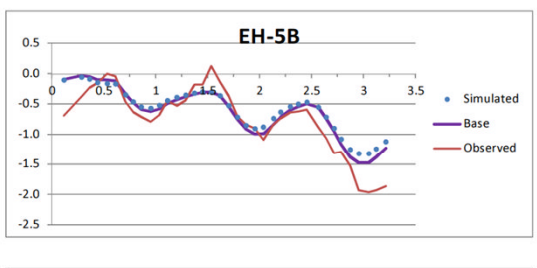


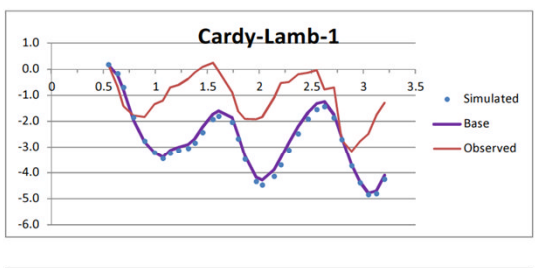


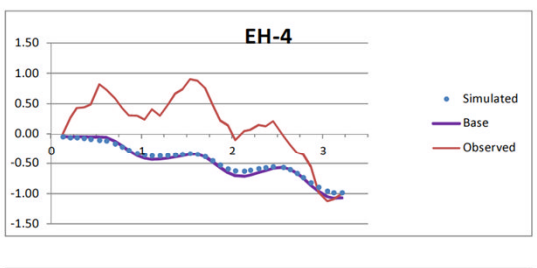


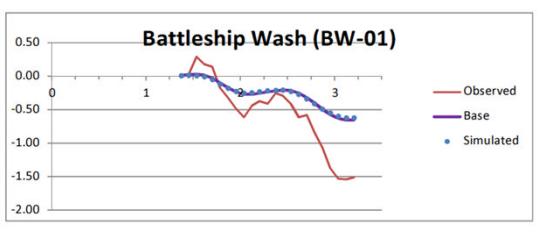


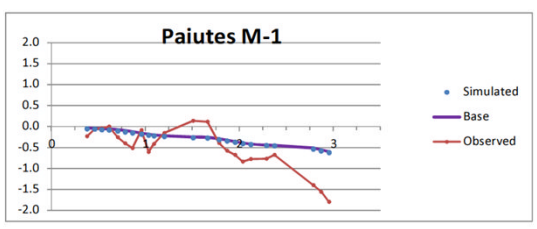


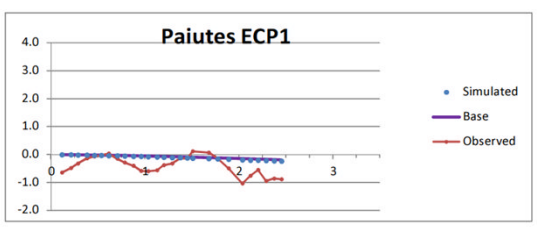


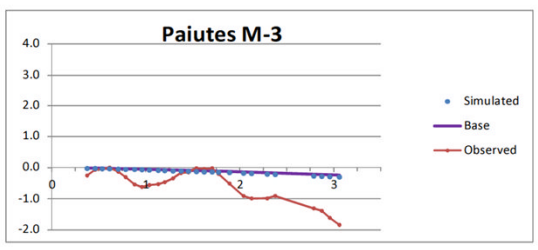


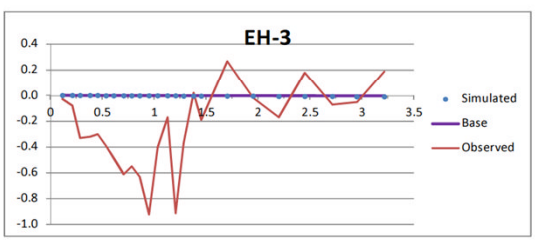


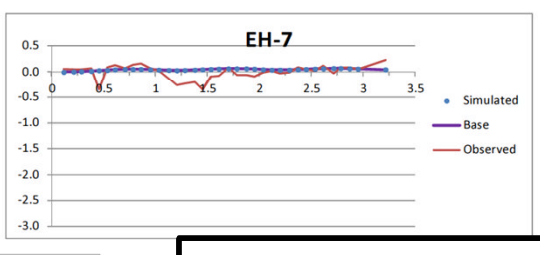


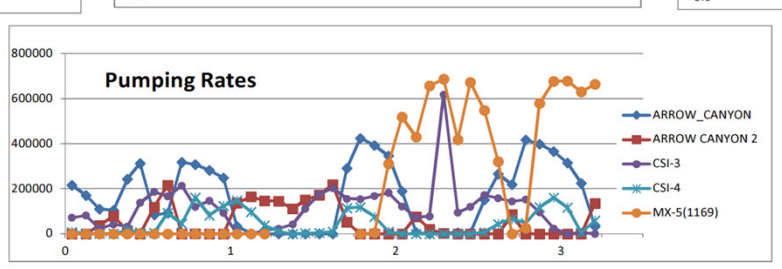








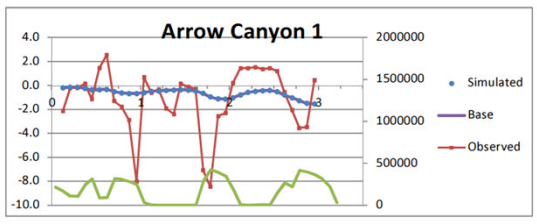


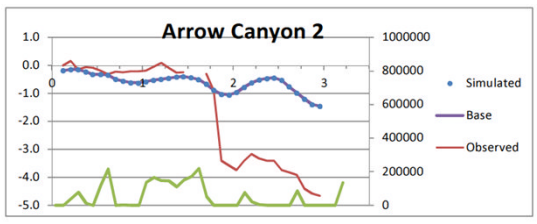


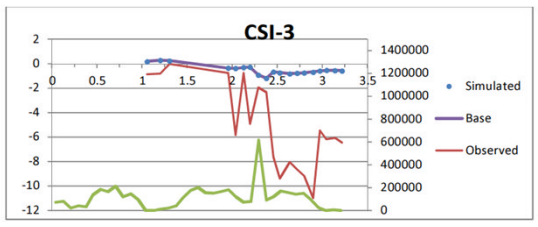
Sensitivity of Simulated Drawdown to Dividing KX_CAU_3 by 2

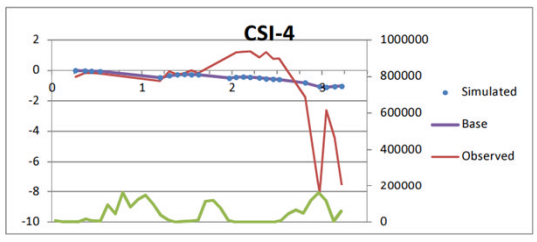
Lower Colorado River Flow System

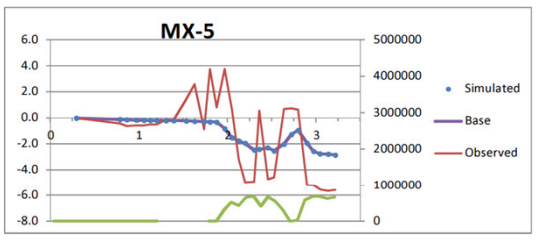
TETRA TECH GEO

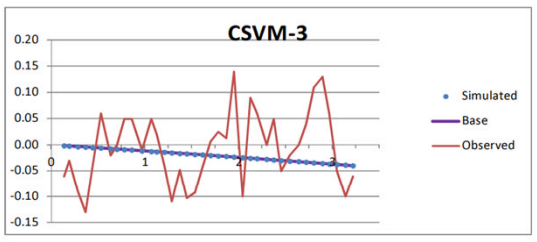


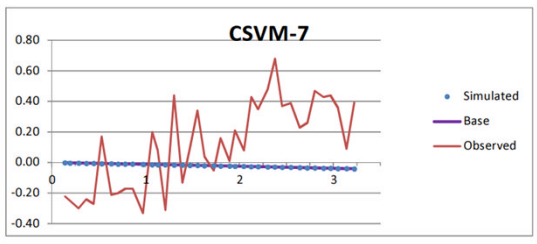


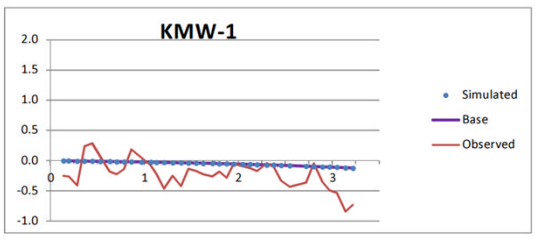


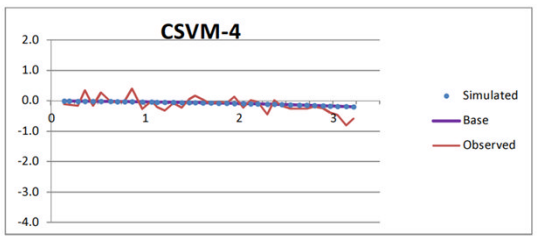


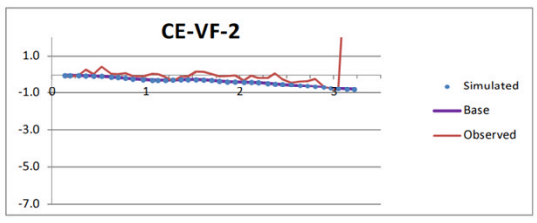


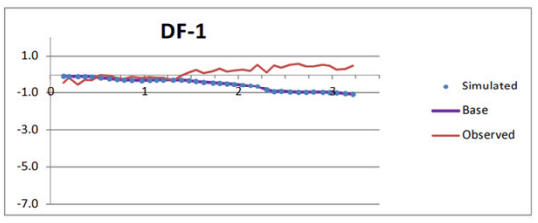


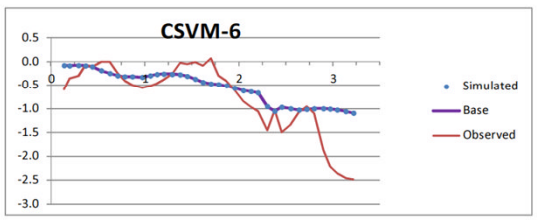


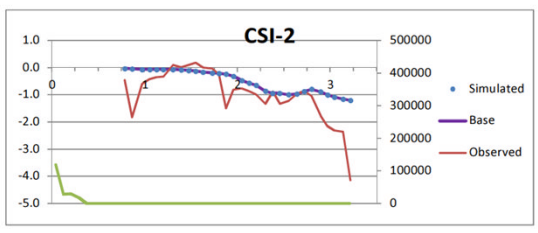


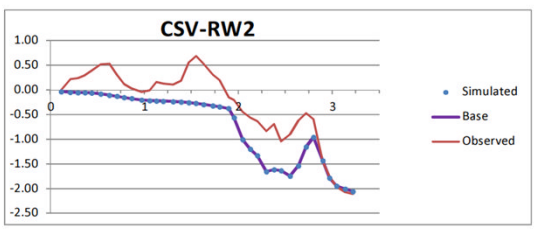


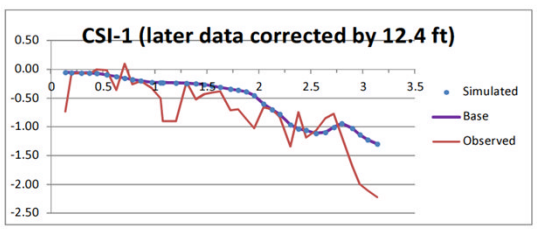


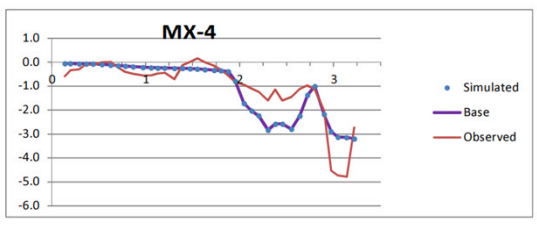


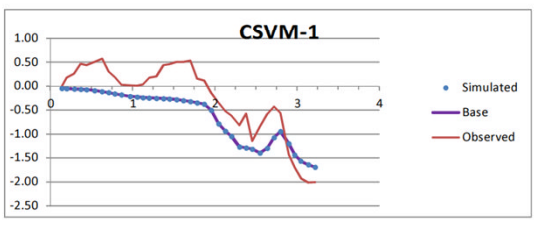


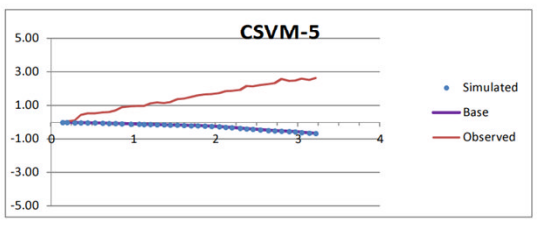


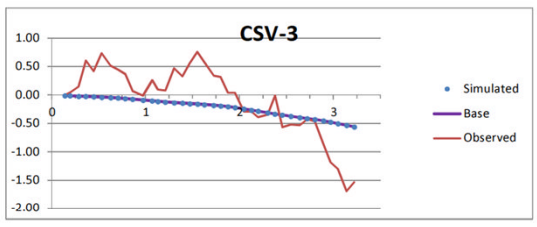


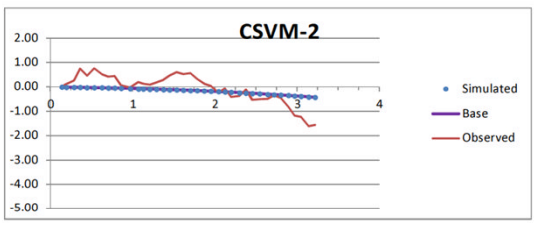


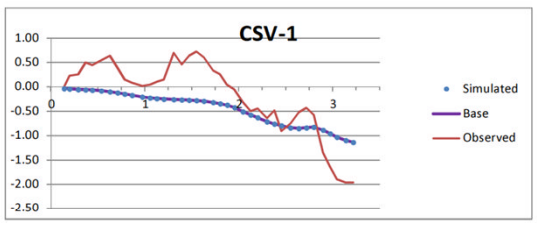


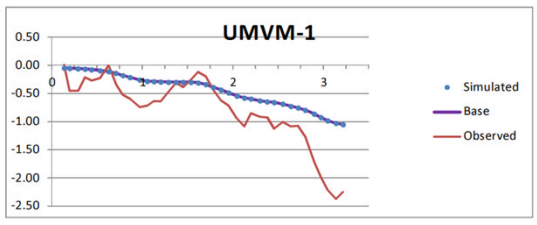


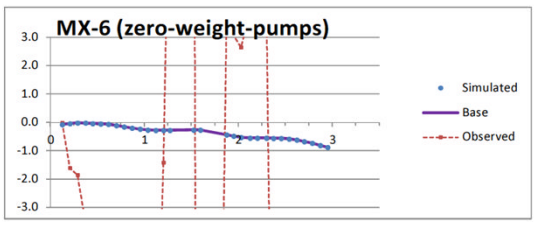


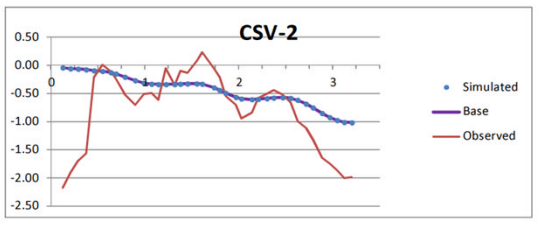


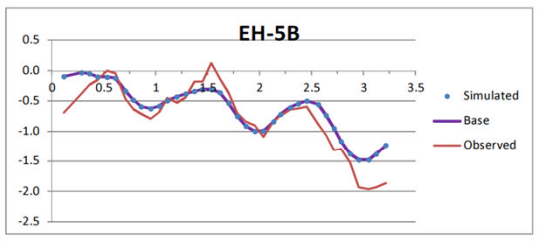


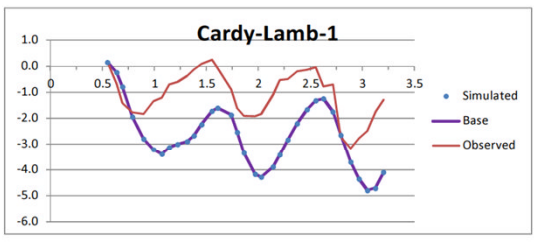


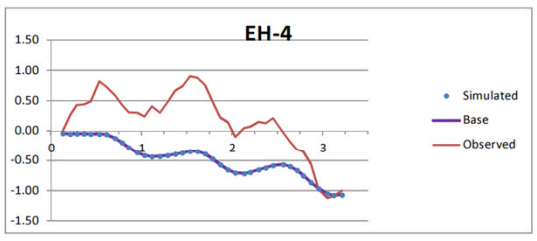


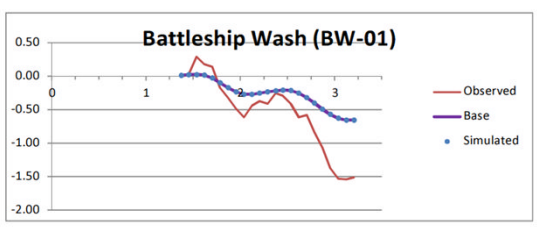


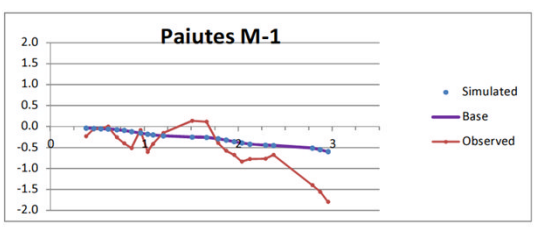


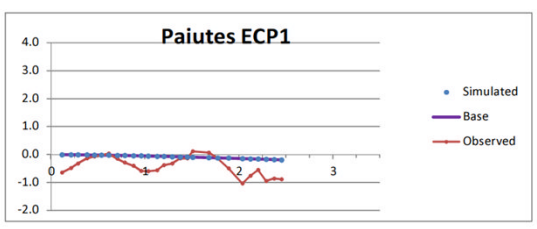


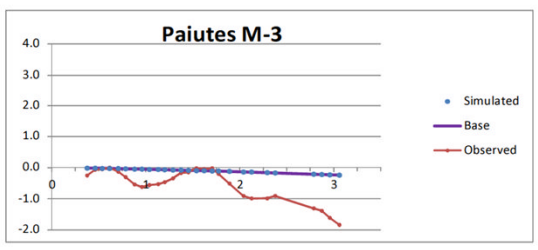


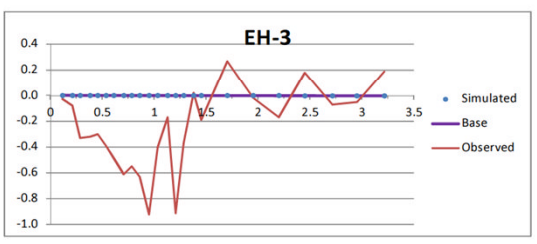


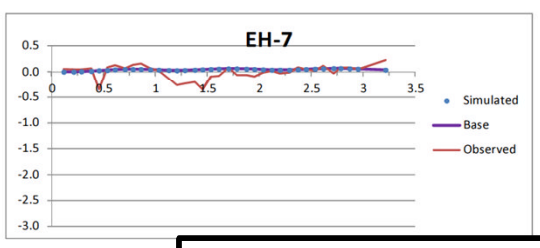


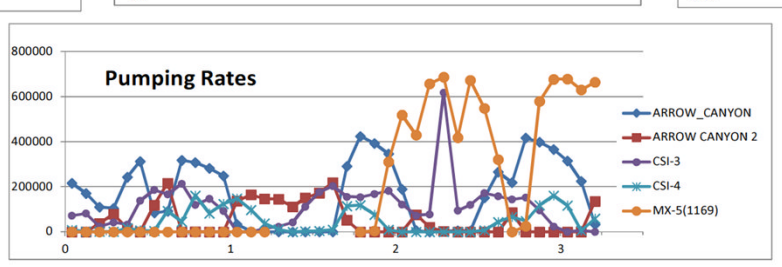








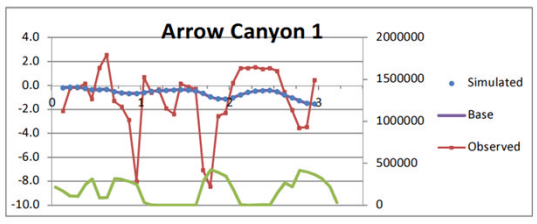


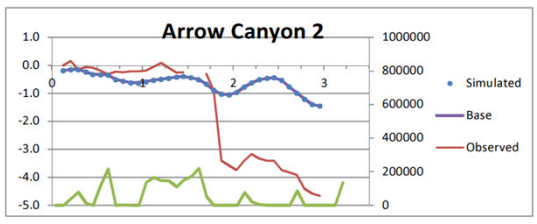


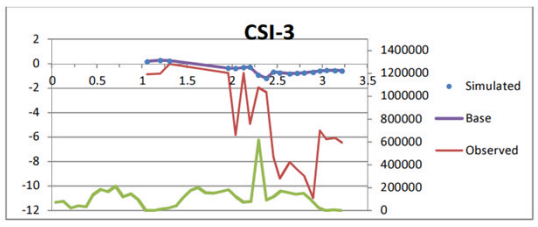
Sensitivity of Simulated Drawdown to Multiplying KX_PC1 by 2

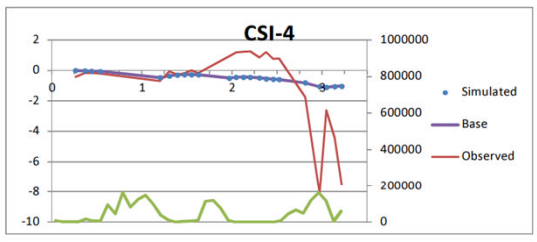
Lower Colorado River Flow System

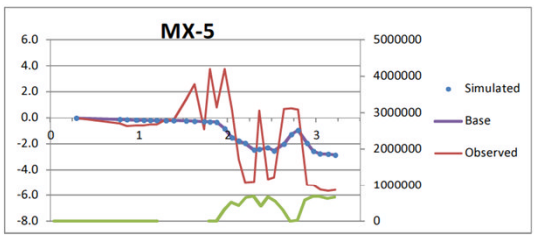
TETRA TECH GEO

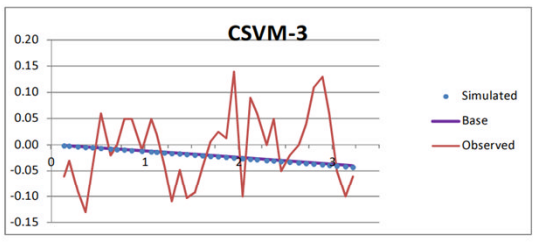


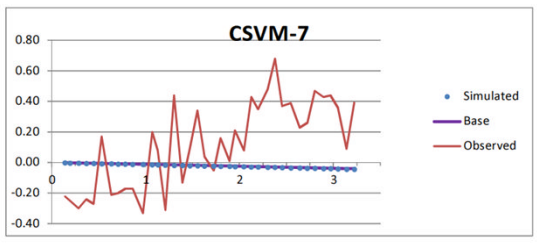


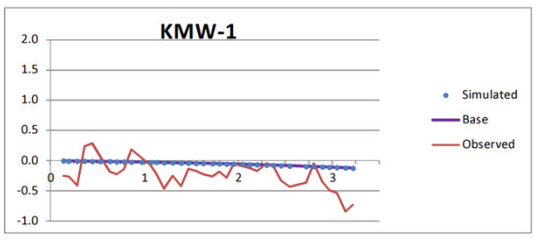


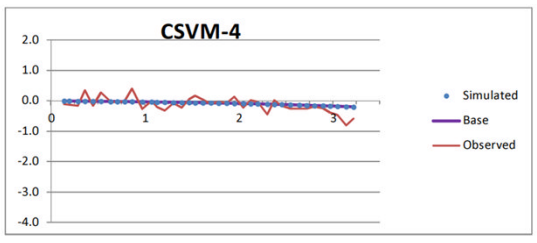


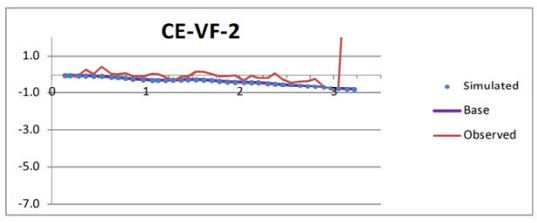


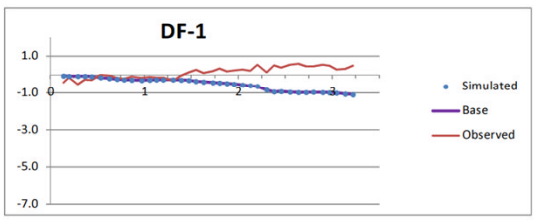


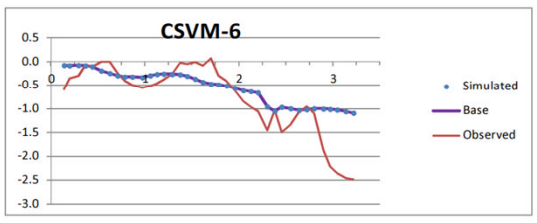


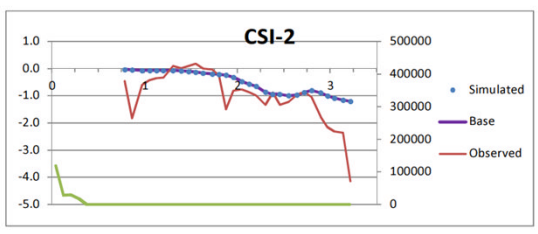


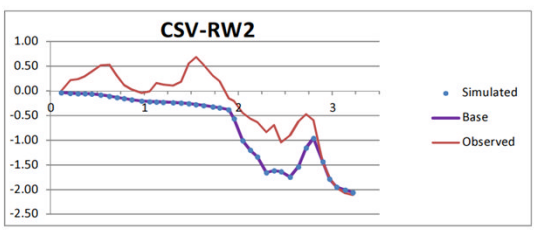


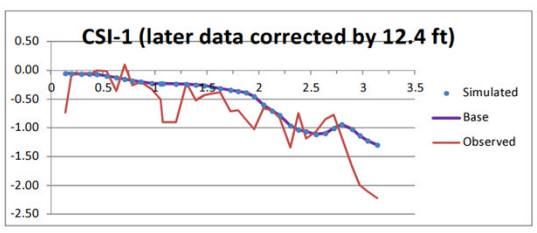


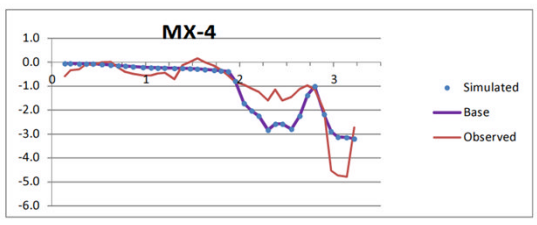


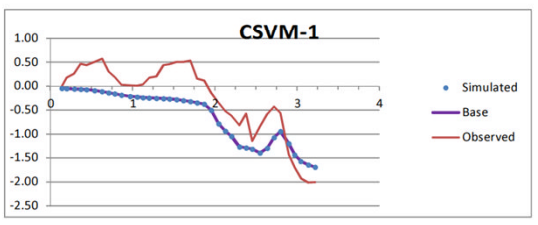


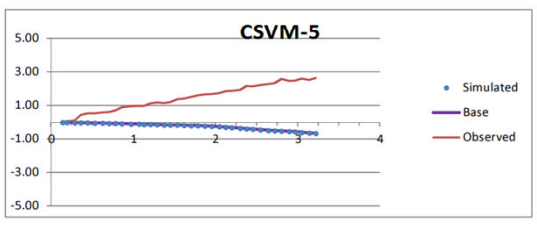


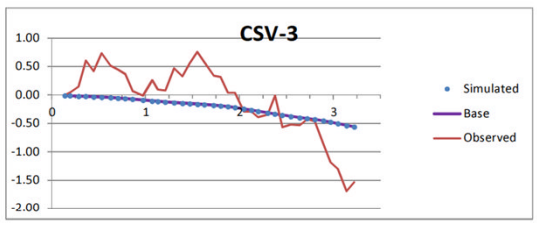


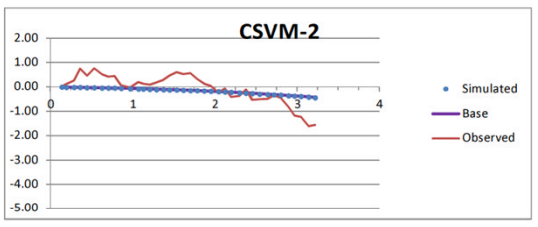


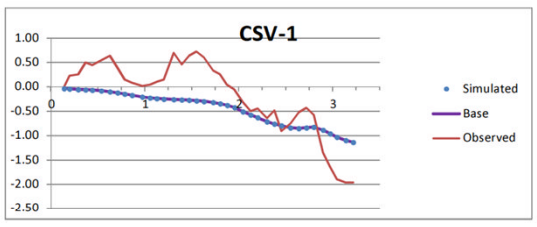


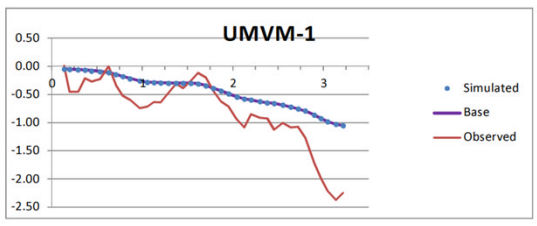


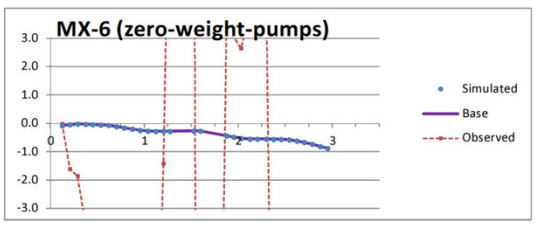


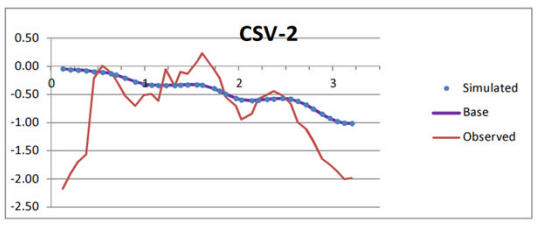


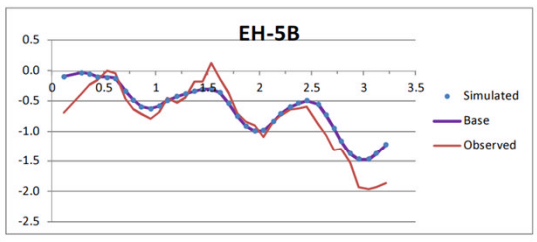


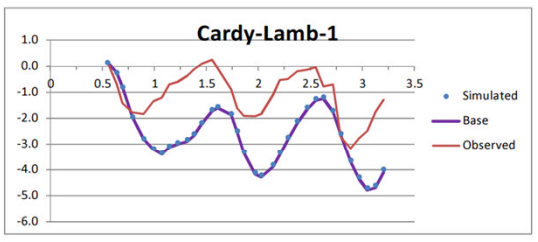


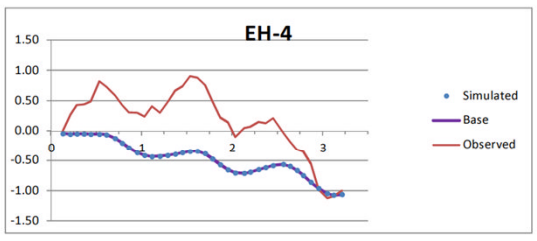


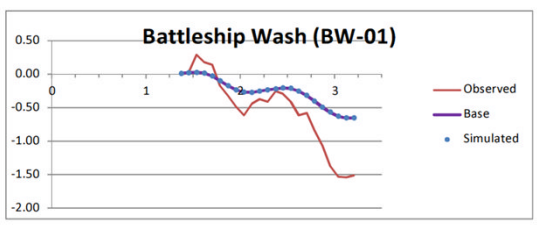


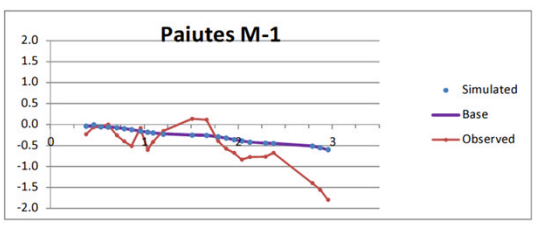


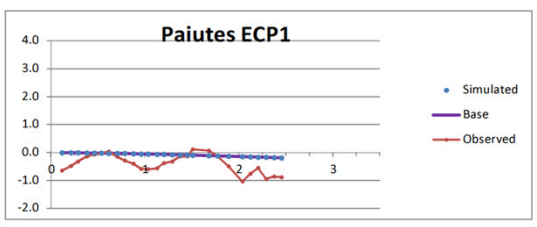


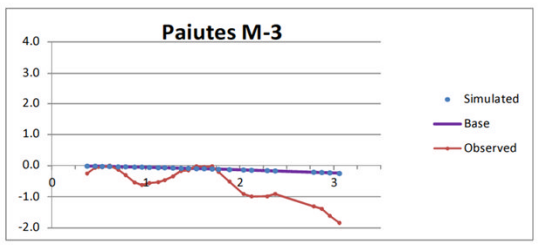


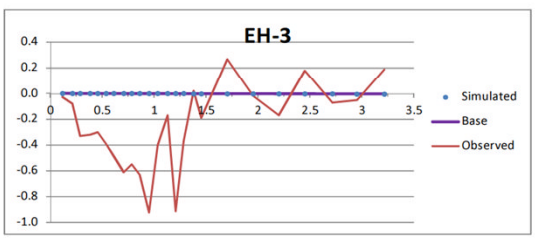


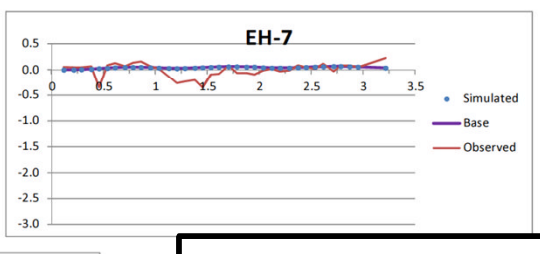


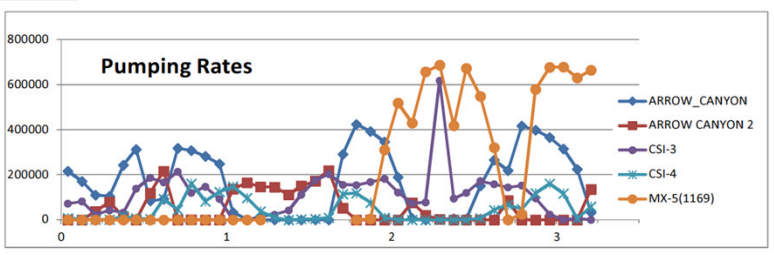








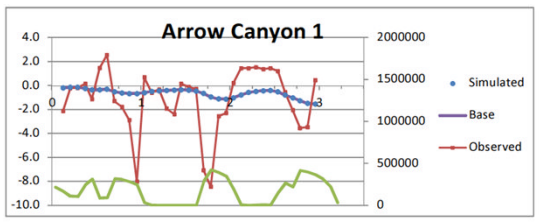


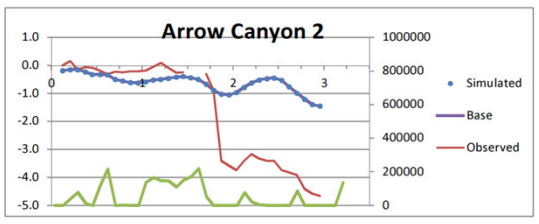


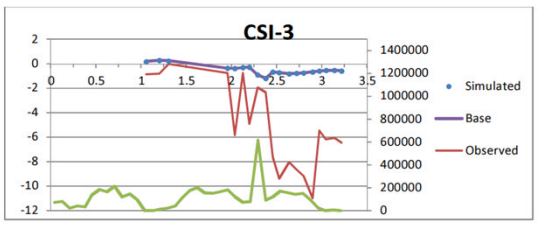
Sensitivity of Simulated Drawdown to Multiplying SFAC by 1.25

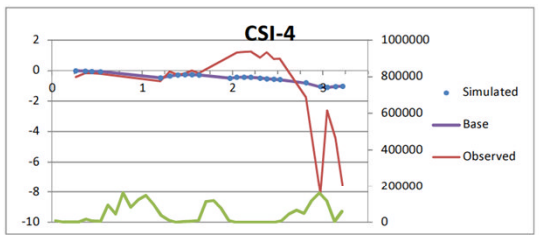
Lower Colorado River Flow System

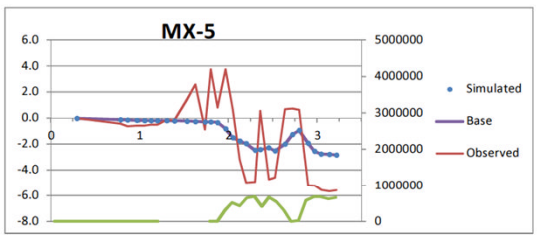
TETRA TECH GEO

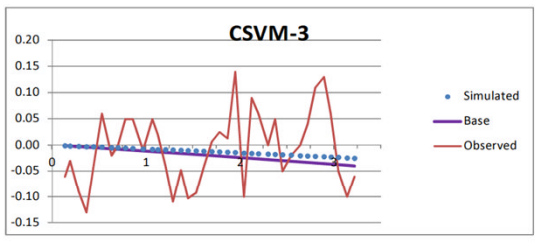


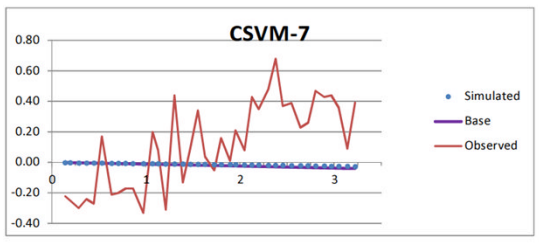


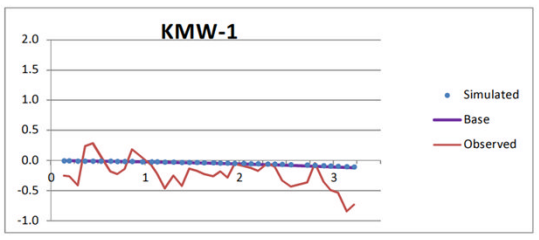


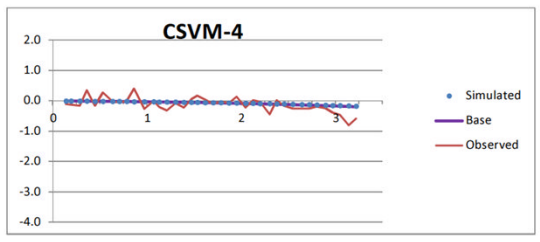


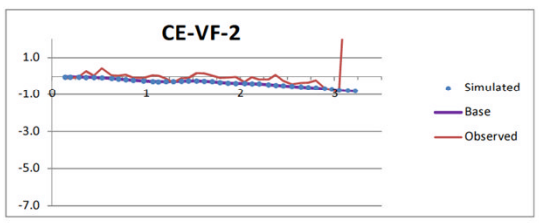


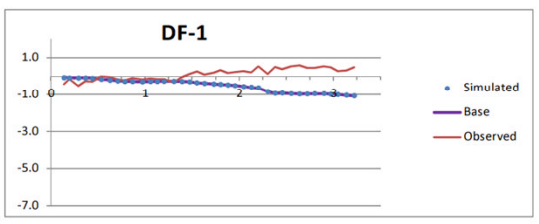


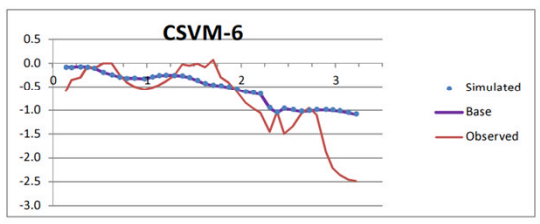


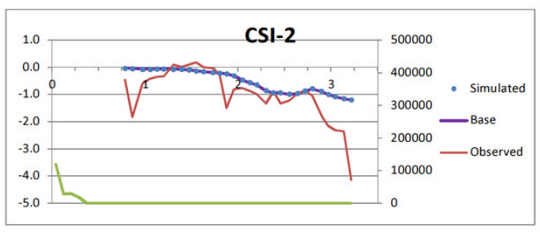


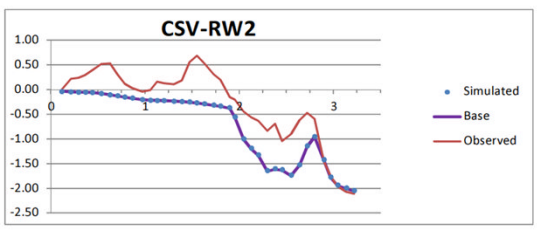


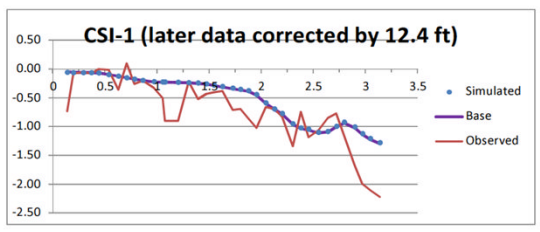


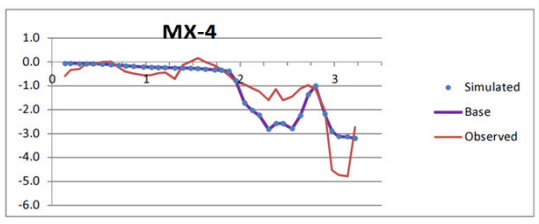


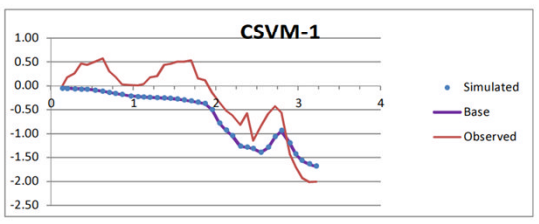


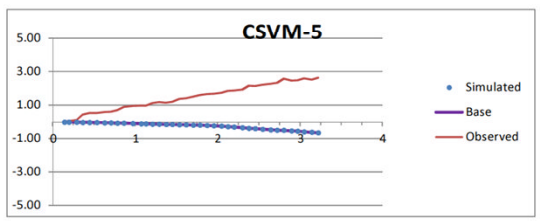


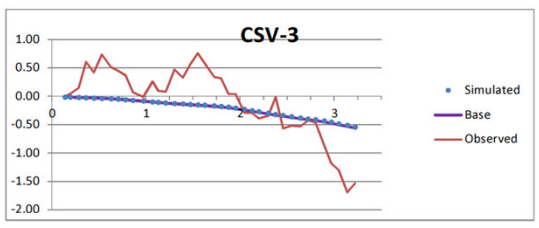


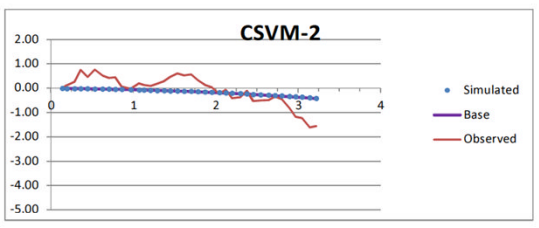


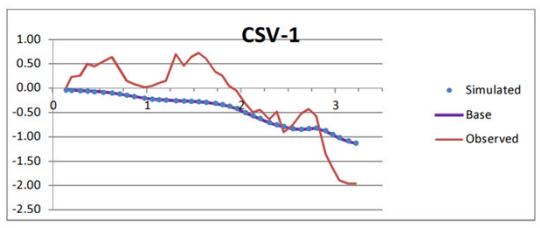


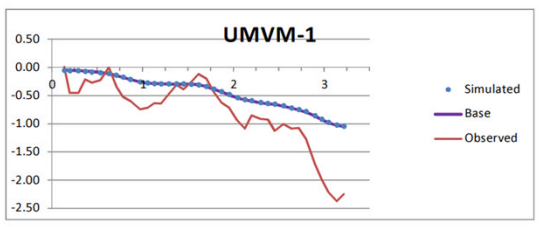


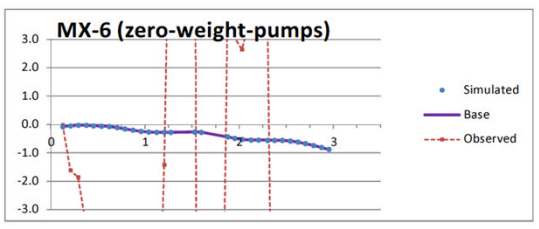


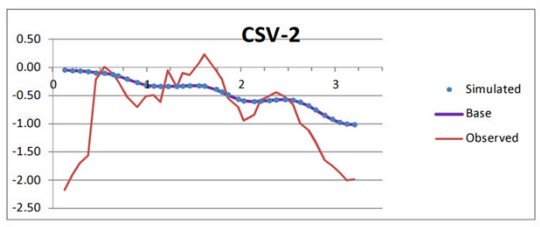


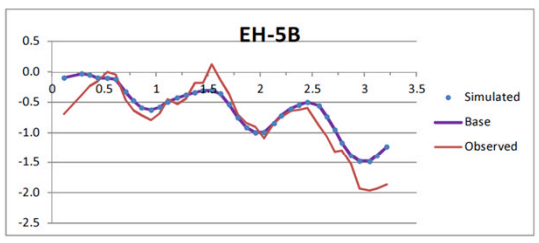


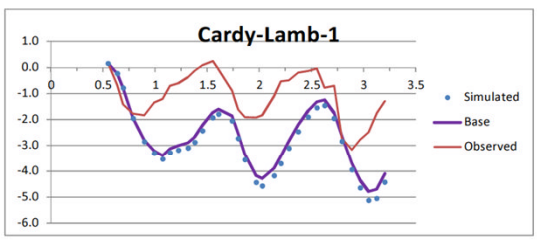


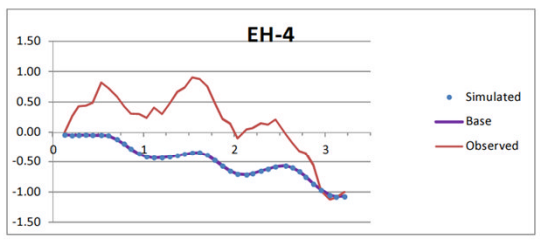


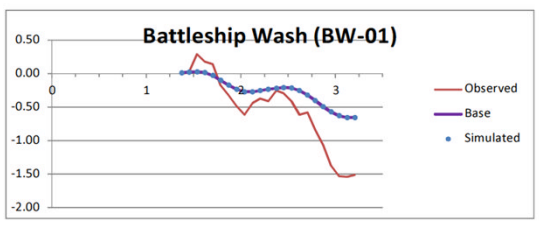


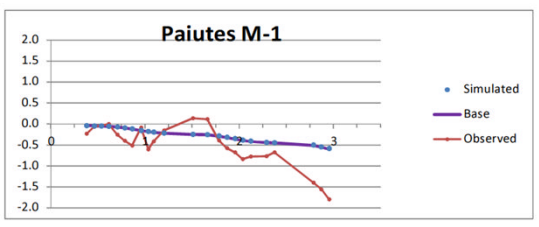


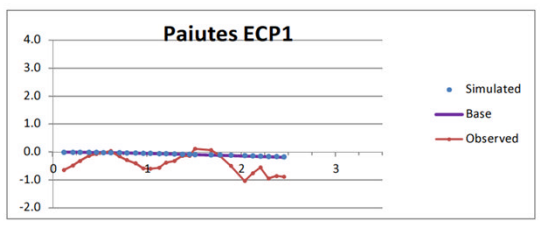


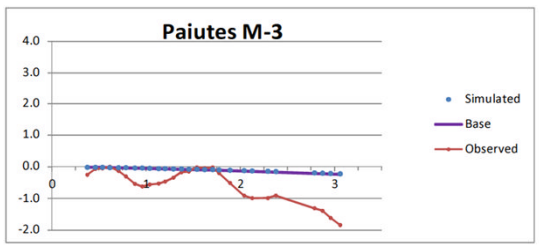


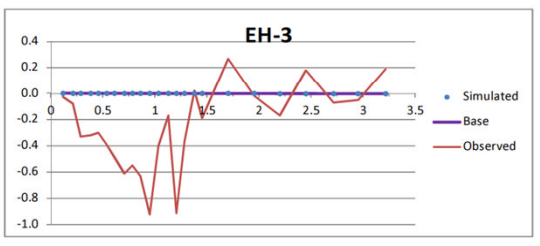


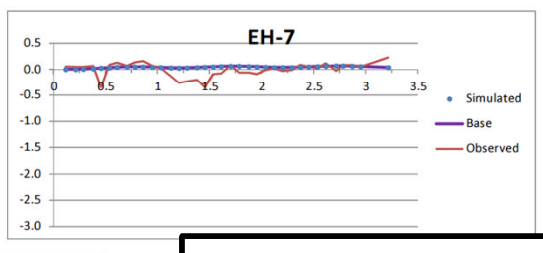


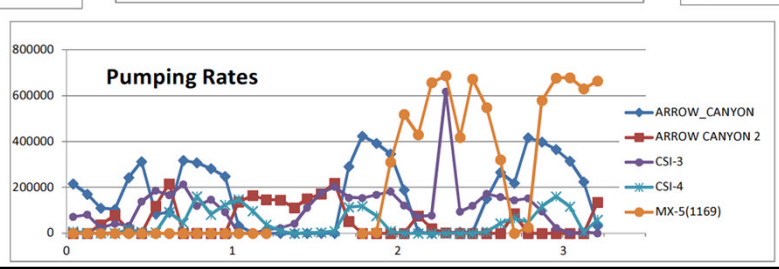








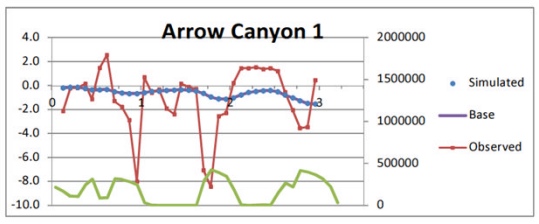


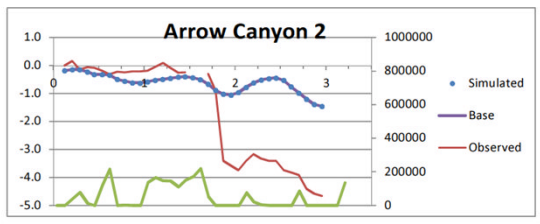


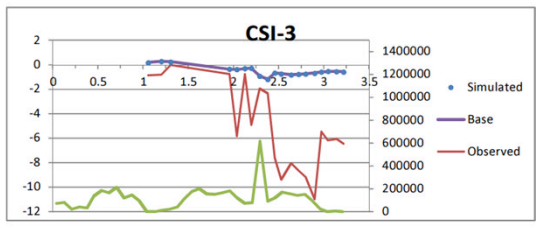
Sensitivity of Simulated Drawdown to Multiplying SFAC by 0.8

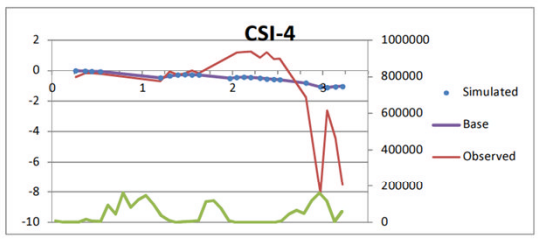
Lower Colorado River Flow System

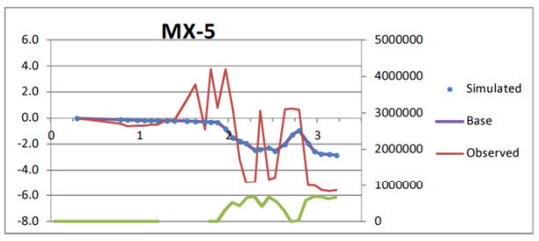
TETRA TECH GEO

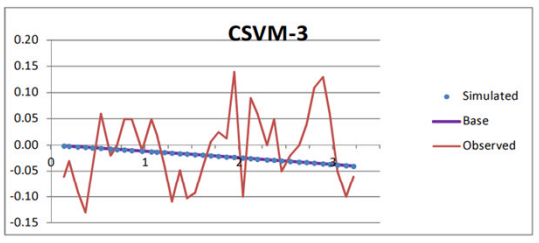


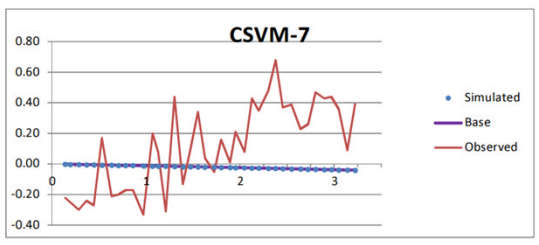


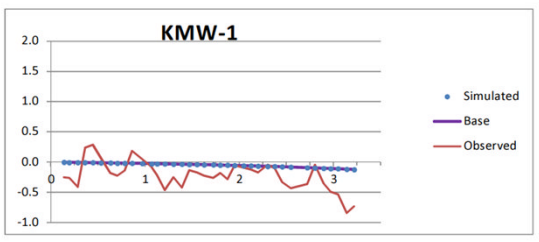


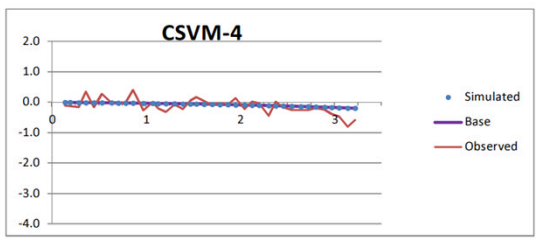


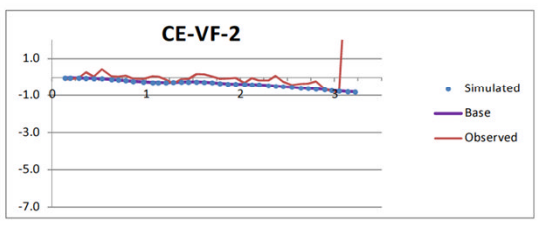


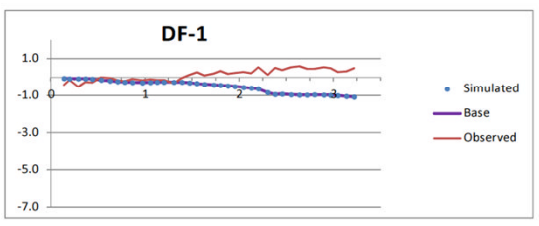


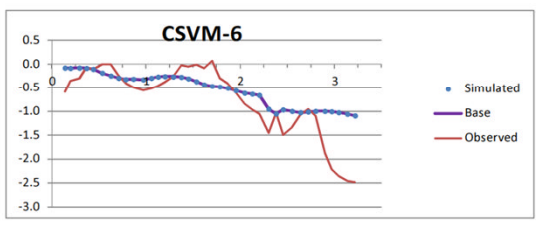


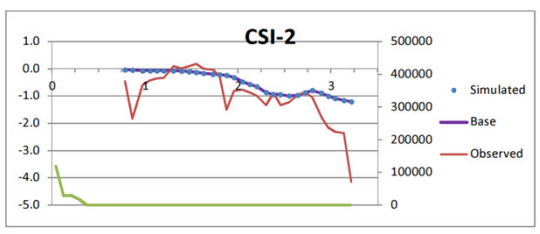


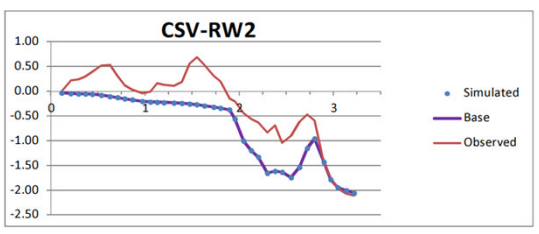


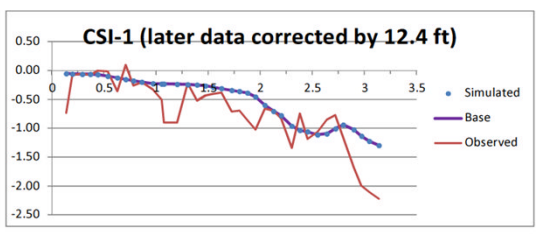


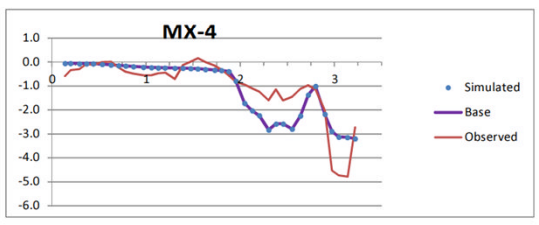


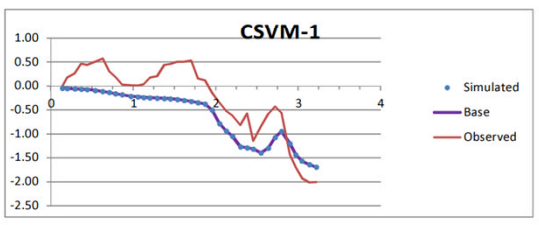


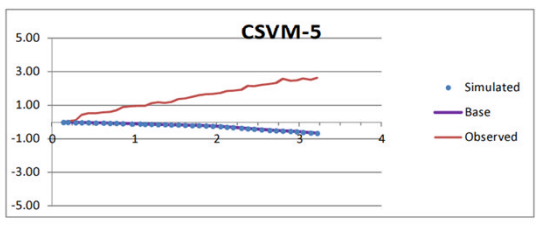


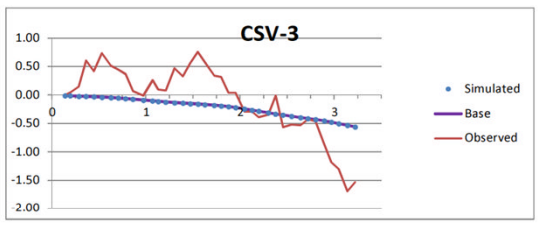


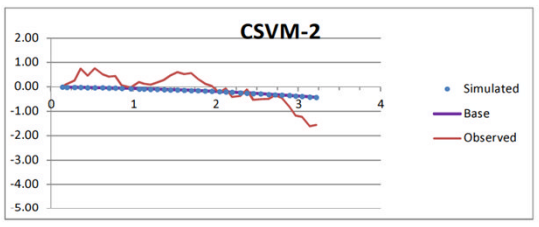


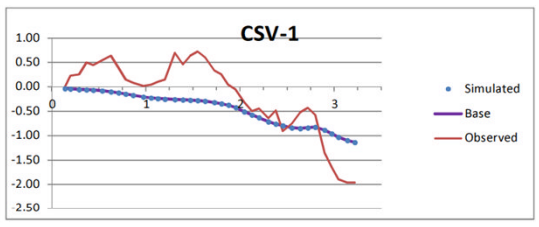


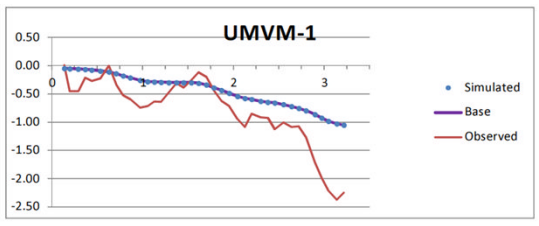


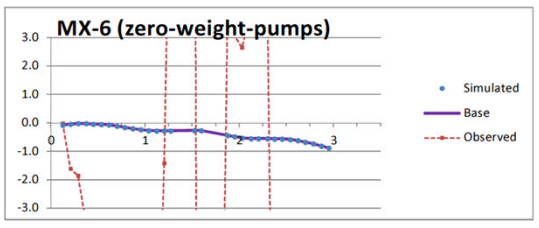


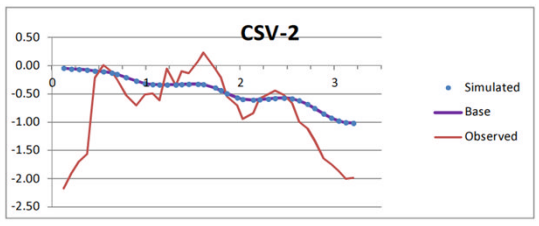


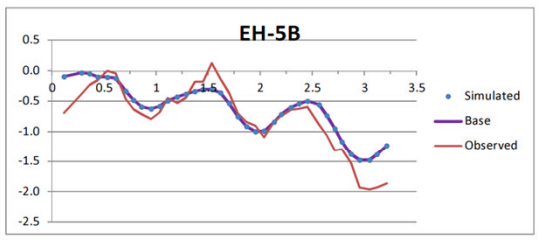


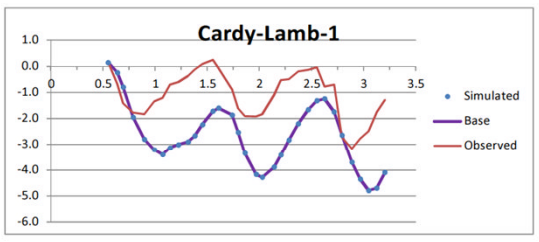


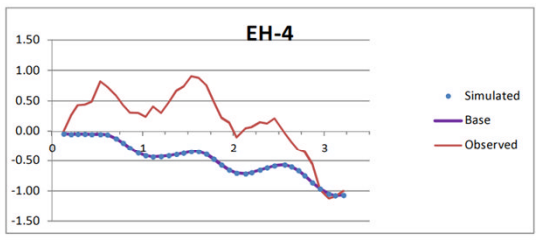


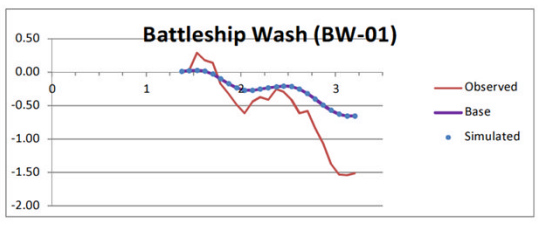


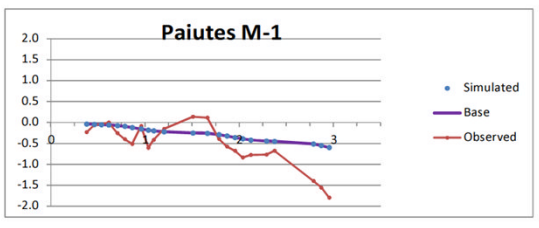


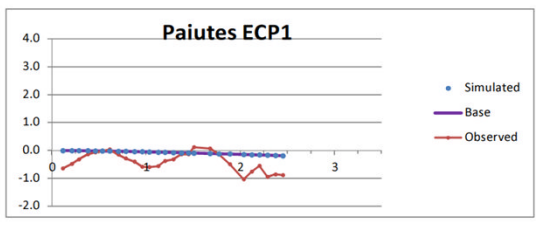


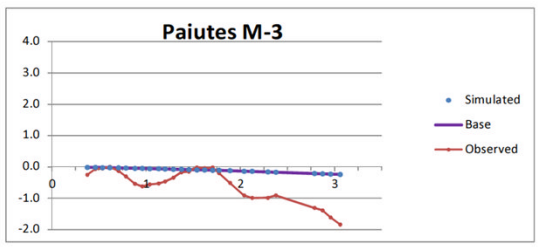


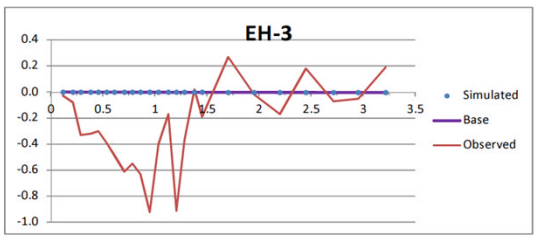


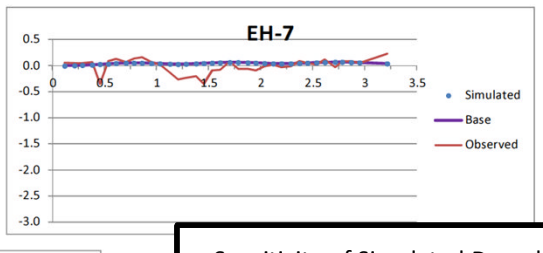


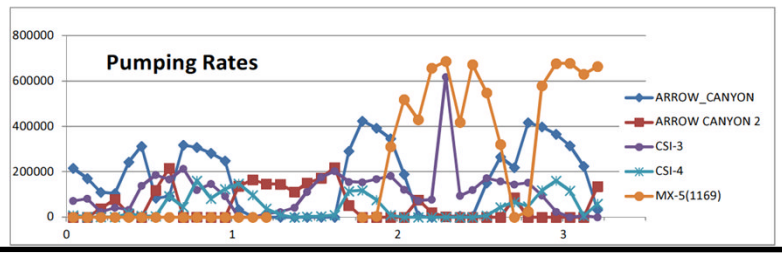








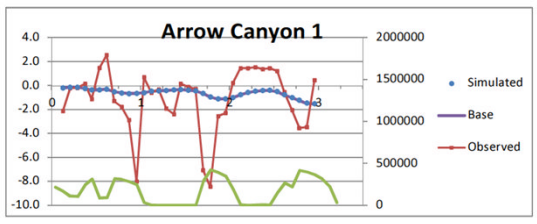


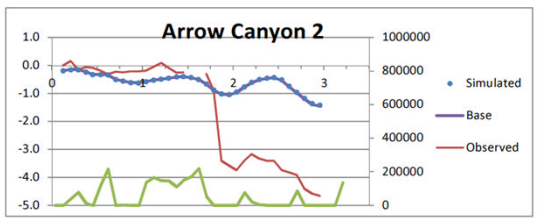


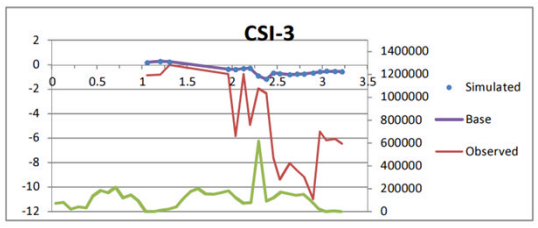
Sensitivity of Simulated Drawdown to Multiplying SFACMM by 2

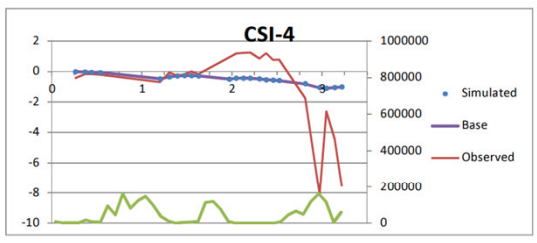
Lower Colorado River Flow System

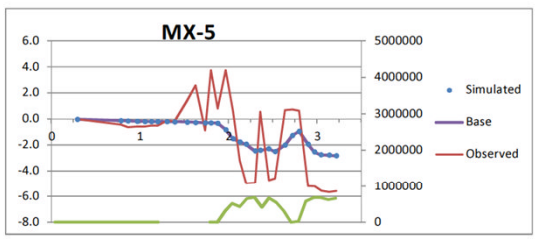
TETRA TECH GEO

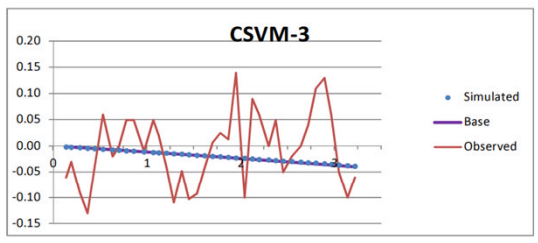


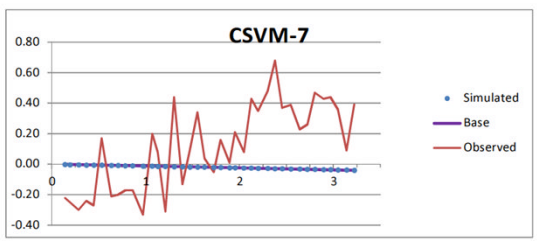


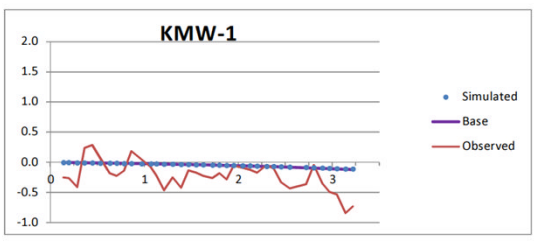


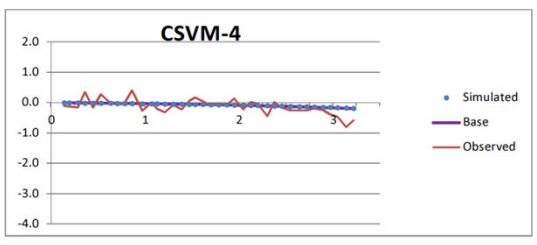


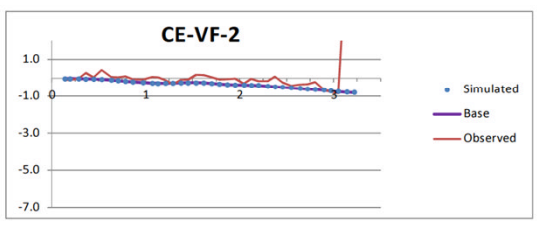


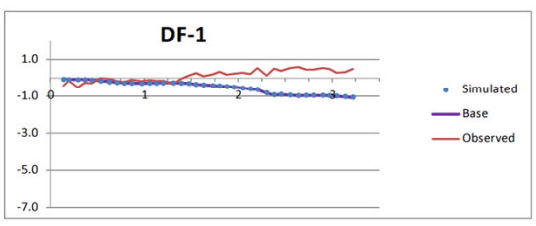


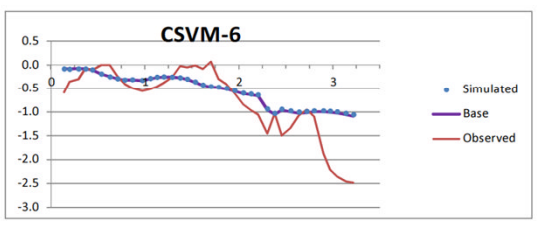


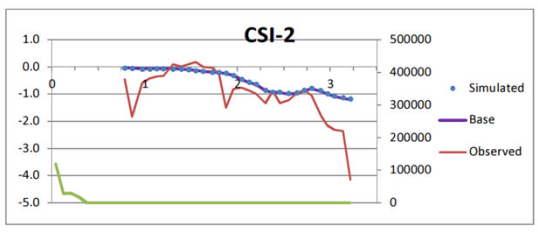


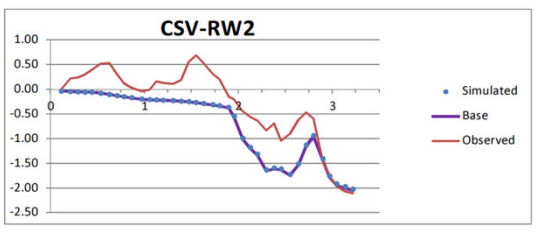


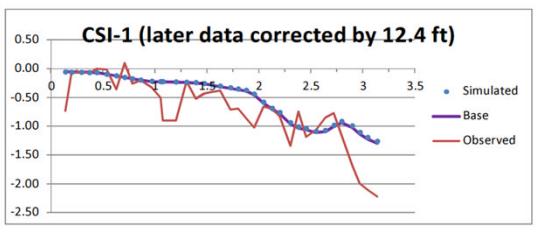


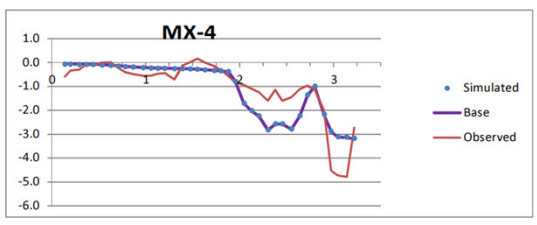


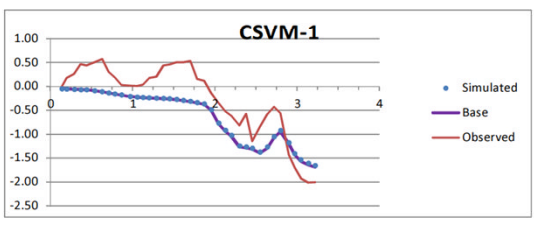


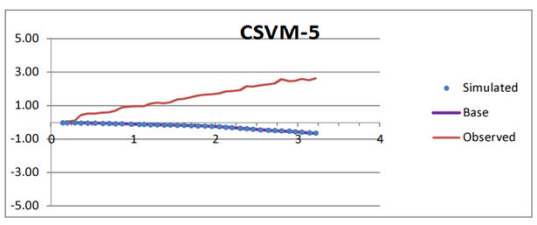


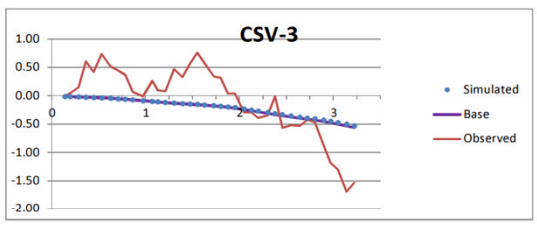


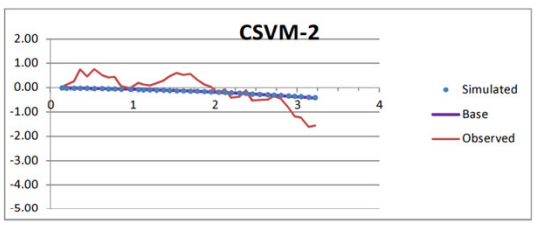


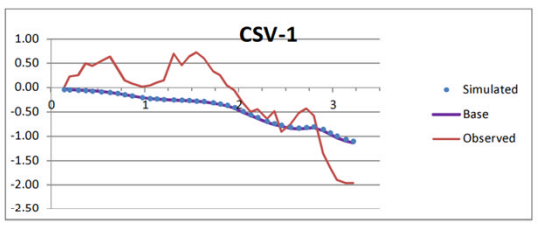


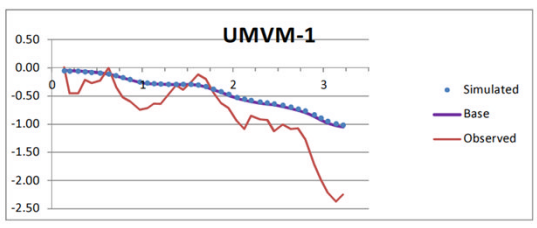


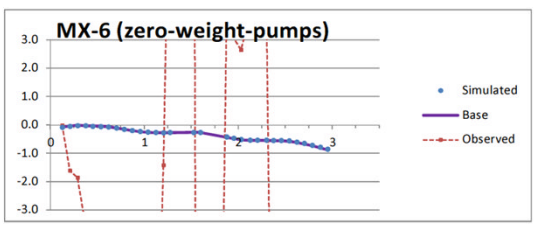


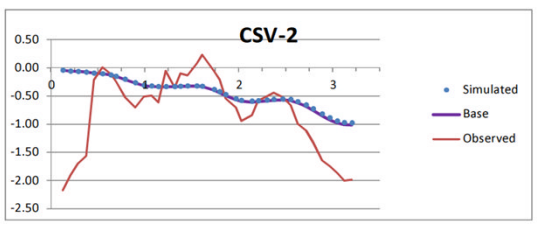


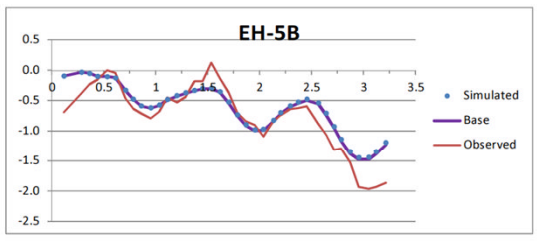


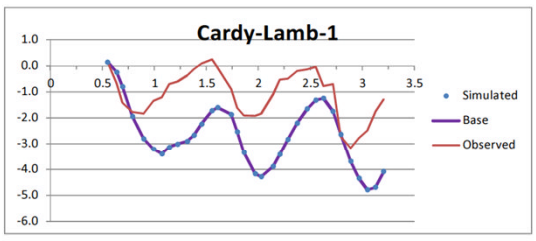


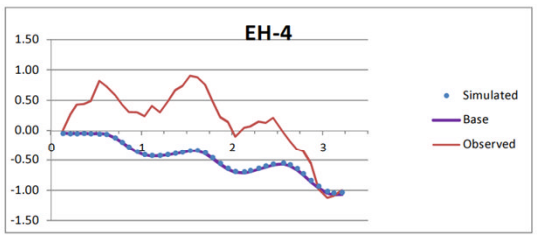


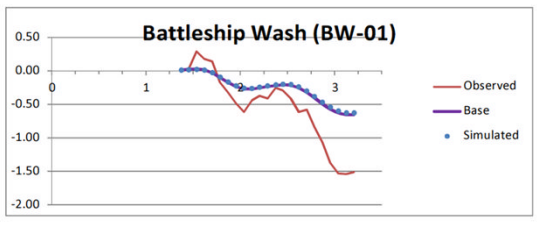


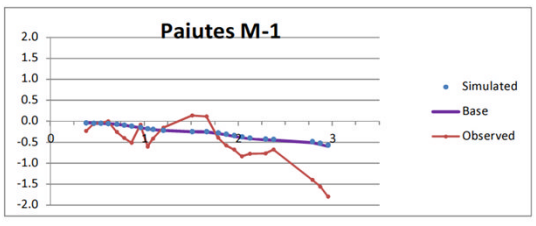


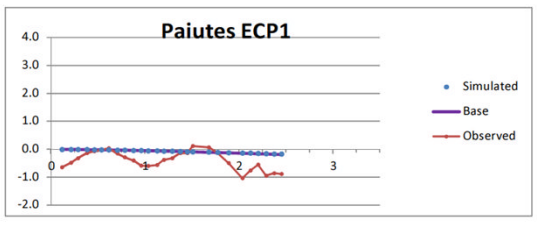


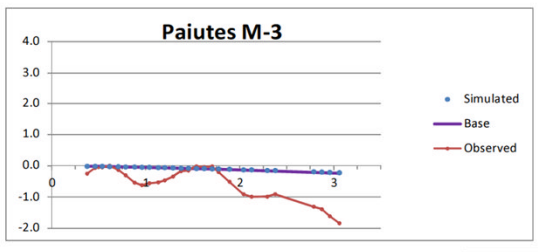


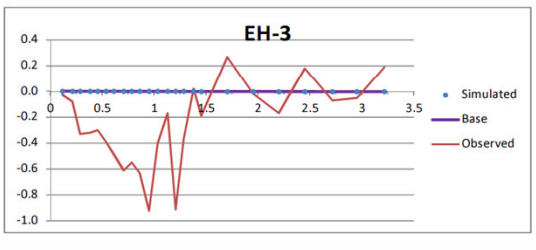


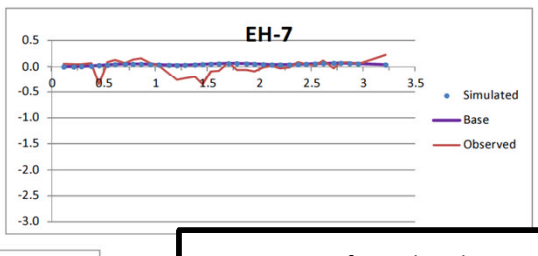


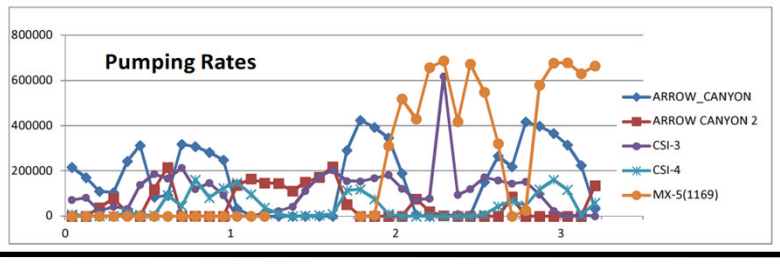








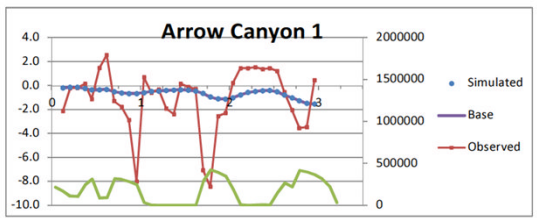


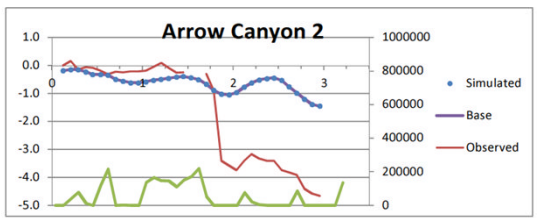


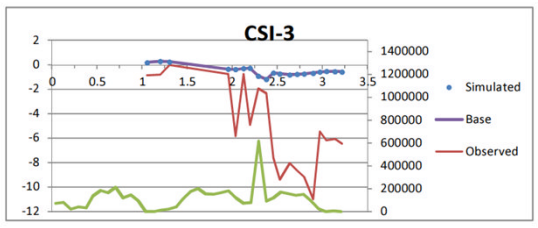
Sensitivity of Simulated Drawdown to Multiplying SS_PC4 by 2

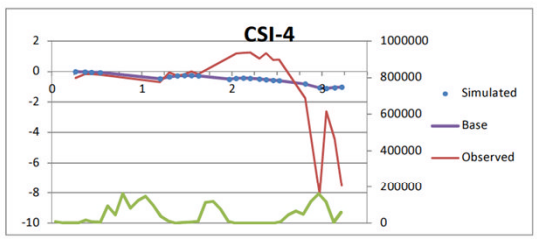
Lower Colorado River Flow System

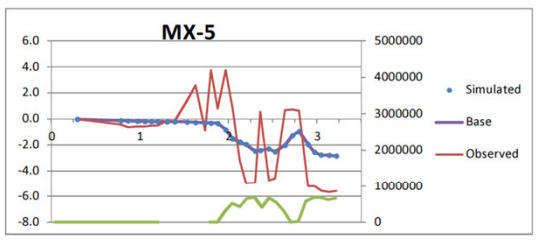
TETRA TECH GEO

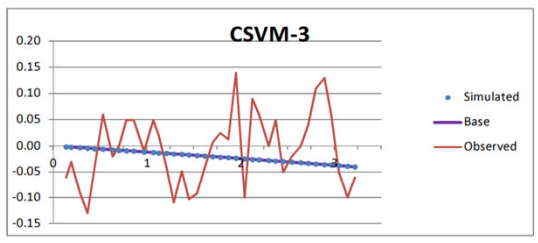


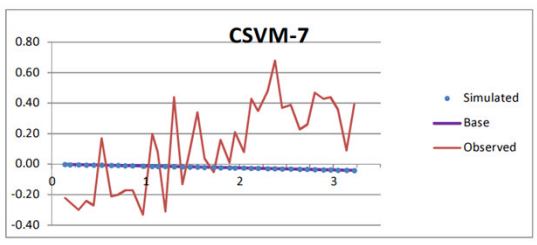


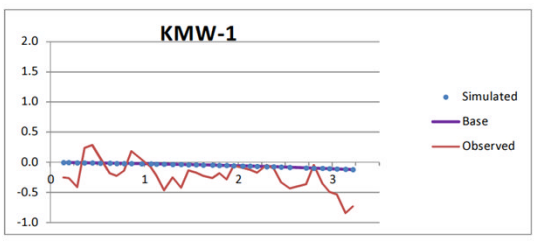


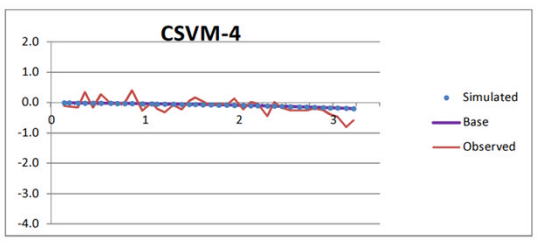


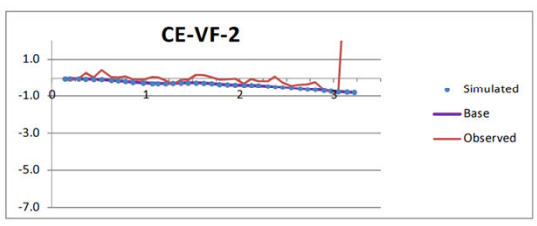


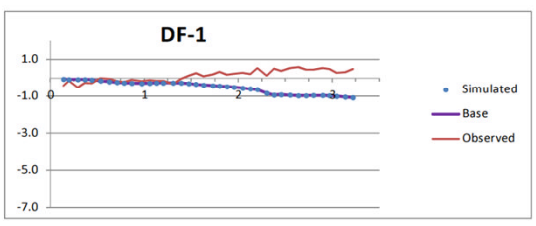


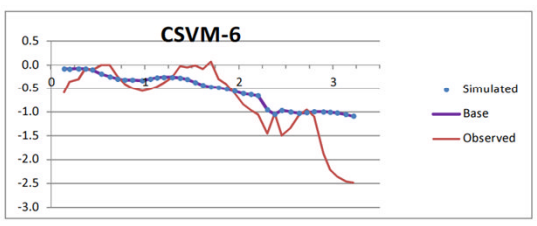


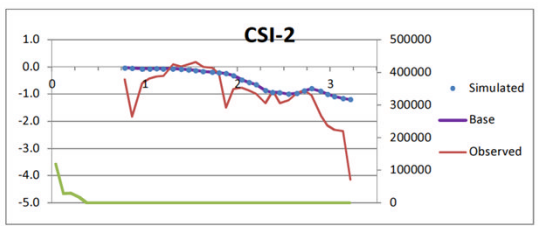


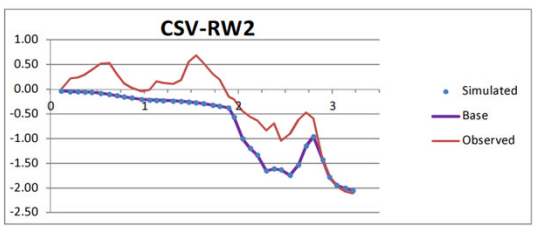


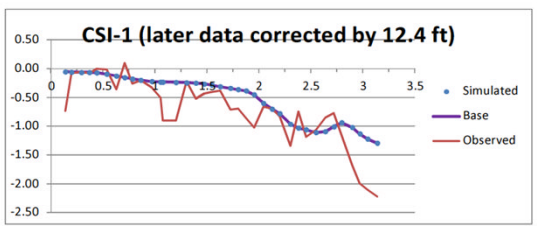


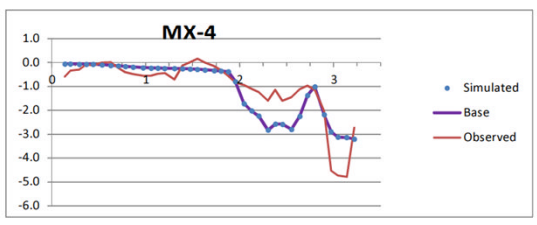


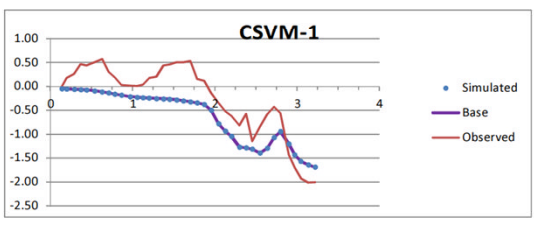


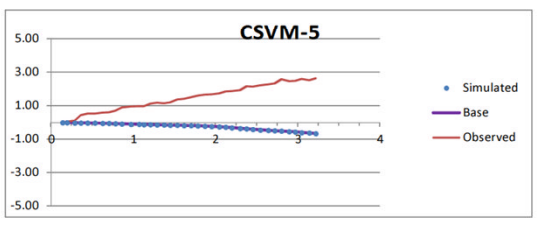


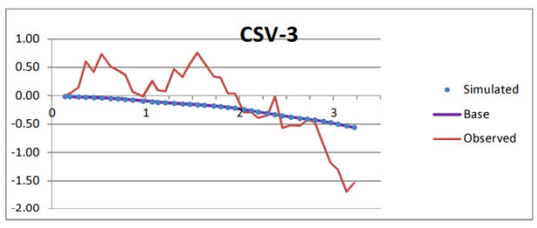


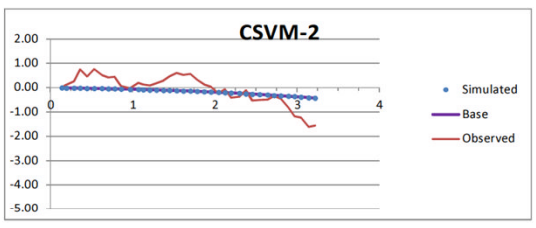


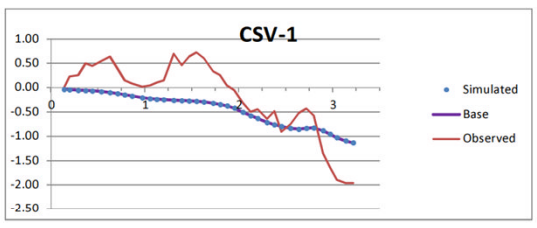


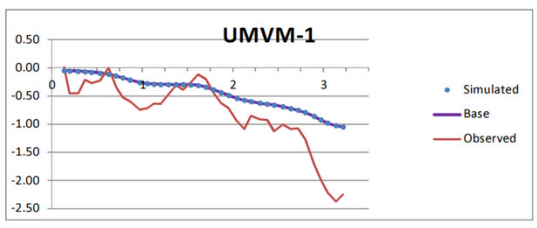


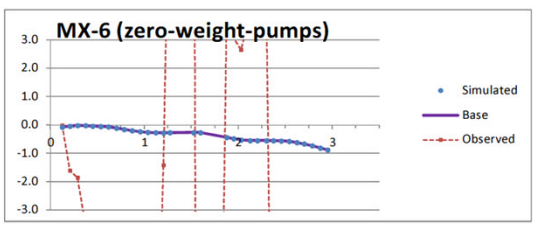


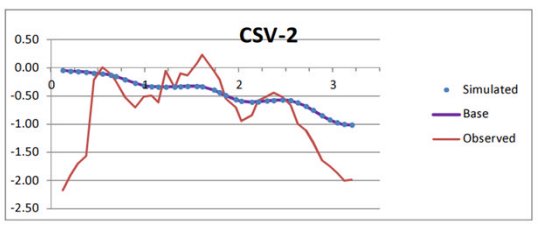


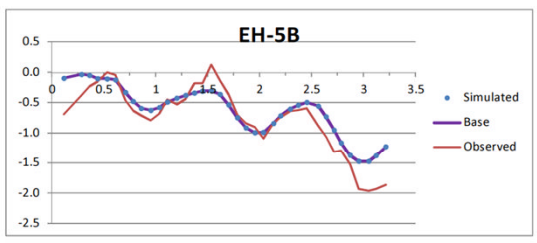


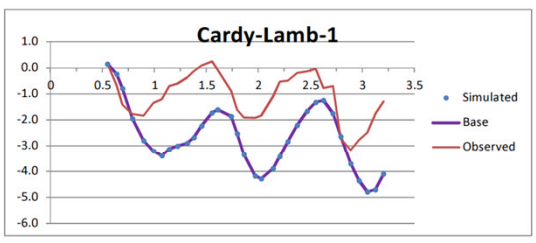


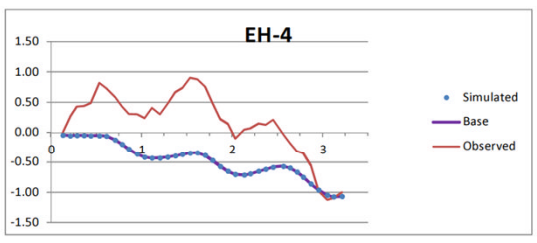


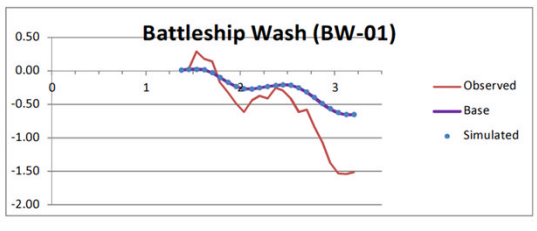


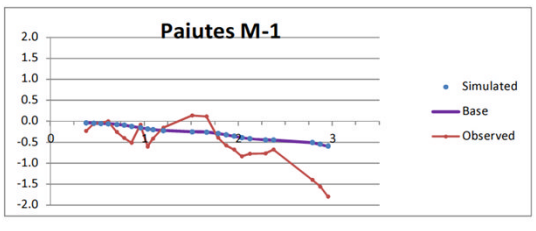


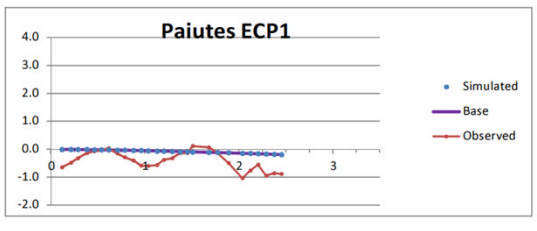


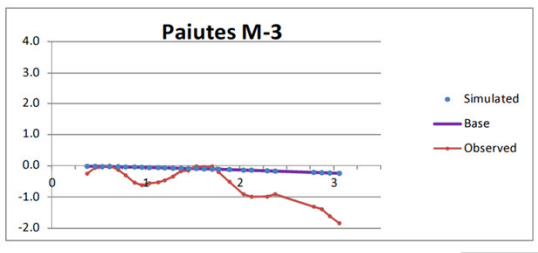


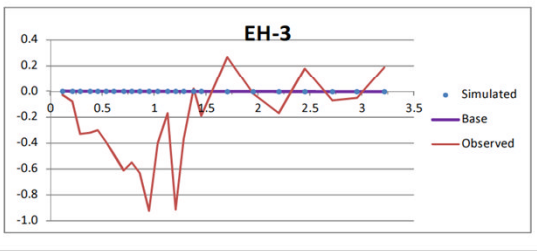


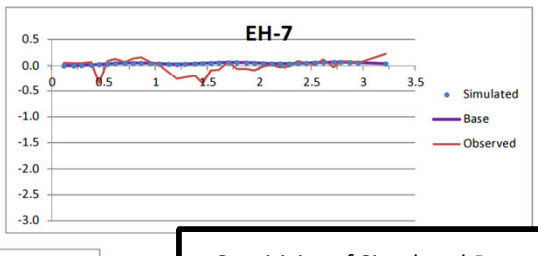


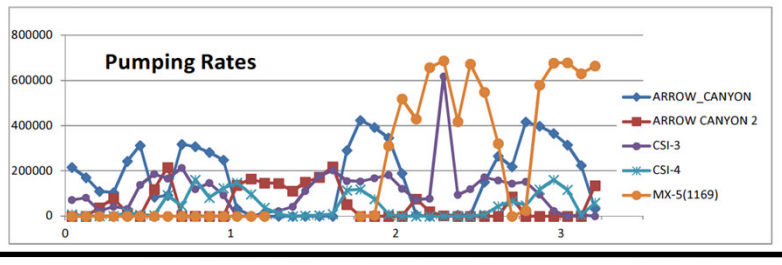








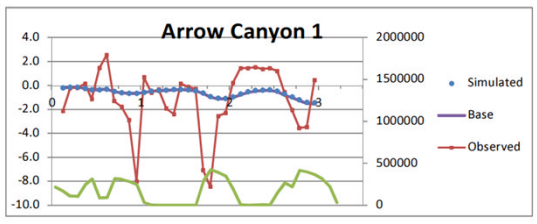


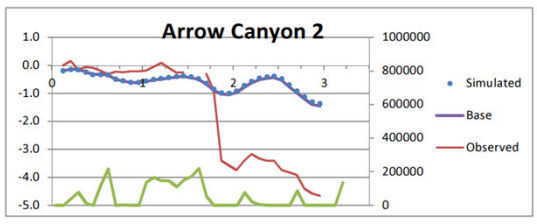


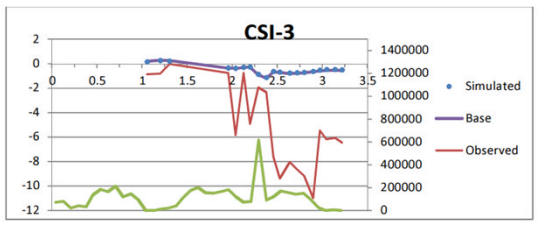
Sensitivity of Simulated Drawdown to Multiplying SY_PC4 by 1.125

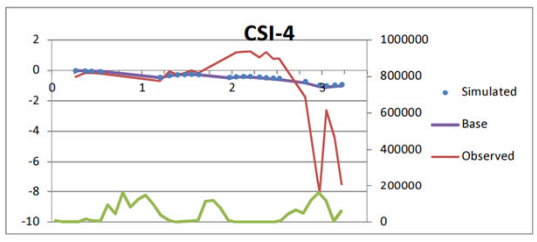
Lower Colorado River Flow System

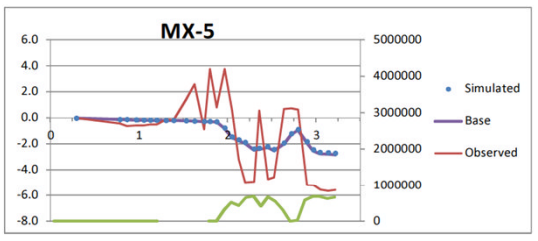
TETRA TECH GEO

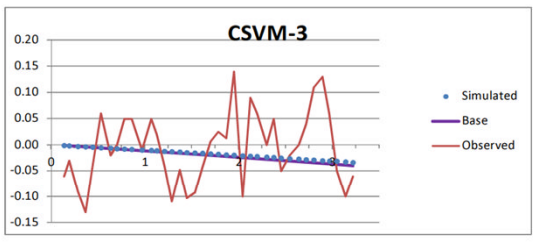


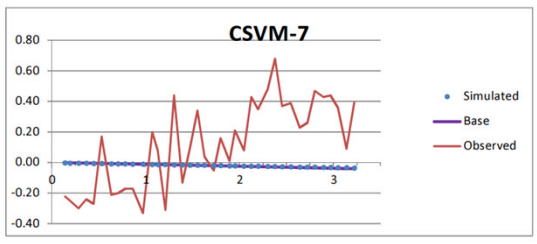


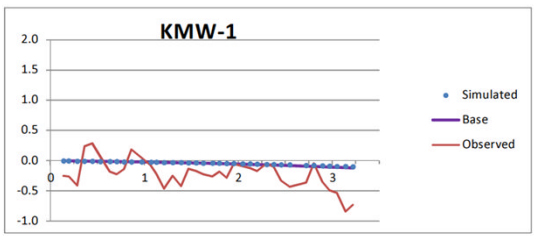


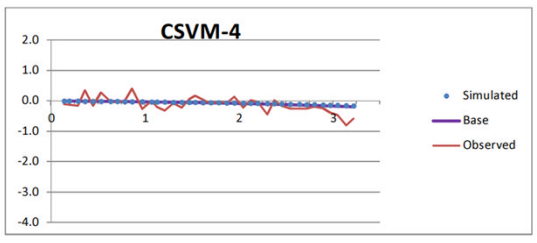


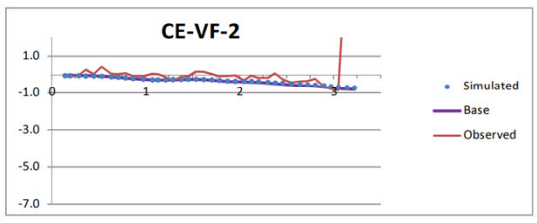


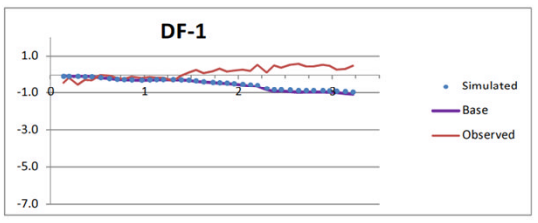


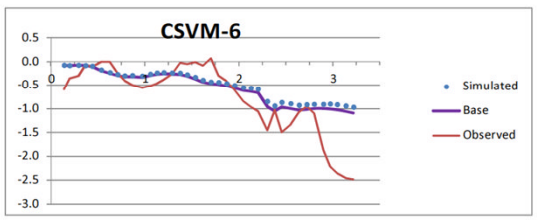


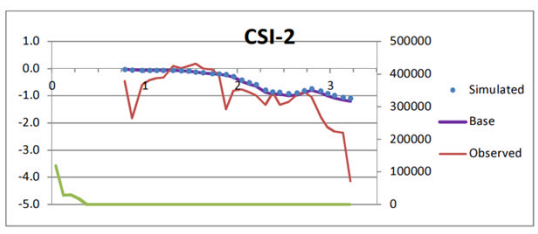


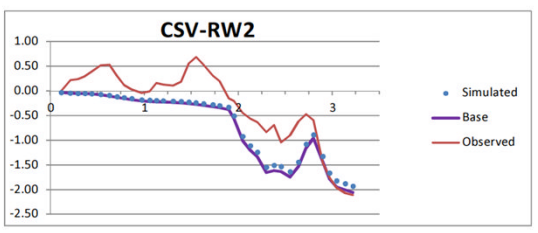


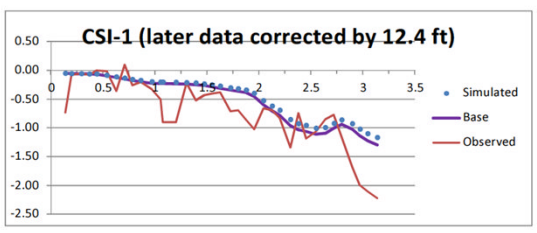


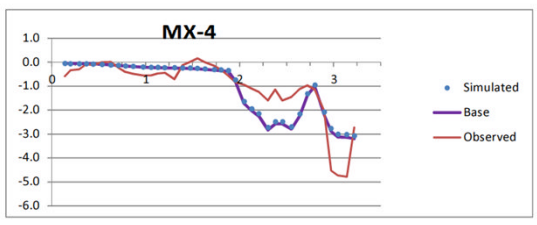


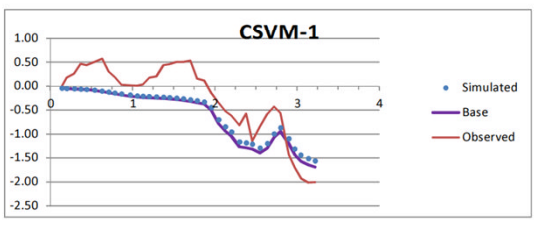


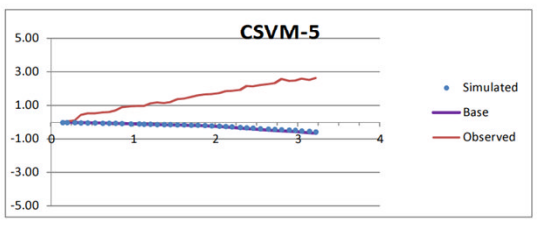


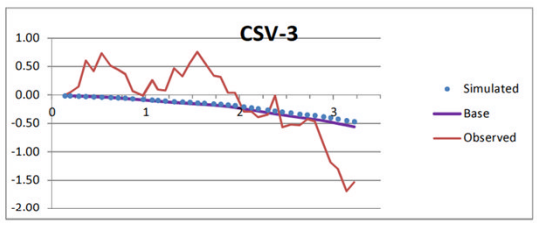


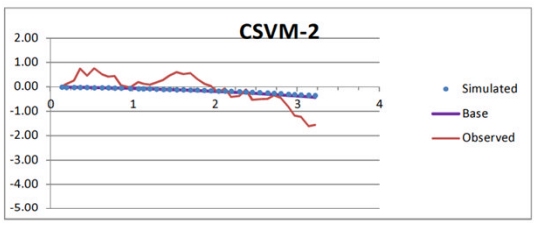


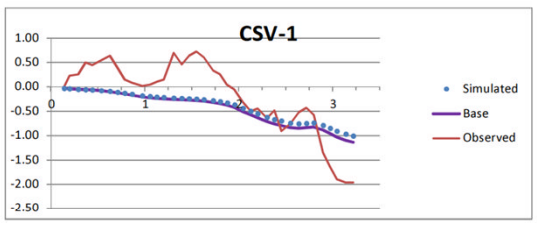


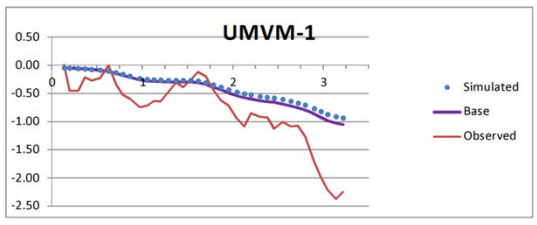


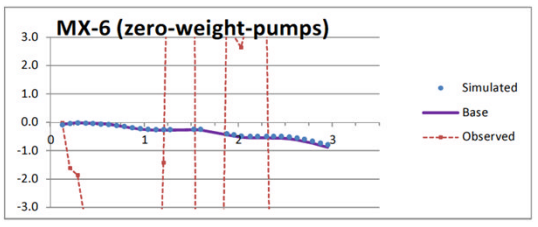


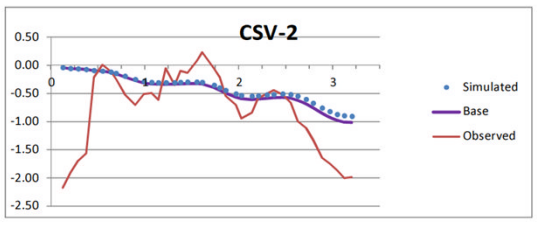


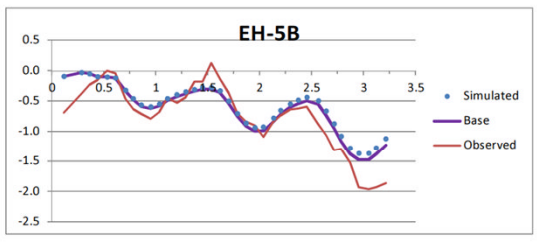


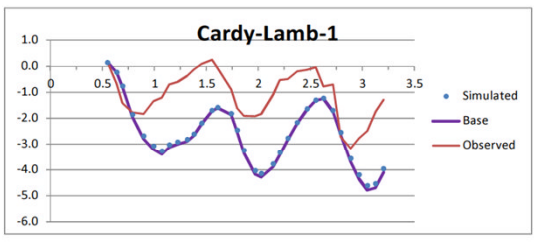


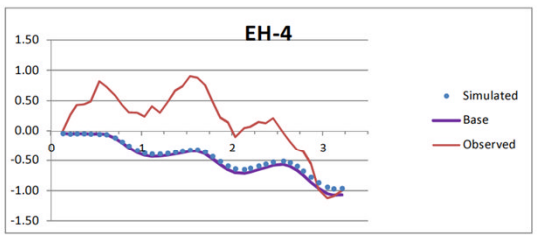


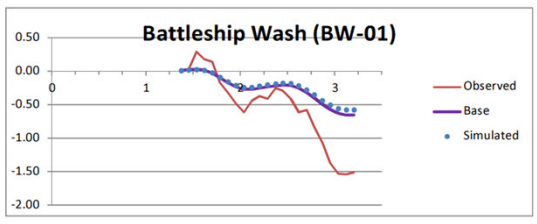


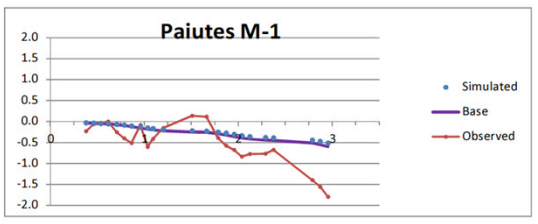


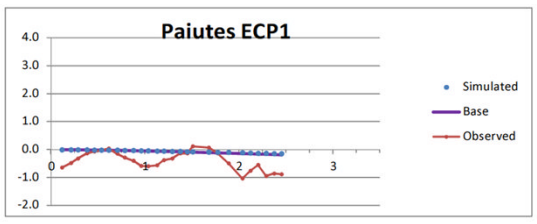


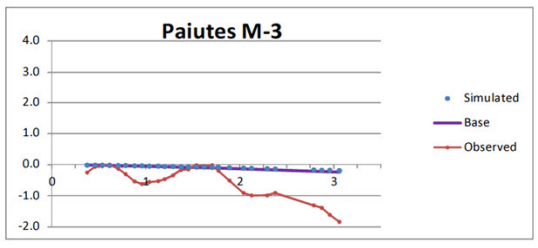


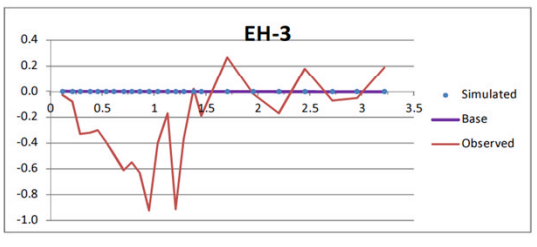


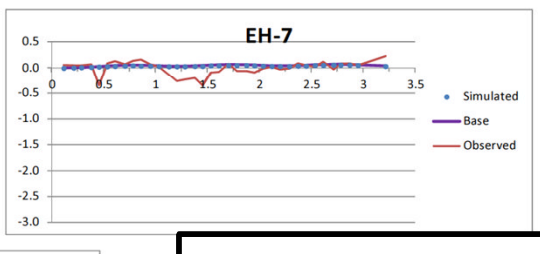


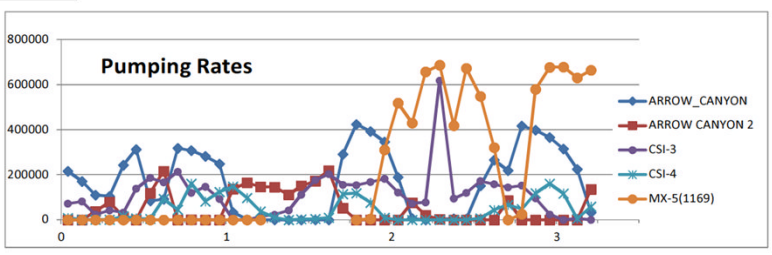








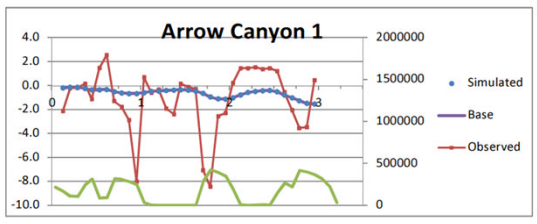


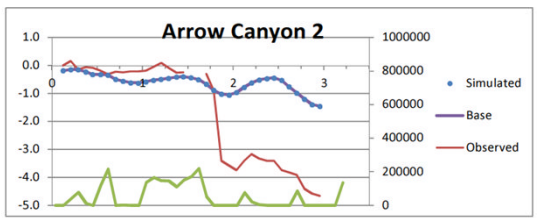


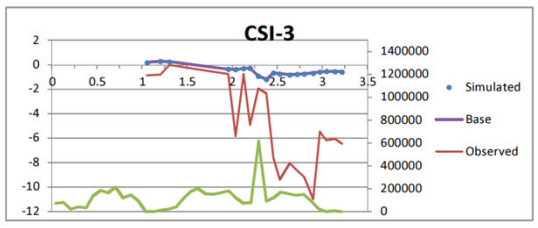
Sensitivity of Simulated Drawdown to Multiplying SY_CAU by 1.125

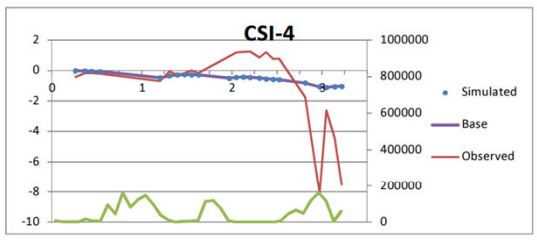
Lower Colorado River Flow System

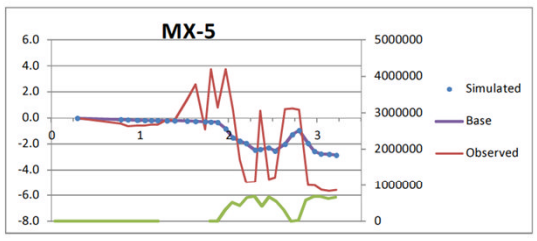
TETRA TECH GEO

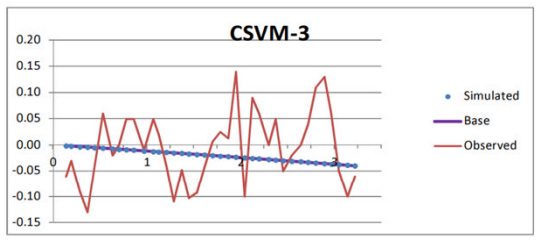


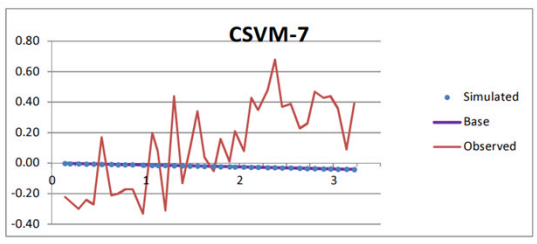


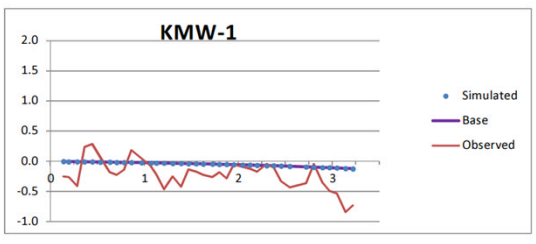


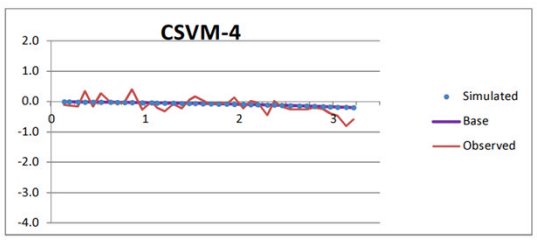


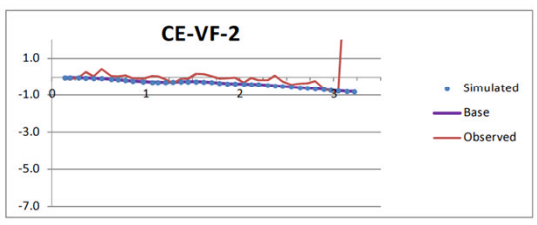


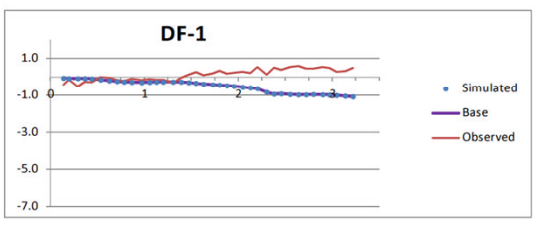


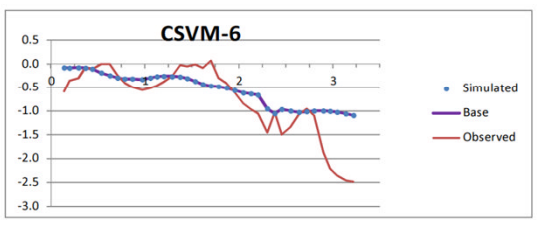


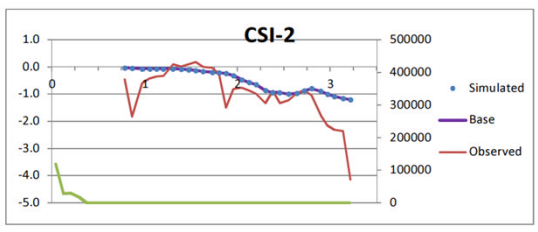


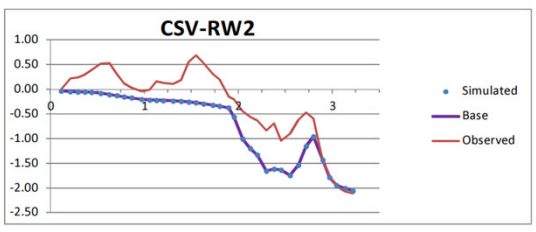


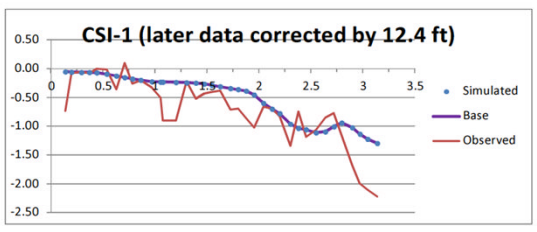


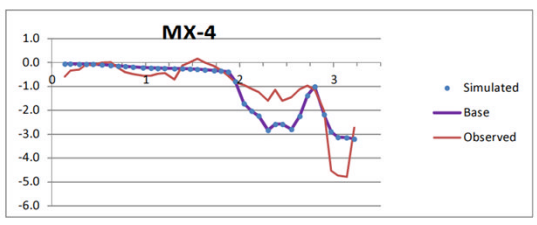


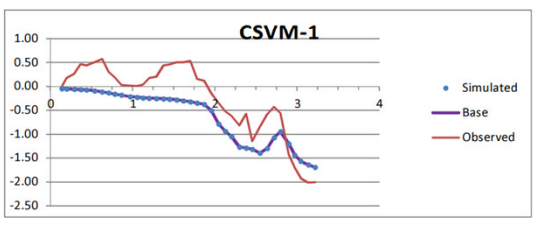


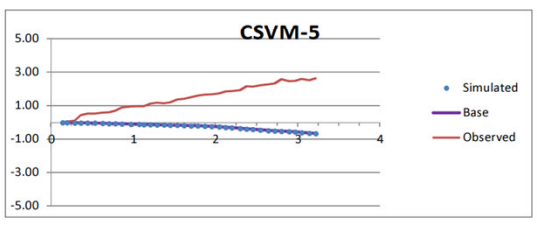


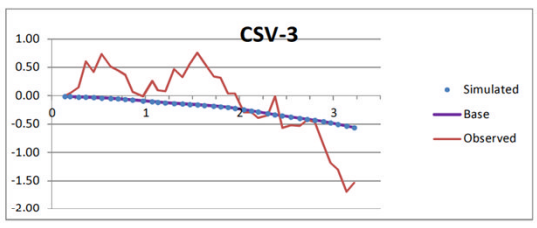


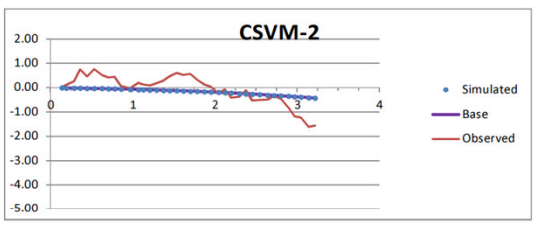


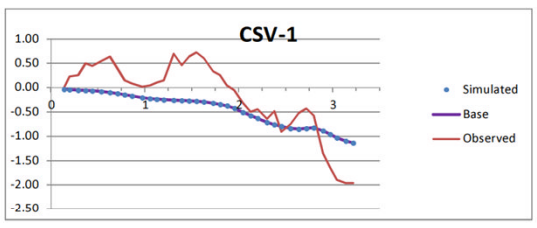


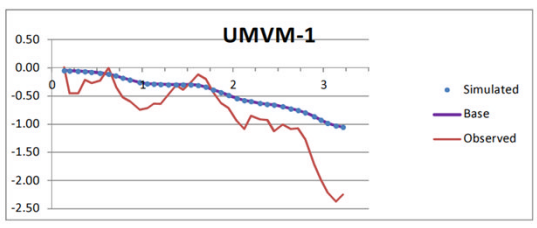


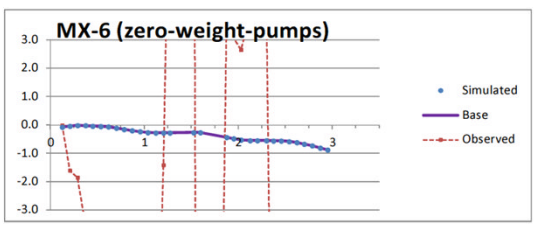


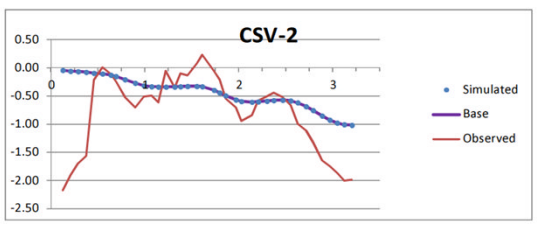


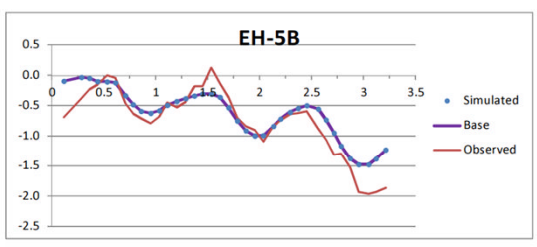


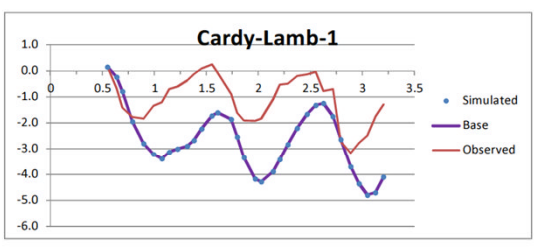


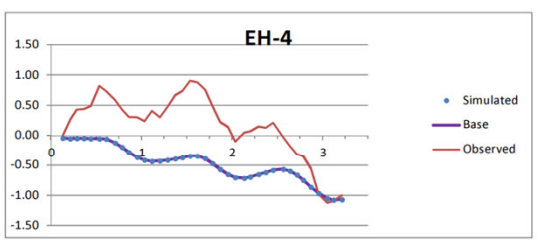


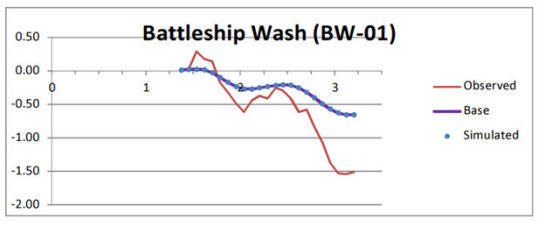


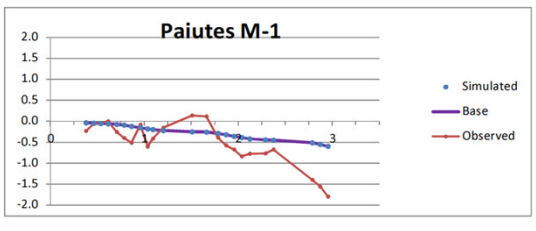


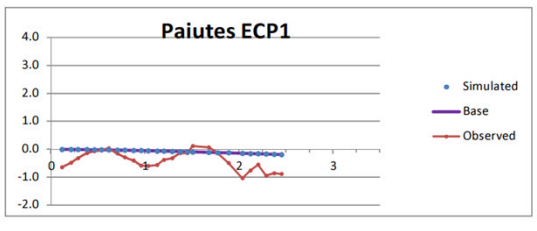


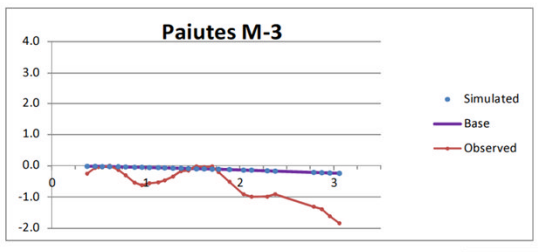


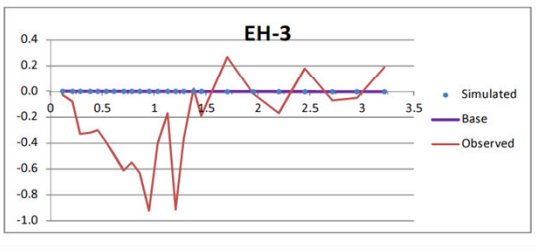


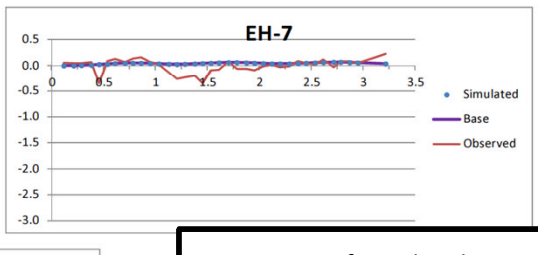


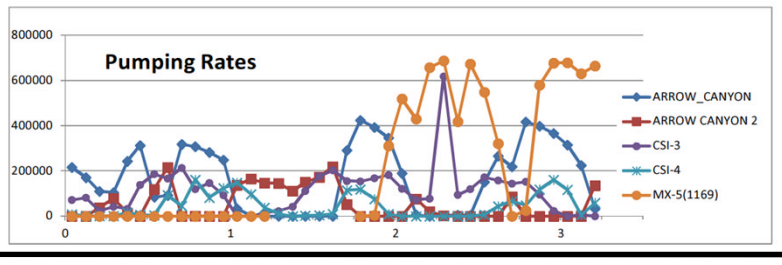








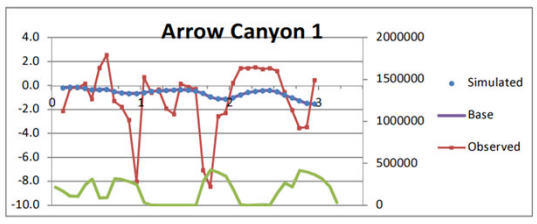


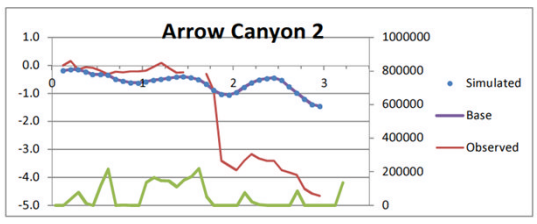


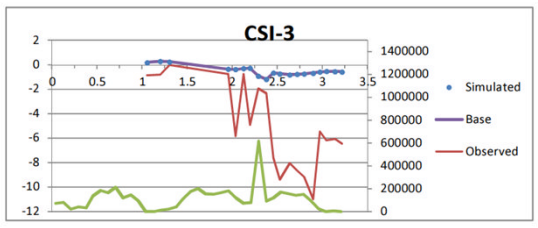
Sensitivity of Simulated Drawdown to Multiplying HF_MMT_N by 2

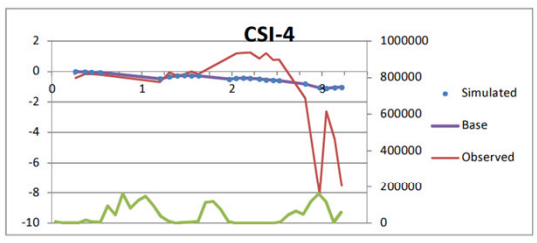
Lower Colorado River Flow System

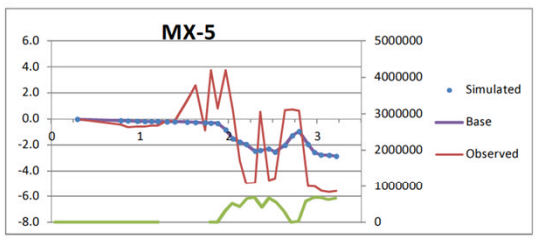
TETRA TECH GEO

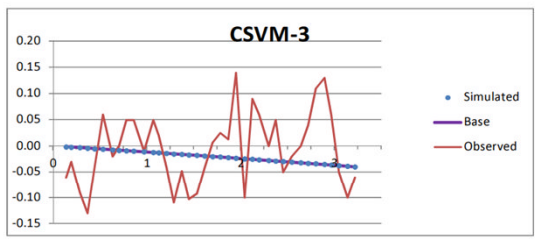


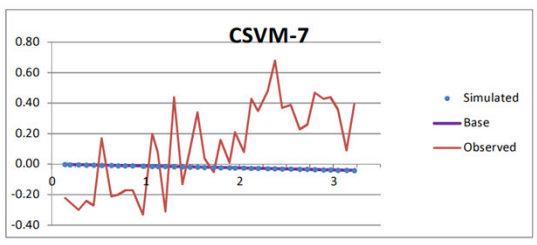


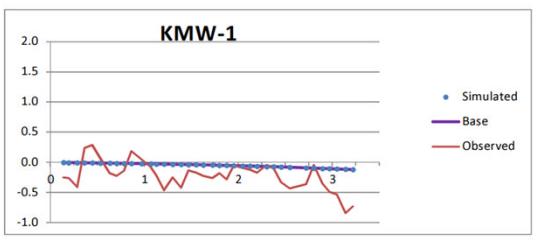


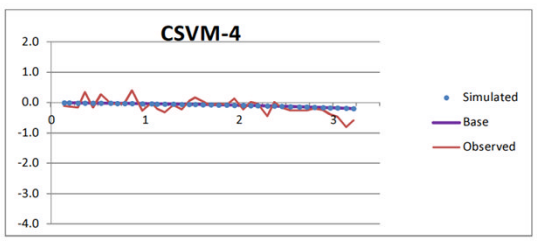


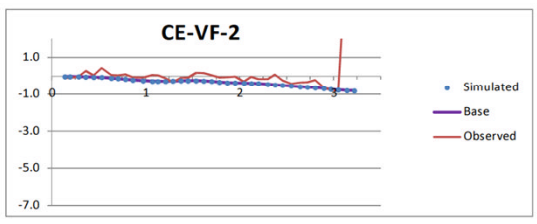


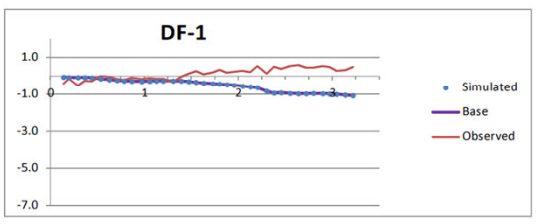


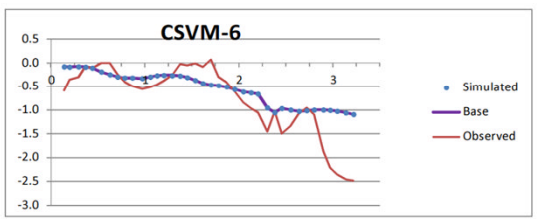


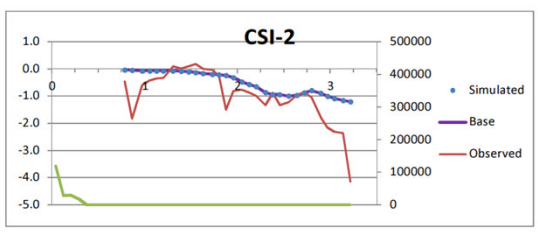


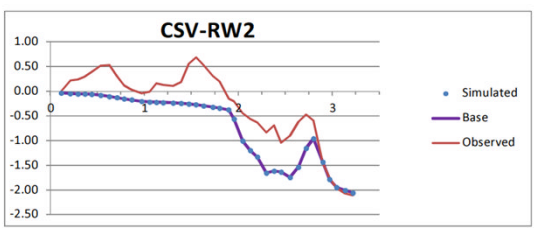


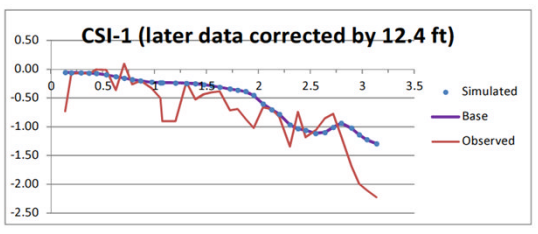


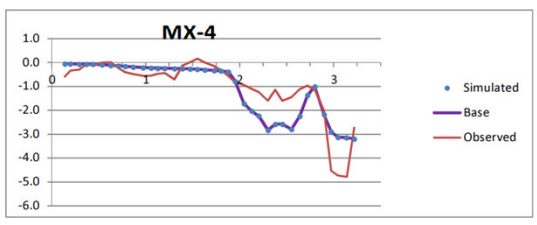


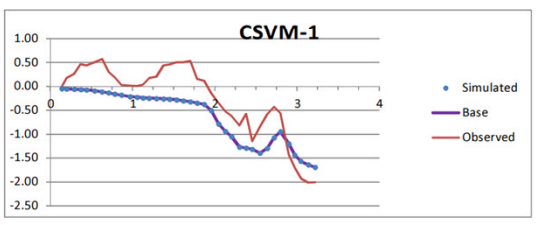


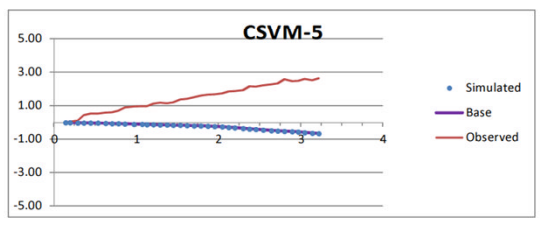


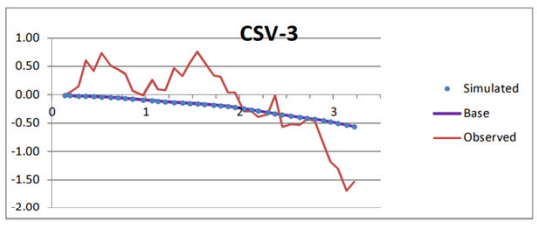


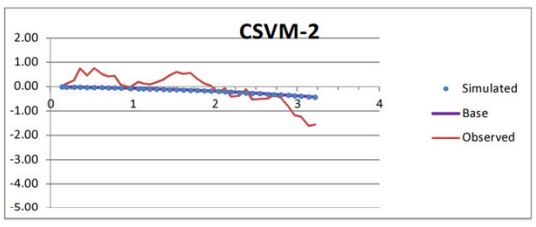


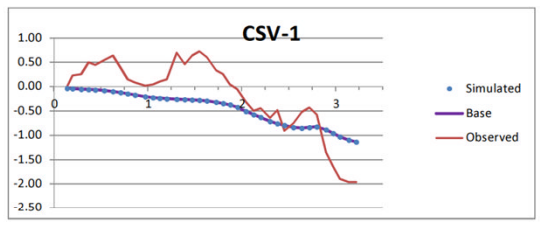


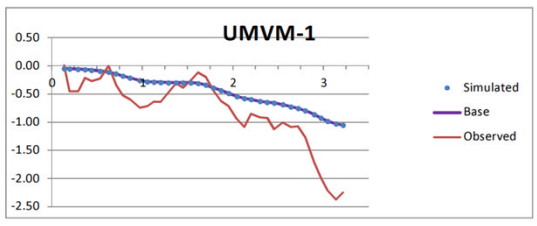


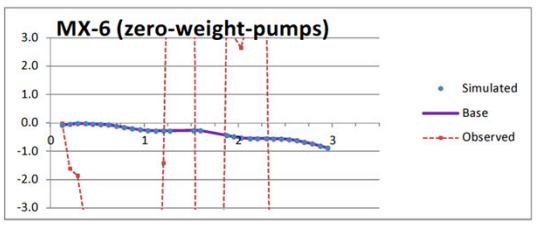


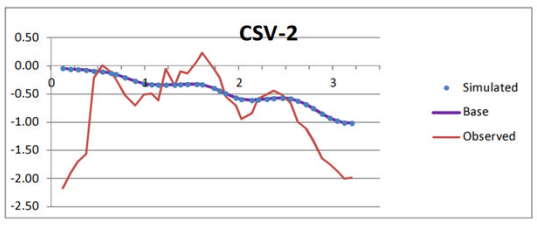


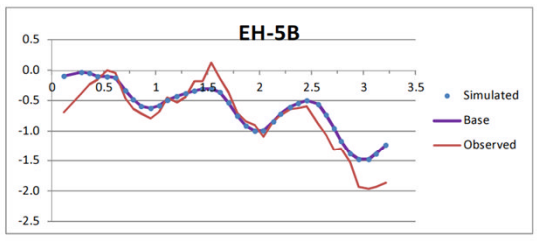


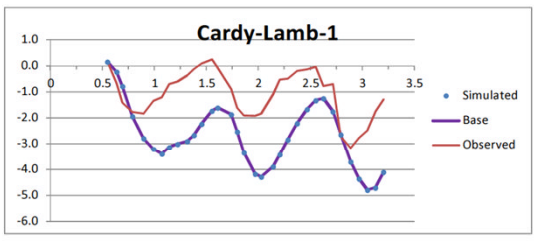


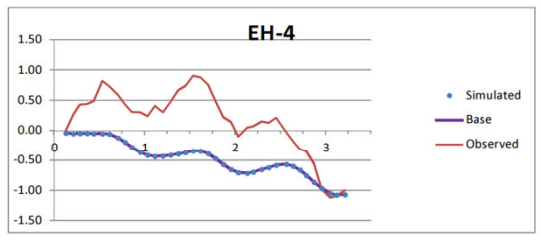


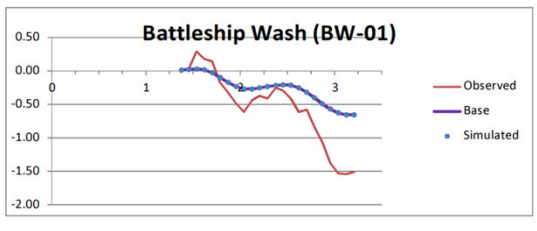


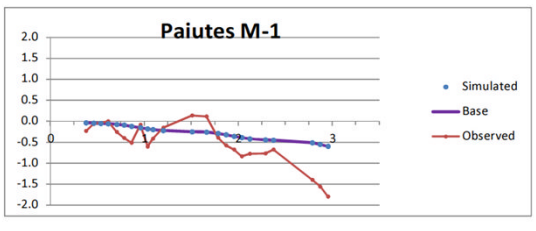


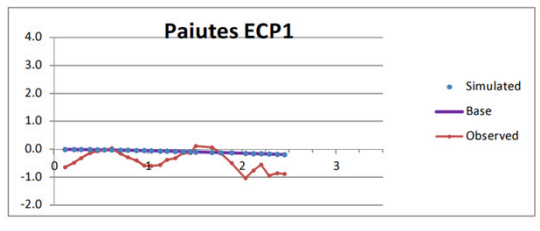


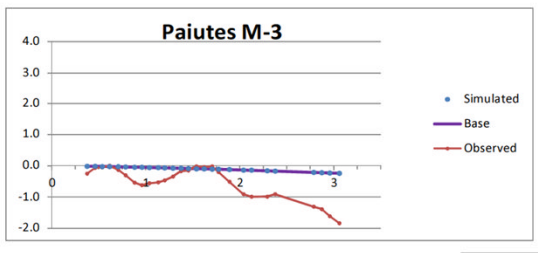


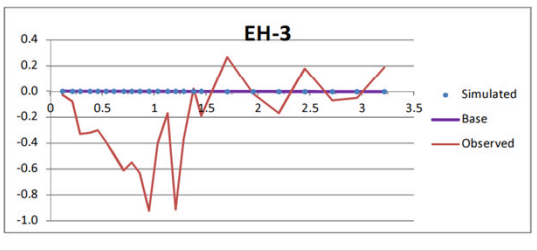


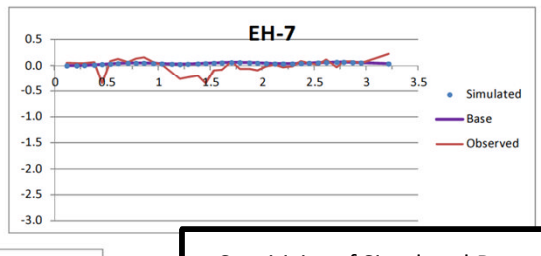


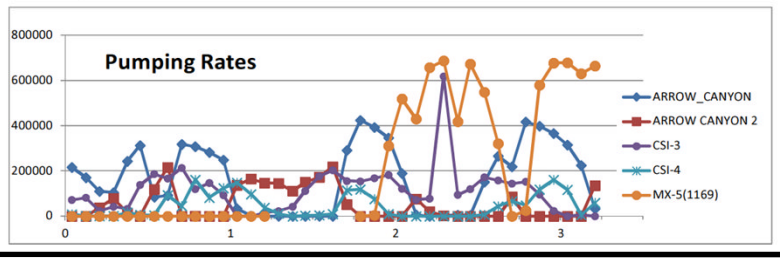












Sensitivity of Simulated Drawdown to Multiplying HF_MMT_S by 2

Lower Colorado River Flow System

TETRA TECH GEO